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GROUND TRANSPORTATION OPTIMIZATION FOR THE MARINE EXPEDITIONARY UNIT DURING HUMANITARIAN ASSISTANCE AND DISASTER RELIEF OPERATIONS

December 2023

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EXPEDITIONARY UNIT DURING HUMANITARIAN ASSISTANCE AND
DISASTER RELIEF OPERATIONS**

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ABSTRACT

This research evaluated the ground transportation equipment belonging to a Marine Expeditionary Unit (MEU) and available for humanitarian assistance and disaster relief (HA/DR) operations. This study will assist military and civilian planners in deciding the most efficient way to move personnel and equipment for a disaster operation. The analysis also aims to provide senior leaders with a more accurate planning aid response before they request support. Natural disasters are not going away, and the MEU represents a capable force with the necessary personnel and equipment to assist in relief operations. The literature review looks at relevant literature surrounding our topic, beginning with recent world events and a short synopsis of what doctrine states about our subject, and then addresses gaps in the information. Our methodology used a linear programming method to develop a transportation model that captures the transportation and materiel handling costs associated with disaster relief response. The results from our research indicate that a mixed composition of vehicles, with heavy usage of Medium Tactical Vehicle Replacement, yields the most cost-effective option for commanders and may allow relief planners a suitable starting point from which to begin planning.

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LIST OF ACRONYMS AND ABBREVIATIONS

ARG	Amphibious Ready Group
BLT	Battalion Landing Team
DOD	Department of Defense
FHA	Foreign Humanitarian Assistance
HA/DR	Humanitarian Assistance and Disaster Relief
HMMWV	High Mobility Multi-Purpose Wheeled Vehicle
JLTV	Joint Light Tactical Vehicle
JP-8	Jet Propellant 8
LVSR	Logistics Vehicle System Replacement
MARFORCOM	U.S. Marine Forces Command
MARFORPAC	U.S. Marine Forces Pacific
MCDP	Marine Corps Doctrinal Publication
MCTP	Marine Corps Tactical Publication
MEU	Marine Expeditionary Unit
MiTAMS	Mission Tasking Assignment Matrix
MTVR	Medium Tactical Vehicle Replacement

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Brandon Futrell

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I. INTRODUCTION

This chapter begins by introducing the authors and their motivation behind the topic. The remainder of the chapter introduces the problem then explains how the authors addressed it.

A. MOTIVATION

In May 2020, I (Captain Gurrister) reported to Combat Logistics Battalion 31 with the 31st Marine Expeditionary Unit (MEU). Prior to reporting. During my time with the MEU time, I served as the Combat Logistics Company Commander with a platoon of Marines specializing in Motor Transportation, Engineering, and Landing Support. Our primary mission was to provide logistical support to the 31st MEU and its subordinate units. An additional billet that I was assigned was the Humanitarian Assistance and Disaster Relief (HA/DR) Mission Officer in Charge, later renamed the Foreign Humanitarian Assistance Mission Officer in Charge. My responsibilities in this role were to be the lead planner, coordinator, and mission executor of all aspects of this mission. The 31st MEU has a robust amount of equipment and Marines who are able to perform a wide variety of missions including humanitarian relief. We successfully executed multiple training exercises on how our unit would plan and execute humanitarian operations if required while deployed.

Planners tended to face the challenge of providing accurate estimates for the amount of time it would take the force to perform certain missions. Specifically, the struggle I had was in estimating the amount of time it would take to clear roads and transport cargo over roadways with unknown conditions. I attempted to research this problem but found nothing that would align well with the forces in the MEU and the type of operations I was planning for. This lack of an available framework resulted in my providing overly wide time estimates that would be revised when on the ground, which was the only time to truly understand the scale of the work that would be required. It is from this experience that the idea for this report came to be and the desire to provide an effective planning tool for humanitarian relief forces.

I (Major Futrell) echo Jason’s sentiments after experiencing similar planning frustrations seven years prior in 2013 as our unit, attached to the 31st MEU, made parallel preparations in response to Typhoon Haiyan, mentioned in Section B. In retrospect, planning seemed to be comprised of guesswork with little reference to guidelines or planning factors specific to disaster relief, but instead, war planning factors—quantities of meals ready to eat, estimates for potable water, vehicle readiness and capabilities, ammunition availability, et cetera. We largely emphasized what we “thought” we would need rather than considering what doctrine says we should if facing a man-made disaster or natural disaster, or when operating within a first-world nation versus the third world. In the latter case, the probability of relying on host nation support or services dramatically diminishes. All of these factors and more served as the impetus for our research in hopes of creating a repository of information that we were sorely missing.

B. BACKGROUND

On November 8, 2013, Typhoon Haiyan made landfall in the Philippines, claiming more than 6,000 lives while injuring more than 28,600 others (Esteban et al., 2015). Haiyan was recorded as the most destructive typhoon on record to have devastated the region, causing severe damage to the eastern islands of Leyte and Samar. I (Major Futrell) was a Second Lieutenant during that time executing a unit deployment program tour with Battalion Landing Team Two Four (BLT-2/4) in Okinawa, Japan while attached to the 31st Marine Expeditionary Unit (MEU). My unit was just concluding our six-month rotation and was scheduled to be replaced by our sister battalion within a few short weeks when Typhoon Haiyan struck the Philippines. During that time, the final decision had yet to be made as to whether BLT-2/4 would deploy to assist with security in support of HA/DR operations in the area, or our successors would be given the assignment. Preliminary planning had commenced immediately upon notification of the impending typhoon and intensified once it struck the coast.

Planning for Haiyan began with discussions around capabilities and maintenance readiness. The storm had damaged an estimated 1,140,332 homes and displaced countless personnel (Esteban et al., 2015). The assignment would ultimately be given to our

replacements, but the decision was not made without a week of deliberations and debates. The approach to supporting the HA/DR mission in the Philippines following Haiyan was not much different from past exercise planning, with heavy emphasis on combat operations, unit deployment and redeployment, and both ground and aerial resupplies—all of which are predominantly rehearsed and executed by Marine logisticians. As unique as planning for these types of operations may be, such planning is diametrically opposed to that of HA/DR mission planning. Whereas the former—exercise planning tailored toward conventional combat—may rely heavily on the supply and resupply of the colloquial “beans, bullets, and band aids,” the latter relies more heavily on beans, band aids, and various other peculiarities associated with disaster response.

The need for a framework from which Marine Corps combat service support planners can glean a baseline of information for initial disaster planning has never been more necessary than today. For more than six decades, natural disaster occurrences have been on the rise, with future incidences anticipated to continue the trend, presumably as a result of global warming (Apte et al., 2013) . The Marine Corps operates as Marine Air Ground Task Forces (MAGTFs) which are integrated combined arms forces comprised of a command, ground, aviation, and logistics element (Department of the Navy Headquarters United States Marine Corps [DONUSMC], 2015). These MAGTFs are further categorized into the following four sub elements: Marine Expeditionary Force (MEF), Marine Expeditionary Brigade (MEB), Marine Expeditionary Unit, and Special Purpose MAGTFs. The focus of our research centers on the MEU as MEUs are routinely forward-deployed for fast response and serve as extensions of their larger MEF and MEB components. MEUs, when embarked aboard Navy Amphibious Groups (ARGs), form ARG/MEUs. Although typically responsible for maintaining a forward presence in key parts of the world, ARG/MEUs historically have responded to immediate crises and contingencies in accordance with their assigned region or location. At any time, ARG/MEUs are expected to be able to project a U.S. presence forward and provide assistance to allies and partners (DONUSMC, 2015).

Currently, the Marine Corps maintains seven standing MEU command elements as shown in Figure 1. Six of these MEUs remain in constant rotation, which allows for a

continuous American presence in key parts of the globe. The seventh MEU—the 31st MEU based in Okinawa, Japan and the most familiar to this paper’s authors—is permanently forward deployed and assigned to the Pacific. The other six MEUs are evenly distributed and assigned to the Commander Marine Forces Pacific (MARFORPAC) and Commander Marine Forces Command (MARFORCOM). Commander MARFORPAC maintains the 11th, 13th, and 15th MEUs while Commander MARFORCOM maintains the 22nd, 24th, and 26th MEUs (DONUSMC, 2015). The depth of operations that ARG/MEUs are capable of conducting is vast yet limited in scope. In 2010, an ARG/MEU was directed to conduct FHA operations in Pakistan while simultaneously conducting antipiracy and combat operations in the Gulf of Aden and Afghanistan, respectively (DONUSMC, 2017). Another MEU found itself conducting FHA operations in Haiti following the 2010 earthquake.



Figure 1. Locations of Marine Expeditionary Units. Adapted from Google Maps (2023).

Since MEUs are the most widely used MAGTF element of the Marine Corps, their relatively small size allows for rapid deployment and fostering a consistent presence anywhere on the globe that suits American interests. It is also for this reason that MEUs are often the first onsite to assist partner nations abroad following a natural disaster, making the study of natural disaster planning essential for those most likely to be involved—the

logisticians. By contributing to the nascent literature surrounding disaster planning, specifically within the Marine Corps, we hope to bridge the gap that currently exists regarding what to focus on during initial planning as it pertains to ground transportation.

C. PROBLEM STATEMENT

This research evaluated the ground transportation equipment belonging to the MEU and available for humanitarian assistance and disaster relief (HA/DR) operations. This study assists military and civilian planners decide the most efficient way to move personnel and equipment for a disaster operation. Previous studies have focused on optimizing air assets in the Marine Corps for disaster relief operations. However, collectively, across the Marine Corps, we must conduct more research on optimizing ground assets. This study addressed the gap in planning for ground transportation, given the challenges that commonly arise following natural disasters with movement on the ground. The study also aims to provide senior leaders with more accurate planning aid response times before they request support. Analyzing Typhoon Haiyan addressed these problems, helping us understand the common challenges associated with providing humanitarian support and the current timelines used. Initially, a transshipment model—a component of a basic transportation model with flows that both give and receive—was believed to be the best option for addressing our problem but was later abandoned due to its complexity and irrelevance for this initial study (Balakrishnan et al., 2013). Instead, we decided that a basic transportation model was more efficient in providing the initial results we sought to optimize cost and time.

Natural disasters are not going away, and the MEU represents a capable force with the necessary personnel and equipment to assist in relief operations (Apte, 2019). The Marine Corps needs a comprehensive planning model for the time associated with moving personnel and equipment on the ground to support disaster relief operations. Although researchers have conducted some studies on Marine capabilities in support of HA/DR operations, they have focused entirely on vertical lift platforms, leaving room for future research on ground equipment (Gastrock & Iturriaga, 2013, pp. 57–58). Another analysis showed that the Marine Corps could be more effective in its response to disasters if it

adjusted how, it employed air assets (Scott & Watson, 2018). Both pieces of research demonstrate a need for research looking at ground equipment for optimizing transportation in disaster operations.

HA/DR operations have long been a storied forte of the Marine Corps MEUs. Still, more doctrine is needed for the combat service support planners planning for and executing these missions. Current doctrine within the Marine Corps defines and addresses the types of foreign humanitarian assistance operations, the role of civil affairs in humanitarian assistance, non-government and government relations during humanitarian aid, and other topics unrelated to logistical planning at the tactical level for planners facilitating support. The absence of this information only complicates and protracts U.S. response—particularly for the Marine Corps—in the event of disasters. The work conducted by Dr. Aruna Apte and Dr. Keenan Yoho in their report titled *Strategies for Logistics in Case of a Natural Disaster* successfully addresses disaster planning as seen in Figure 2. It provides the framework necessary for civilian and military planners to reference as they coordinate supply chain activities in challenging environments.

Logistics Strategy				
Surge	●	●	○	○
Phased Deployment	●	◐	◐	◐
Proactive Deployment	○	○	●	●
Prepositioning	◐	●	◐	◐
Disaster Category	I	II	III	IV
	Dispersed & Sudden	Localized & Sudden	Localized & Slow	Dispersed & Slow

Disaster Classification

○ Undesirable
◐ Desirable
● Very Desirable

Figure 2. Proposed Disaster Polices. Source: Apte and Yoho (2011).

Dr. Apte and Dr. Yoho’s breakdown of disasters into four classifications was the first time either author of this paper had seen a thorough system of disaster classifications linked to a specific logistics strategy as seen in Figure 2. Class I and IV disaster types are characterized as dispersed, sudden, and slow occurring, while Class II and III disasters are

more localized, sudden, and slow occurring. From Dr. Apte and Dr. Yoho's research, we deduced that Class I and II type disasters pose the biggest challenge for Marine Corps logistics planners as their occurrence is sudden and attributable to dispersed or localized regions. For these types of disasters, proactive deployments are undesirable because the sense of urgency and unpredictability is relatively high (Apte & Yoho, 2011, pp. 21–24). It must also be assumed that prepositioning supplies is unreasonable, and therefore, even a cursory review of a HA/DR framework could effectively improve planning.

This research provides a framework from which all seven MEUs can pull information to begin contingency or response planning for HA/DR missions. Since doctrine for these operations is scarce, minor contributions to the subject will enable more focused planning, improve efficiency, and potentially save lives. This model aims to provide planners with a foundation for beginning their planning by highlighting an optimal capacity and low-cost solution for ground equipment utilized during military operations other than war. Although its solutions are predicated on the distribution of Class I Supplies, its utility is applicable to most classes of supply. Uninhibited ground lines of communication—the delivery of supplies and personnel by way of ground transportation—are essential to maintaining tempo during any operation regardless of the type, and by seeking to optimize cargo load capacities while minimizing monetary costs, this paper aims to sustain ground supply chains during HA/DR operations.

D. CHAPTER BREAKDOWN

This chapter introduces the motivation for our study. Chapter II reviews relevant literature surrounding our topic, beginning with recent world events and a short synopsis of what doctrine states about our subject, and then addresses gaps in the information. Chapter III then leads into our research approach, describing how we collected and analyzed our data. Chapter IV showcases our results, particularly highlighting themes and categories discovered from our analysis. Chapter V concludes with our summary and recommendations, paving the way for further development of our conclusions.

II. BACKGROUND AND LITERATURE REVIEW

To help us understand the problem and determine what other research has been done in this field, the authors conducted a literature review to gather information. There is a wide variety of previous research that addresses both the civilian and military aspects of responding to humanitarian disasters. In this review, the authors concentrated mainly on the military's contributions to providing relief support. The inclusion of both civilian and military research was considered to enhance civilian-military efforts and pinpoint gaps that could be addressed in this report.

A. GAPS IN THE LITERATURE

Natural disaster occurrences have been steadily rising over the years (Apte, 2019). Therefore, improvements in doctrine that facilitate faster and more responsive planning by the MEU logistics staff are crucial to successful future implementation. Joint Publication 3-29 (JP 3-29), published in 2019, governs the actions of the United States Armed Forces during joint humanitarian assistance and disaster relief operations. It addresses interagency considerations between governmental, nongovernmental, and multinational partners and their inter-organizations (Department of Defense, 2019). JP 3-29 further designates Foreign Humanitarian Assistance (FHA) as the moniker to describe DOD test activities outside the United States in support of foreign nations or partners (JP 3-29). Our research focuses on these FHA activities, specifically its subcomponent, Foreign Disaster Relief (FDR) missions. Figure 3, taken from JP-3-29, illustrates the causes of FDR missions and the DOD's response to them.

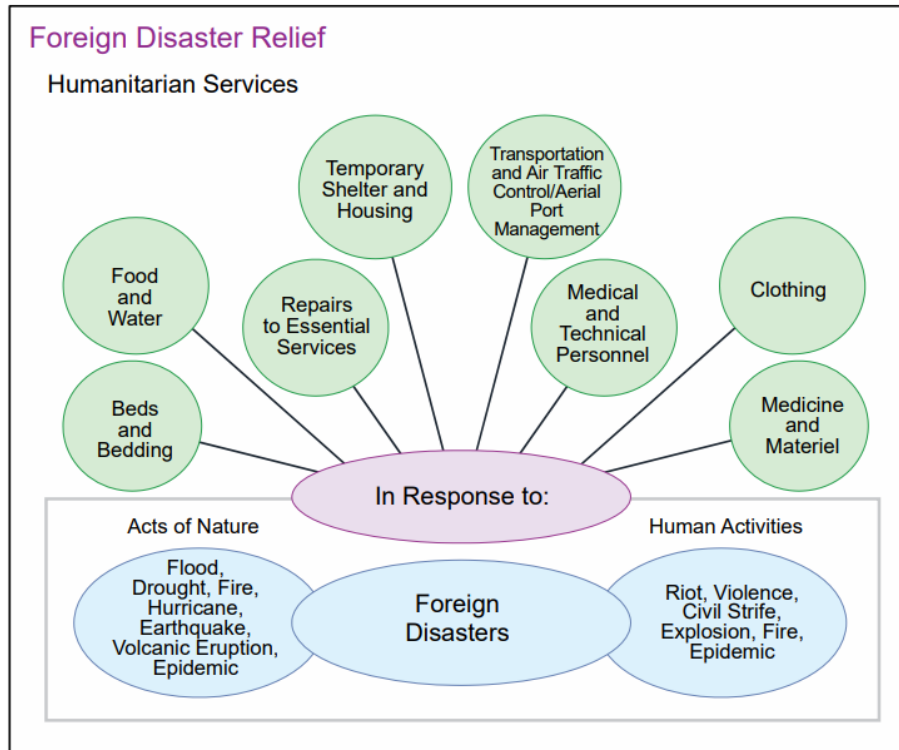


Figure 3. Foreign Disaster Relief Activities. Source: Department of Defense (2019).

B. LITERATURE REVIEW

The following sections are meant to provide additional sources for information related to disaster relief operations. For this the authors used a variety of academic literature, formal publications, and news articles to gather information about the subject.

1. Academic Research

To assist with the literature review, resources detailing humanitarian operations and military efforts during their conduct were reviewed. The writings by Dr. Aruna Apte and Dr. Keenan Yoho were very helpful for understanding previous research that had been done in both of these areas and the types of problems that were encountered. Specifically, the report *Analyzing Resources of the United States Marine Corps of Humanitarian Operations* identified that there are resources that the Marine Corps can bring to disaster relief operations that can ensure that the conduct of the response may be executed more

fluidly (Apte & Yoho, 2014, p. 1). Additional research was also reviewed covering broad topics like logistics strategy. The importance of costs associated with operating different pieces of equipment were highlighted in *The Logistics Support Resource Strategy Map: A Design and Assessment Tool* (Ford & Dillard, 2008, p. 8). This source highlighted that the problem of costs in logistics operations affects both military and civilian operations.

To understand previous efforts made in the military disaster relief environment, the team conducted a review of other thesis projects. The report, titled *An Analysis of Vertical Lift Platforms in Support of Humanitarian Assistance and Disaster Relief Operations*, presents an examination of the problem statement in this project. It provides insights into what the Navy, equipped with aircraft, can contribute to these types of operations (Chirgwin & Katakura, 2020). Other research that has been previously conducted includes efforts that focus on optimizing transportation assets in support of disaster efforts and the need for effective planning tools (Mogilevsky, 2013, p. 27). Mogilevsky's research focused on air planning tools, but similar planning considerations can be applied to ground planning, which is the focus in this work.

A review of formal doctrinal publications was conducted to understand what the Department of Defense's (DOD) planning and guidance was for humanitarian operations with the military. Figure 3 depicts foreign disaster causes and the DOD's policy guidance for reducing human suffering, yet as beneficial as JP 3-29 is to defining the "what" of HA/DR, it leaves the "how" up to the Joint Force Commander and individual service components. Marine Corps Tactical Publication 3-03D (MCTP 3-03D), which focuses on Security Cooperation, is the primary source for Marine Corps logistics planners to retrieve information in anticipation of initial disaster relief planning. Nevertheless, its information is limited in scope. While MCTP 3-03D does address coordination between governmental, nongovernmental, and multinational entities in much the same way as JP 3-29 does, it segues more into the realm of security and stability activities, which, though undoubtedly are just as important, still does not facilitate preparation for the logistics planner (Marine Corps Security Cooperation Group, 2020). As a result, planners will need to combine literature from lessons learned from past FHA operations with service-specific staff planning estimates or tools simply to initiate planning. This due diligence could lead to

precious time being wasted on reinventing the wheel as opposed to making essential advances towards rendering aid. The United States Agency for International Development provides support to many disasters around the world. It also provides manuals and guides to assist planners in a wide range of situations (United States Agency for International Development, 2005). There is a large amount of knowledge that can be gained from employing this agency and looking at the disasters it has supported.

2. Time, Costs, and Resources

The speed at which supplies are able to be transported once in the area of the disaster is greatly affected by the condition of the roads. There is a high potential for downed trees, washed-out roadways, or other debris that severely limit ground transportation assets' ability to move. The time it takes to remove this debris is influenced by the type and size of the debris along with how long it takes to get equipment to the area to begin work. The company StormAdvisor states that factors affecting the time to remove a tree include “the size of the tree, accessibility, tools available, and expertise of the people” (StormAdvisor, 2023). While the location and causes of a disaster may change the need for debris removal, removal remains an enduring part of any disaster relief operation. For reference, the Florida Department of Transportation (FDOT) communication office stated, regarding Hurricane Idalia which made landfall in Florida on August 30, 2023, “To date, FDOT crews have picked up over 100,000 cubic yards of debris within two weeks of Hurricane Idalia making landfall”—(FDOT Communication Office, 2023). This statement reflects the work of proper planning prior to a natural disaster and having a robust number of resources available once the storm has passed. This will not always be the case, especially in countries that the Marine Corps is likely to support.

Cost is an important measurement tool, because it provides a quantifiable value that can be used to compare different scenarios against a common metric. During research, it was found that even in humanitarian disaster efforts, a concern that is faced is the total cost of aid (Apte & Yoho, 2017). It is understandable why planners would need to understand a variety of disasters and different response options in order to come up with a cost estimate. There has been additional research on specific disaster relief efforts that were

supported by the military to better understand the costs associated with them like the work done on the 2011 Tohoku Earthquake and Tsunami. This research found that there was too quick of action to begin working to aid in the disaster before fully understanding the problem (Herbert et al., 2012). This research and others like it again highlight the need to accurately capture what was done in previous scenarios so that they can be improved on in the future.

A big contributor to cost estimates is the type of equipment or supplies that is being used. The main design of U.S. military equipment was not designed with just disaster relief in mind, but this equipment does bring capabilities that are needed in disaster relief (Apte & Yoho, 2018). This article provides a better understanding of the capabilities of different military equipment and how it may be effectively employed from a naval perspective. On the Marine Corps side of the house there has been research into how the Marine Corps can process information requirements when it comes to disaster relief (George & Harbison, 2018). As technology and equipment change, it will increase the need for planners to understand what tool to use for the job. Failure to understand this could significantly increase the costs of responding to disasters worldwide (Apte et al., 2020). The proper combination of costs, resources available, and time allow planners to deliver the best support available while taking into account their limited resources.

III. METHODOLOGY

Our research sought to identify how the MEU could optimize its ground motor transport capabilities while supporting HA/DR operations and provide a baseline planning model that could aid future mission planners in responding to natural disasters. The model must offer estimates that optimize time and cost to accomplish this. Initially, the transshipment model was believed to be the most relevant model for what we sought to accomplish, but we eventually abandoned it in favor of creating a basic transportation model that utilized linear programming to analyze distances, route clearance times, route trafficability (whether a particular route is obstructed or unobstructed), and material handling equipment cost. We also identified routes with the shortest transit time and the most minor obstructions. The transportation model techniques employed during our research originate from the textbook *Managerial Decision Modeling with Spreadsheets*, specifically Chapter V which introduces and discusses the transportation model (Balakrishnan et al., 2013, pp. 161–175). In the end, our goal was to form a mathematical model that minimized the cost of transportation by deciding where to place ground transportation equipment and what routes to take. As is common in real-world scenarios, requirements on the ground may change rapidly and unexpectedly. Therefore, planners should continuously reevaluate this mode—preferably every 24 hours—to optimize transportation costs while ensuring that the supply demands of the affected area are satisfied. This model could then be paired with other models that incorporate constraints based on the probability of events happening to prepositioned supplies (Salmerón & Apte, 2010). The combination of these models would add additional tools to the arsenal of humanitarian disaster relief planners.

A. SELECTION OF THE BASIC MODEL

To enhance our planning, we based our research on the 2013 Typhoon Haiyan in the Philippines, assigning a MEU the task of delivering disaster relief support/supplies to three distinct disaster sites (DS): DS1, DS2, and DS3 (refer to Figure 4). Employing a real-world scenario enabled us to more accurately devise realistic parameters and constraints

for tailoring our model. It also provided a backdrop for us to test the relevance of our model and its solution as we worked through some of the nuances of theoretical assumptions and reality.

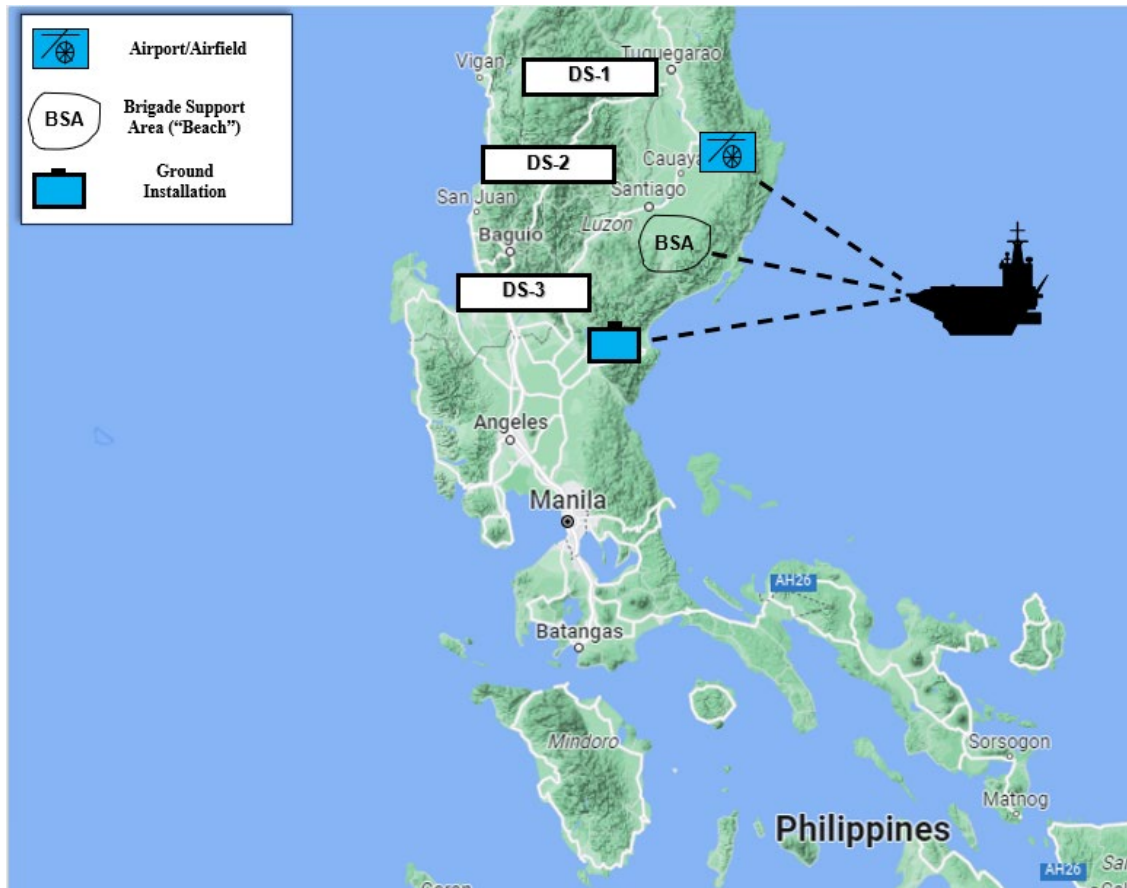


Figure 4. Model of the Proposed Distribution Network. Adapted from Google Maps (2023).

Typically, four main types of equipment—MTVR, JLTV, HMMWV, and LVSR—are utilized for ground transportation whenever a MEU is embarked and deployed. Once it reaches its destination outside the continental United States while supporting HA/DR operations, the MEU may—and for our research, did—establish three base camp locations at an airfield, a beach, and an urban city center. The maximum quantity of supplies available for transport was limited to the carrying capacity of both the ship and the vehicles themselves, not to mention the storage capacity at the staging area: our supply source (s).

Also, storage capacity varied and depended on the site, considering that resupply missions were continuous and involved various other friendly agencies operating in the area.

Three possible routes lead from the base camps to the disaster sites as depicted in Figure 4. Each route has advantages and disadvantages regarding distance, travel speed, and trafficability. Depending on its trafficability, the selected course may incur additional costs, which will dictate the necessary engineering equipment for clearing the way. It is essential to factor in this consideration in the overall cost. We palletized all supplies for ease of transport and accountability. There are a limited number of ground transportation assets available to support operations. Although aircraft are available, the commander wants to plan if all air assets are unavailable for the next 96 hours.

B. VEHICLE CHARACTERISTICS DATA

We selected Typhoon Haiyan to test our model. Selecting a recent disaster provided a realistic baseline for distances and required real-world requirements. The model focused on optimizing the responsiveness of ground equipment in disaster relief operations. It contained a product mix of equipment available to the MEU and was meant to provide support to multiple locations. It also included an additional constraint of route clearance times based on the time required to remove debris from the road, making it accessible for ground vehicles. For the model, transported cargo was consolidated into only items palletized for transport.

1. Ground Equipment Cost

For ground equipment cost, the model only includes the costs of operating based on fuel consumption of the vehicles. The model does not include the costs associated with establishing a base camp from which to run all operations. Such costs would have included items like floodlights, generators, refrigerators, and other equipment required to sustain the disaster relief forces. Table 1 is a collection of the characteristics of the equipment that would be embarked aboard an MEU. The technical manual for motor transportation, *Principal Technical characteristics of U.S. Marine Corps Motor Transportation Equipment TM 11240-ODA*, was used to collect information on fuel efficiency and cargo capacity characteristics of Marine Corps vehicles (Department of the Navy United States

Marine Corps, 2019). The Marine Corps engineering equipment manual, *Principal Technical Characteristics of U.S. Marine Corps Engineer Equipment TM 11275-15/3D*, was used to capture the specifications for the cargo handling capabilities and operating efficiency (Department of the Navy United States Marine Corps, 2010). This information was used to determine the ratio of the number of pallets of cargo that could be carried by a particular platform along with determining the amount of cargo in pounds per miles per gallon of fuel ratio. These ratios provide insight into which piece of equipment is able to transport the greatest amount of cargo in terms of fuel efficiency. The results of the fuel calculations are shown in Table 1. The engineer equipment data was collected from *Principal Technical Characteristics of U.S. Marine Corps Engineer Equipment TM 11275-15/3D*, (Department of the Navy United States Marine Corps, 2009). The engineer equipment listed in Table 1 is not used as a principle means to transport cargo from one location to another; rather, it is required to be paired with motor transportation equipment to facilitate the loading and unloading of cargo. Engineer equipment is not characterized by how many miles per gallon the equipment gets, but rather by the gallons of fuel per hour used while in operation (Department of the Navy United States Marine Corps, 2009, pp. 2–3).

Table 1. Ground Equipment Characteristics. Adapted from Department of the Navy United States Marine Corps (2009, 2010, 2019).

Ground Equipment Characteristics							
TAMCN	Nomenclature	MPG Rate	GPH	Cargo Capacity (lbs)	Fording Depth (in)	Bucket/ Blade Size (in)	Cargo per MPG Ratio
D0001/D0003/ MTVR Family	Truck, Cargo, 7 Ton	4.5	N/A	14000	60	N/A	3111
D00157	Wrecker, 7 Ton	4.5	N/A	N/A, Vehicle Recovery	60	N/A	N/A, Heavy Equipment
D01877/ HMMWV Family	Truck, Utility	11	N/A	4400	30	N/A	400
D00487 / JLTV Family	Joint Light Tactical Vehicle, Utility	12.5	N/A	5100	60	N/A	408
D0876 / LVSR Family	Trailer, Powered, 22.5 Ton, Container Hauler	2	N/A	25000	60	N/A	12500
B0040	Multi-Terrain Loader	N/A	3	N/A, Heavy Equipment	N/A	14	N/A, Heavy Equipment
B0060	Medium Crawler Tractor	N/A	7	N/A, Heavy Equipment	N/A	140	N/A, Heavy Equipment
B0063	Tractor, Rubber-Tired, Articulated Steering, Multi-purpose (TRAM)	N/A	8	N/A, Heavy Equipment	N/A	108	N/A, Heavy Equipment
B0078	120M Motorized Road Grader	N/A	4	N/A, Heavy Equipment	N/A	144	N/A, Heavy Equipment

2. Cargo Capacity per Vehicle in MPG

Table 2 represents the technical specifications of the ground equipment cargo space when compared to its fuel efficiency. Figure 5 shows that based on the maximum off-road cargo capacity of the ground equipment options, the LVSR is the most efficient choice.

Table 2. Ground Equipment Fuel Operating Costs. Adapted from Department of the Navy United States Marine Corps (2009, 2010, & 2019).

Ground Equipment Fuel Operating Costs							
TAMCN	Nomenclature	MPG Rate	GPH	Miles Driven per day	Hours of Operation	Fuel Cost per gallon	Fuel Cost per Day
D0001/D0003/MTVR Family	Truck, Cargo, 7 Ton	4.5	N/A	100	N/A	\$ 2.51	\$ 55.78
D00157	Wrecker, 7 Ton	4.5	N/A	100	N/A	\$ 2.51	\$ 55.78
D01877/HMMWV Family	Truck, Utility	11	N/A	100	N/A	\$ 2.51	\$ 22.82
D00487 / JLTV Family	Joint Light Tactical Vehicle, Utility	12.5	N/A	100	N/A	\$ 2.51	\$ 20.08
D0876 / LVSR Family	Trailer, Powered, 22.5 Ton, Container Hauler	2	N/A	100	N/A	\$ 2.51	\$ 125.50
B0040	Multi-Terrain Loader	N/A	3	N/A	10	\$ 2.51	\$ 75.30
B0060	Medium Crawler Tractor	N/A	7	N/A	10	\$ 2.51	\$ 175.70
B0063	Tractor, Rubber-Tired, Articulated Steering, Multi-purpose (TRAM)	N/A	8	N/A	10	\$ 2.51	\$ 200.80
B0078	120M Motorized Road Grader	N/A	4	N/A	10	\$ 2.51	\$ 100.40

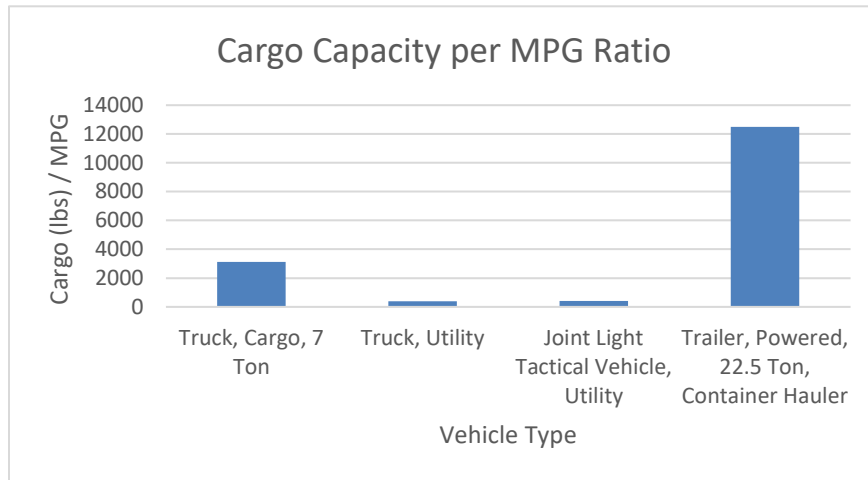


Figure 5. Cargo Weight Capacity per Mile per Gallon Ratio. Adapted from Department of the Navy United States Marine Corps (2009, 2010, & 2019).

3. Fuel Costs

The technical manuals for motor transportation and engineer equipment show that both categories of equipment use a common type of fuel (Department of the Navy United States Marine Corps, 2019). The fuel, JP-8, is provided from the Defense Logistics Agency at a uniform price to the DOD as listed in Table 2 (Defense Logistics Agency, 2023). The miles driven per day and the hours of operation listed in Table 2 are used as baseline values for cost comparison. Utilizing engineer equipment leads to a large total of daily fuel operating costs when compared to motor transportation equipment. This is to be expected as engineer equipment provides motor transportation equipment with the embarkation capability that is needed to move large and heavy cargo. Figure 6 shows a comparison of the daily operating fuel costs of motor transportation and engineer equipment. Certain equipment like the wrecker, 7-ton, only provides a support capability in the form of vehicle recovery. This capability could be useful in disaster relief operations, but for the purpose of this model it does not contribute to the movement of cargo. It is important to note that recovery vehicles must accompany whatever ground equipment is used, because if the motor transportation or engineer equipment becomes stuck or inoperable, they are not able to accomplish their relief mission.

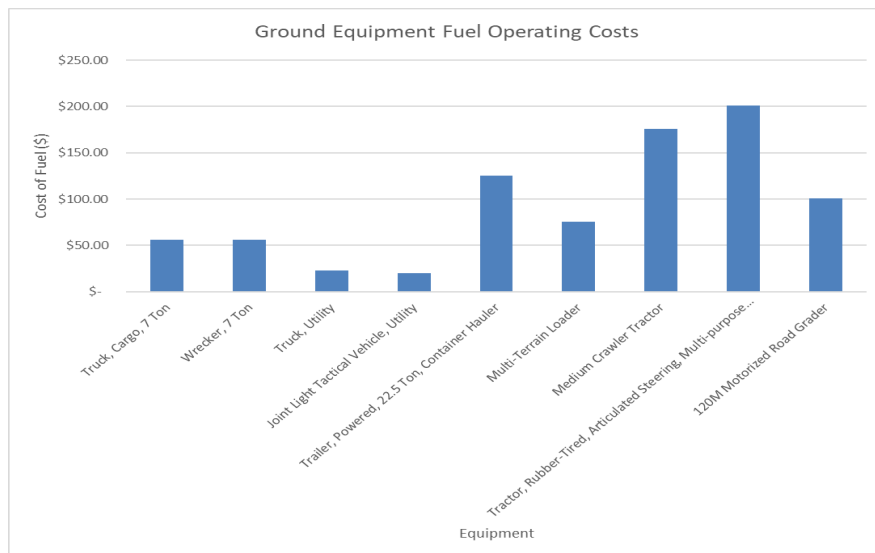


Figure 6. Ground Equipment Fuel Operating Costs. Adapted from Department of the Navy United States Marine Corps (2009, 2010, 2019).

C. DESIGN OF THE MODEL

The planning for a response force to a humanitarian disaster for a Marine Corps unit can start in a wide variety of ways. The flowchart in Figure 7 represents the planning process developed to solve the model for the ground transportation problem. This flowchart is meant to be used within the Marine Corps Planning Process. It does not include what goes into the Marine Corps Planning Process; instead, it begins with the condition that an MEU has been tasked to provide disaster relief support by transporting cargo from one location to another. The flowchart in Figure 7 proceeds as follows:

1. Start – The MEU has been tasked with providing disaster relief support.
2. Input the locations of the supply points and demand points on a map.
3. Determine the requirements for what cargo needs to be moved from each supply location to the demand points. This information will be provided by units located on the ground.
4. Determine all available ground routes between the supply points and demand points. Give each route a name. Determine the trafficability of each route based on information that is provided from units on the ground.
5. Input the number of ground transportation assets that the MEU force will use for this mission (number of 7-tons, JLTVs, etc.). The fuel characteristics for these types of vehicles are known and are already listed in the model.
6. Decision point: Will more than one location be used to support all the disaster sites?
7. If the answer is no, meaning that only one site will be used:
8. With only one supply point, the model can be run to determine the quantity of vehicles that should be used along each route. Before running the model, answer the question, “Is support required”? This question asks if there is still a demand for supplies at a location, representing that the relief operation is still ongoing.

9. After the model has been run, support operations can begin. At a predetermined time (for this model it is run daily), the model should be rerun based on the new supply and demand numbers from each site.
10. Once the answer to the question, “Is support required?” is no, then the process will exit the loop.
11. If the answer is yes for the question asked at Step 6, meaning there will be two or more supply sites used, steps for having two or more supply sites are the same as only having one. The difference is that more routes will be available between the supply and demand points that can be traveled.
12. When the question, “Is support required?” is answered with no, the relief operation is over.
13. All forces will then redeploy back to their home locations.
14. End of the flowchart process.

Ground Transportation Planning Process Flow Chart



Figure 7. Ground Transportation Planning Process Flowchart.

D. RUNNING THE MODELS

In our model, the available supplies exceed the demand requirement at each DS. Also, supply resources at either source are capped at 1,000 short tons, while the demands at DS1, DS2, and DS3 are 100, 500, and 800, respectively. This model description is shown in Figure 8.

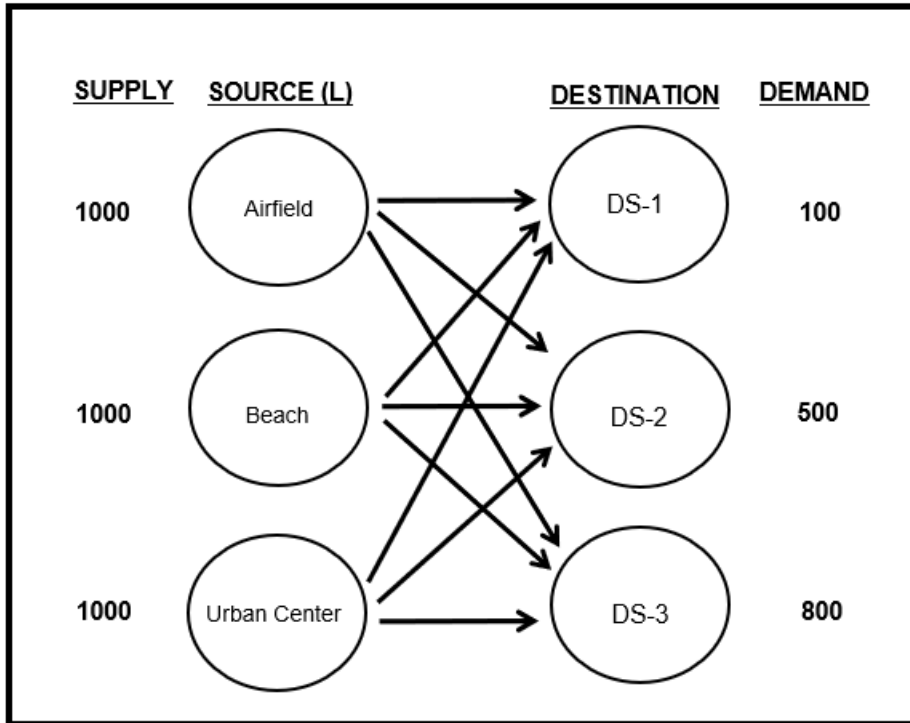


Figure 8. Network Model for Distribution of Supplies to Fictional Disaster Sites (Dummy nodes not utilized)

E. INDICES AND SETS

This section introduces the variables that are used to indicate the source and demand locations that are used in the model.

$s \in S$ The set “s” is comprised of the following sources (S)

$d \in D$ The set “d” is comprised of the following disaster sites (D)

$v \in V$ The set “v” is comprised of the following vehicle type (V)

$r \in R$ The set “r” is comprised of the following route conditions (R)

F. PARAMETERS

To analyze the costs of fuel consumption, each vehicle type was given a variable. Using the variables for distance, price of fuel, and the route condition, a monetary value was calculated.

F_v	Fuel efficiency of vehicle v (in miles per gallon)
$Dist_{sd}$	Distance from source s to disaster site d (in miles)
P	Price of fuel in \$/gallon
$Supply_s$	Supply of cargo in short tons at source s
$Demand_d$	Demand in short tons at disaster site d
Q_v	Quantity of vehicle v
C_v	Carrying capacity of vehicle v
R	Route Condition Codes (C = Clear, L = Low Impact, M = Medium Impact, H = High, Impact, I = Impassable)

G. CALCULATED DATA

Part of the model setup requires a series of calculations based on the quantity and types of vehicles available to the planners. The following paragraphs address the necessary calculations to make the model run successfully.

1. Tonnage Capacity

Each vehicle has a specific cargo capacity that it is able to transport. The model had to calculate the maximum amount of cargo a particular vehicle type could move based on its specifications. Equation (1) calculates the total carrying capacity for a particular vehicle type (C_v) while Equation (2) calculates the total tonnage carried by all vehicles simultaneously.

$$Total_v = Q_v C_v \tag{1}$$

$$TotalTonnage = \sum_v^V Total_v \quad (2)$$

2. Route Condition Cost Multipliers

For the model to perform correctly, it was necessary to provide a numeric value to each route based on its trafficability. Doing this allows the model to compare a short route that is very difficult to travel to a long route with no obstruction. The route condition cost multipliers establish a uniform scale for comparing all routes by assigning a value to each route condition code, which is then multiplied by the total distance of the respective route. Table 3 illustrates the values assigned to each route condition type.

Table 3. Route Condition Cost Multipliers

Route Condition Time Multipliers		
Variable	Route Condition	Multiplier
C	Clear	1
L	Low Impact	1.5
M	Med Impact	2
H	High Impact	3
I	Impassable	100

For this calculation, determine the impact of debris, damage, and flooding on each available route. This calculation is usually performed by the Humanitarian Assistance Surveillance Team or other organizations already on the ground. The calculation is performed as follows:

Based on the assessment of the route from the ground team assign a route condition variable from Table 3. It is also necessary to record the distance of each route, terrain features, or other man-made features. As shown in Equation (3), divide the distance from the airfield to DS1 by the fuel efficiency of a 7-ton vehicle. Multiply this value by P , representing the fuel price per gallon. Then multiply this value by the route condition multiplier, which clearly has a value of 1 in this example. The final value represents the value of the objective function for that vehicle type along that route.

$$\left(\frac{D}{V_F} \times P \right) \times R = \text{Cost to operate particular vehicle} \quad (3)$$

3. Material Handling Equipment (MHE) Additional Costs

In addition to the route cost condition multiplier assigned to each route, capturing the additional cost associated with needing MHE to travel on a particular route is necessary. This is done by assigning a predetermined set of vehicles to a route condition code. The predetermined packages are listed in Table 4.

Table 4. Route Condition Additional Vehicle Costs Plus Additional MHE Costs

Route Condition Additional Vehicle Costs + Additional MHE Cost				
Variable	Route Condition	Multiplier	MHE Package Required	MHE Costs
C	Clear	1	None	\$0.00
L	Low Impact	1.5	Wrecker	\$55.78
M	Med Impact	2	Wrecker, TRAM	\$256.58
H	High Impact	3	Wrecker, 2xTRAM	\$457.38
I	Impassable	100	None, Unsupportable	\$0.00

In Table 4, a low-impact route condition requires the addition of a Wrecker vehicle to assist other vehicles that move along that route. The additional cost of this equipment is shown in Table 4.

$$\frac{Dist_{sd} * P}{F_v} R_{sd} = FuelCost \quad (4)$$

4. Adjusted Weighted Demand Equations

The total demand is the sum of the demand at all demand sites added together.

$$Total\ Demand\ (TD) = \sum_a^D Demand_a \quad (5)$$

To determine the weighted demand for a particular site, a weighted demand approach was used. This calculation is performed by taking the demand of a particular site and dividing it by the total demand of all the sites. The solution is a percentage that is then multiplied by the total demand of all sites. The new solution is the weighted demand for a particular site in short tons. See Appendix (Equations 16–18) for a complete breakdown of each disaster sites demand requirements.

$$WeightedDemand (\%) = \frac{Demand_d}{TD} \times 100 \quad (6)$$

$$Adjusted\ Demand\ Tonnage = WeightedDemand \times \sum_v^V C_v \quad (7)$$

5. Weighted Demand Calculations

The reason for the adjusted weighted demand is that the actual demand for all sites is currently more than can be moved in a single movement. The calculations used to determine the maximum amount of cargo that can be moved by each vehicle type are shown by Equations (8) through (12) in section F1 of the Appendix. For example, all 7-ton vehicles can only move 189 short tons in a single movement. Realizing this, the Commander has determined that all sites will be supported according to a weighted average of what their actual demand is, multiplied by the max amount of cargo the vehicles can support.

The results of performing the weighted demand calculations are shown in Table 5. The final values show the maximum amount of cargo that can be moved by a single vehicle type and the combined total of all vehicle types.

Table 5. Maximum Amount of Cargo That Can Be Moved

Max Amount of Cargo That Can be Moved			
Type of Vehicle	Quantity of Vehicles	Max Cargo per Vehicle (sht. Tons)	Total Cargo for Vehicle Type (sht.tons)
MTVR (7ton)	27	7	189
JLTV	40	2.55	102
HMMWV	20	2.2	44
LVSR	4	12.5	50
Max Cargo (sht. Tons)			385

6. “if Loop” MHE Cost Addition

An “if Loop” command was used in the LP model to identify and add the cost for MHE use in accordance with the route condition. The following highlights how the command was used to calculate this cost (Note: “#” refers to Q_v , the quantity of vehicles):

Example: $\sum \#7\text{ton Airfield to DS1} + \#\text{JLTV Airfield to DS1} + \#\text{HMMWV Airfield to DS1} + \#\text{LVSR Airfield to DS1}$

$$\text{if } \sum X + Y + Z + W \geq 0$$

if true : add the MHE cost for that route based on the route condition

if false : there is no additional MHE cost

H. DECISION VARIABLES

The decision variables for the model solve for the type of vehicles that should be used for a particular route and the quantity of those vehicles that are required.

$$Q_{sdv} \quad \text{Number of vehicles of type } v \text{ sent from } s \text{ to site } d.$$

I. FORMULATIONS

With the set-up calculations now performed, the results can be input into the model. The following sections addressed the objective function and constraint functions used in the model.

1. Objective Function

The objective function that follows minimizes the costs for transportation of supplies by multiplying the cost associated with each route by the number of vehicles assigned to that route based on vehicle type.

$$\text{Minimize the cost of transportation } \sum_s^S \sum_d^D \sum_v^V Q_{sdv} \text{FuelCost}_{sdv}$$

2. Constraints

The first constraint, Equation (13), ensures that the model does not assign more supplies to a particular vehicle type than it can carry. Equations 16, 17, and 18 in section F2 of the Appendix address the demands at the three demand sites, while Equation (14) addresses the minimum demand at each site. Due to the total actual demand at all three sites exceeding the combined cargo capacity of all the vehicles used in the model, we considered the weighted demand calculation. To ensure that each site receives some

supplies, we base the new demand on a weighted ratio between the original demand at a disaster site and its proportion to the total demand. These constraints ensure that each site receives, at a minimum, a predetermined number of supplies. Lastly, Equation (15) provides that the value must be an integer for the objective formula’s output. This step prevents the assignment of “partial” vehicles to a route. For example, the model does not allow 7.5 JLTVs to be assigned to a route, ensuring that each vehicle is fully loaded each time.

Maximum tonnage of supplies to disaster site by vehicle-type subject to vehicle costs.

$$\sum_d^D \sum_v^V Q_{sdv} C_v \leq \text{Supply}_s \quad \forall S \quad (13)$$

Minimum tonnage of supplies from source by vehicle-type subject to vehicle costs.

$$\sum_s^S \sum_v^V Q_{sdv} C_v \geq \text{Demand}_d \quad \forall D \quad (14)$$

Ensures that the program only delivers solutions that are integers and not fractions.

$$Q_{sdv} \text{ are integers} \quad (15)$$

3. Costs

The model assigns the type of vehicle (X, Y, Z, W) and quantity of that type of vehicle to a particular route. Each route has a unique distance and route condition based on the supply source and demand destination selected by the model. Each route has its distance inserted into Table 6 based on the vehicle type. Based on the fuel consumption of that vehicle over the route distance, the cost is multiplied by the route condition multiplier. This value is reflected in the Adjusted Daily Cost column of Table 7 with this value being used in the objective function for the model. The MHE costs are calculated based on the route condition code and are reflected in the “MHE Cost” column. See Appendix, sections A–D and Tables 19–38 for raw data that was used to determine the cost value of each variable in the objective function.

Table 6. Transportation Costs Adjusted for Route Conditions

Transportation Costs by Vehicle Type					
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)	MHE Cost
Truck, Cargo, 7 Ton	Airfield to DS1	Clear	24	\$ 13.39	\$0.00
	Airfield to DS2	Clear	30	\$ 16.73	\$0.00
	Airfield to DS3	Clear	10	\$ 5.58	\$0.00
	Beach to DS1	Clear	16	\$ 8.92	\$0.00
	Beach to DS2	Clear	21	\$ 11.71	\$0.00
	Beach to DS3	Clear	25	\$ 13.94	\$0.00
	Urban Center to DS1	Clear	20	\$ 11.16	\$0.00
	Urban Center to DS2	Clear	18	\$ 10.04	\$0.00
	Urban Center to DS3	Clear	22	\$ 12.27	\$0.00

Table 7. Transportation Costs by Vehicle Type

Transportation Costs by Vehicle Type				
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)
JLTV	Airfield to DS1	Clear	24	\$ 4.82
	Airfield to DS2	Clear	30	\$ 6.02
	Airfield to DS3	Clear	10	\$ 2.01
	Beach to DS1	Clear	16	\$ 3.21
	Beach to DS2	Clear	21	\$ 4.22
	Beach to DS3	Clear	25	\$ 5.02
	Urban Center to DS1	Clear	20	\$ 4.02
	Urban Center to DS2	Clear	18	\$ 3.61
	Urban Center to DS3	Clear	22	\$ 4.42

J. DISCUSSION

In the previous sections, we have demonstrated the mathematical viewpoint of setting up and executing the model equations. The upcoming areas show how to use the model in Microsoft Excel so that planners can edit its parameters to fit their situation.

1. Software Use

This section explains how Microsoft Excel and Solver run each model iteration. The complete model consists of individual data sheets that relate only to that model

iteration, meaning that data about the costs to travel on clear routes applies only to the iteration with clear routes. How to use the model will be explained in the next paragraph.

2. Model Use

The model uses prebuilt equations to assist the user with calculations. The steps required to run the model are as follows:

1. In the Route Table sheet, input the types of vehicles that are available, each vehicle's fuel efficiency, and the price of fuel.
2. In the Route Table sheet, define all the routes available from the supply sites to the disaster sites. In this model there are three supply sites and three disaster sites.
3. Using the drop-down menu, select the route condition code that applies to that route (If the route has major debris on it that will slow travel, select high impact).
4. Input the distance in miles for each route. Once this value has been entered, the model will automatically calculate the adjusted daily cost from transportation for a vehicle type along that route. This cost is calculated by using an equation for a particular vehicle's fuel efficiency, fuel cost, and distance traveled.
5. Based on the route condition code selected from that route, a value will be automatically populated in the MHE cost cell if that route will require additional equipment in order to be used.
6. This process is repeated for each vehicle type. For this model, there are four vehicle types.
7. On the model routes sheet in Excel, the user will begin inputting their supply constraints.
8. The transport constraints are related to the maximum amount of cargo that can be moved by each vehicle type. To use this equation, the user will input the number of a certain type of vehicle that is available for use. The model

will multiply the quantity of a certain type of vehicle by its cargo capacity to get the total cargo space for that vehicle type (There are 27 7-ton vehicles each with a 7-ton cargo capacity. So, $27 \times 7 = 189$ short tons of capacity is available for all the 7-ton vehicles). This step is repeated for all other vehicles.

9. Formulating the supply source constraint equations requires the user to input the cargo capacity for each vehicle type in the row associated with the supply source. For example, if the airfield is the supply source, then all routes must start at the airfield in order for the cargo to be loaded. In the equation, the amount of cargo being moved is calculated by the amount of cargo that an individual vehicle type can hold multiplied by the number of those vehicles assigned to that route. This process is repeated for each vehicle type that uses the same supply source. This process is repeated for the other supply sources.
10. For the demand constraint equations, the process is similar to that in step #9, but instead of looking at the supply source, the user is focused on the demand point (focus on all routes that lead to a particular demand point). The value for each cell is related to the cargo capacity of an individual type of vehicle that is using that route. This process is repeated for all demand points.
11. The user is now able to use the Solver application in Excel to input the objective, decision variables, and constraints based on the equations listed earlier. The user will solve this problem using Simplex LP option in Solver.
12. After all the inputs are captured and the user clicks “Solve” if all parameters are satisfied, Solver will state “A solution has been found.” The user will then be able to see the values that the program has assigned to the decision variables. These values represent the quantity of each vehicle type that will use a particular route.
13. Now that a solution has been found, there is an equation built into the model that will add the additional MHE costs if required. The equation is executed

using a Microsoft Excel “if” function. The function will determine, from the solution values, the best route for a particular vehicle and then factor in the additional MHE cost. If a route does not have any vehicles using it, then the equation will add a value of “0” indicating that there is no additional MHE cost for that route.

14. The total costs for transportation and MHE are recorded in the model summary and provide the user an easy comparison of costs.

The model incorporates four different vehicle types, each with its own cargo capacity, and assigns them to routes. There are three supply nodes and three demand nodes in this transportation network, with the routes in between being classified based on their trafficability. Routes that are more difficult to travel require additional fuel and MHE equipment in order to be used. With demand being greater than the lift capacity of all vehicles in the system, a weighted priority system is used to ensure that all disaster sites receive some supplies. The model seeks to minimize cost and is able to return the number of each vehicle type that should be assigned to a route, the total transportation cost, and the additional MHE cost as the final solution. Chapter IV discusses the data, results, and analysis of the model.

IV. RESULTS

The model ran successfully for five different iterations by changing the route conditions for various routes. The following sections analyzed the results from different parts of the model.

As a result of using the model, the new transportation model diagram is shown in Figure 9. The number of supplies at each source has remained constant, but the demand values have been updated based on the weighted demand calculations that the model performed.

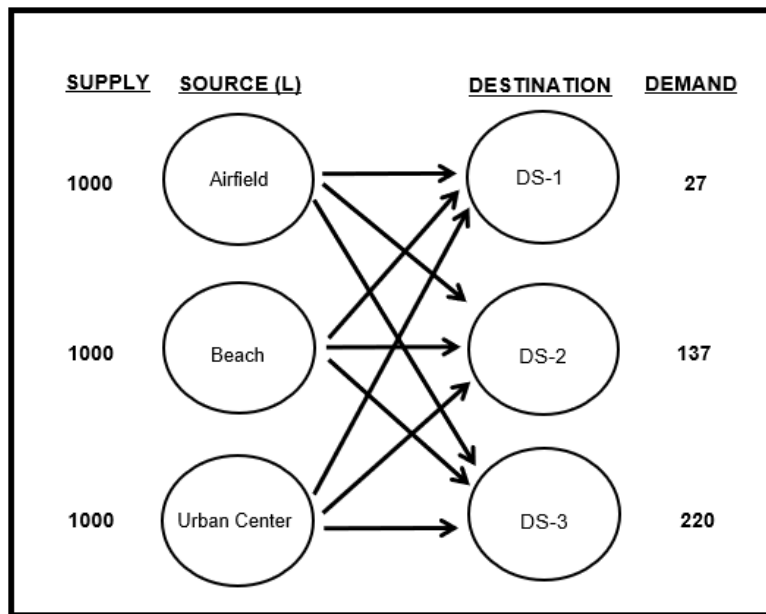


Figure 9. Network Model Distribution of Supplies to Fictional Disaster Sites Based on Weighted Demands

A. MODEL DEVELOPMENT ISSUES

To test the model in its most basic form, the team started with only one vehicle type to prove that the model solved the problem. The model added a second vehicle type, and that's when it uncovered an issue of lift capacity versus the actual demand at the sites. The team solved this problem by using the weighted demand calculations shown in Chapter III.

Using these calculations would ensure that the demand at all the sites would not exceed the lift capacity of all the vehicles in the model. After achieving satisfactory results with our two-vehicle model and updated demand requirements, the team built the final version of the model that would incorporate four vehicle types, three supply sources, and three demand sites.

B. LINEAR PROGRAMMING ANALYSIS

The model was run a total of five times under various route conditions. The distances between sites were kept constant for each model iteration to allow for a cost comparison. As seen in Table 8, as the severity of the route’s increases, so does the total cost and the MHE cost associated with meeting the demand requirements. Table 8 also provides a comparison for what percentage of the total cost is generated from the additional MHE equipment that is required to travel on impacted routes.

Table 8. Model Total Costs Comparison

Total Costs Comparison				
Iteration	MHE Cost (\$)	Transportation Cost (\$)	% of MHE Cost of Total Cost	Total Cost (\$)
All Clear Routes	\$0.00	\$426.71	0.00%	\$426.71
All Medium Routes	\$769.73	\$853.42	47.42%	\$1,623.15
All High Routes	\$1,372.13	\$1,280.13	51.73%	\$2,652.26
Mixed Routes #1	\$568.93	\$954.81	37.34%	\$1,523.75
Mixed Routes #2	\$312.36	\$674.00	31.67%	\$986.35

Figure 10 provides a graphical representation of the costs associated with each model. As the routes increase in difficulty to travel on, the MHE cost becomes a much larger percentage of the total cost. Eventually, if all routes are impacted to a certain degree, there will be more costs from the amount of MHE equipment needed than the actual transportation of cargo along the routes.

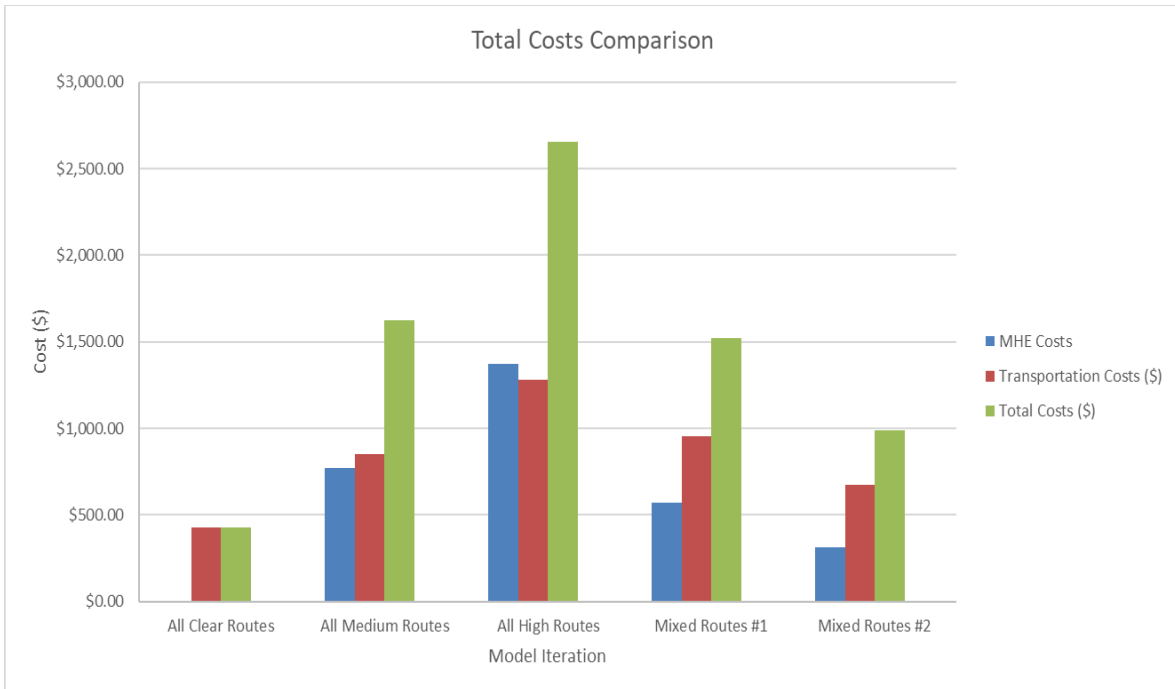


Figure 10. Total Costs Comparison

Figure 11 shows how the percentage of MHE costs changes as the route conditions change for each model iteration. Besides the first iteration that required no MHE support, all other iterations' total costs were made of at least 1/3 MHE costs. This total cost may seem high, but it should be noted that all the distances for routes were less than 30 miles. The MHE costs are calculated based on the equipment's hours of operation and not on how long a particular route is. If the MHE did have to clear a longer route, it would be expected to take more time, but it would not rise at the same rate transportation costs increase for having to travel longer distances.

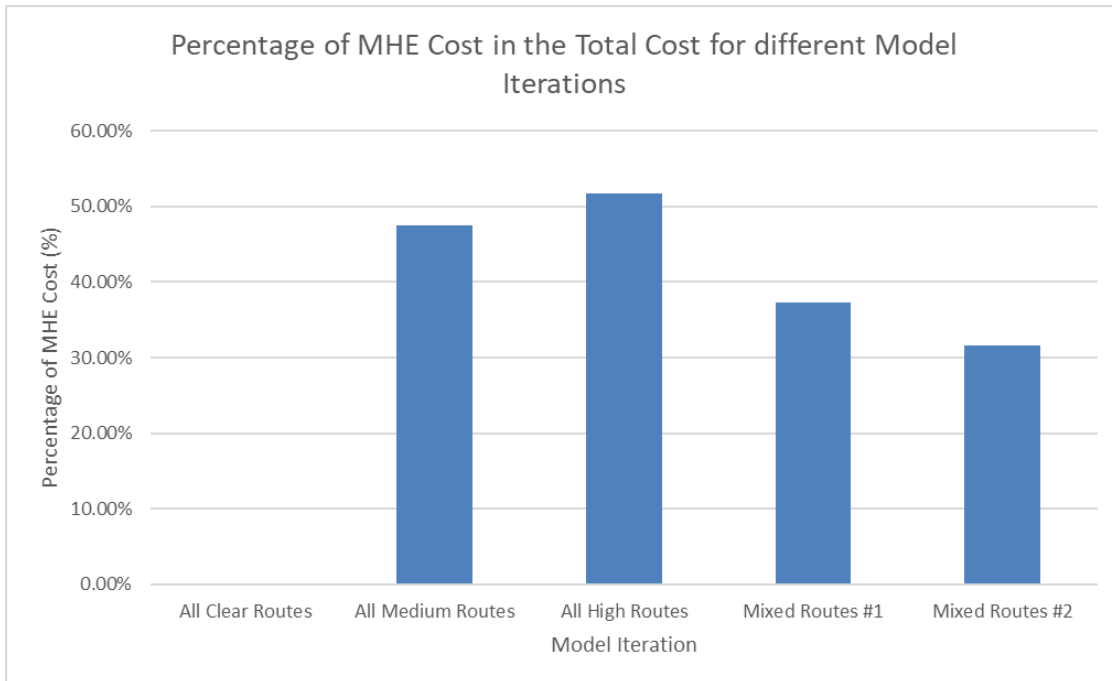


Figure 11. Percentage of MHE Costs in the Total Cost

C. MODEL OUTPUTS

Tables 9–18 represent the five outputs from the model iterations. Each model shows the number of, and which type of vehicles should be assigned to each route. Using this model at regular intervals would allow planners to understand how to minimize the cost of transportation while meeting the demand requirements in the model.

Table 9. All Routes Clear Model Iteration

		All Routes Clear Iteration																																															
		Transportation to Destination Routes																																															
		Airfield to DS1 via 7 ton	Airfield to DS1 via JLTV	Airfield to DS1 via HMMWV	Airfield to DS1 via LVSR	Airfield to DS2 via 7 ton	Airfield to DS2 via JLTV	Airfield to DS2 via HMMWV	Airfield to DS2 via LVSR	Airfield to DS3 via 7 ton	Airfield to DS3 via JLTV	Airfield to DS3 via HMMWV	Airfield to DS3 via LVSR	Beach to DS1 via 7 ton	Beach to DS1 via JLTV	Beach to DS1 via HMMWV	Beach to DS1 via LVSR	Beach to DS2 via 7 ton	Beach to DS2 via JLTV	Beach to DS2 via HMMWV	Beach to DS2 via LVSR	Beach to DS3 via 7 ton	Beach to DS3 via JLTV	Beach to DS3 via HMMWV	Beach to DS3 via LVSR	Urban Center to DS1 via 7 ton	Urban Center to DS1 via JLTV	Urban Center to DS1 via HMMWV	Urban Center to DS1 via LVSR	Urban Center to DS2 via 7 ton	Urban Center to DS2 via JLTV	Urban Center to DS2 via HMMWV	Urban Center to DS2 via LVSR	Urban Center to DS3 via 7 ton	Urban Center to DS3 via JLTV	Urban Center to DS3 via HMMWV	Urban Center to DS3 via LVSR												
Number of vehicles		0	0	0	0	0	0	0	0	9	39	18	4	3	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										
Adjusted Costs for Objective Function		\$13.39	\$4.82	\$5.48	\$30.12	\$16.73	\$6.02	\$6.85	\$37.65	\$5.58	\$2.01	\$2.28	\$12.55	\$8.92	\$3.21	\$3.65	\$20.08	\$11.71	\$4.22	\$4.79	\$26.36	\$13.94	\$5.02	\$5.70	\$31.38	\$11.16	\$4.02	\$4.56	\$25.10	\$10.04	\$3.61	\$4.11	\$22.59	\$12.27	\$4.42	\$5.02	\$27.61	\$400.77											
Constraints																														LHS	Sign	RHS																	
Total Vehicle Assets	Tonnage via 7-tons Available, X	7				7							7																											189	<=	189							
	Tonnage via JLTV's Available, Y		1				1								1																											40	<=	40					
	Tonnage via HMMWV's Available, Z			1				1								1																											18	<=	20				
	Tonnage via LVSR's Available, W				12.5				12.5								12.5						12.5																					50	<=	50			
Supply Sources	Max Airfield Supply	7	1	1	12.5	7	1	1	12.5	7	1	1	12.5																															170	<=	1000			
	Max Beach Supply													7	1	1	12.5	7	1	1	12.5	7	1	1	12.5																					21	<=	1000	
	Max Urban Center Supply																										7	1	1	12.5	7	1	1	12.5	7	1	1	12.5	7	1	1	12.5					106	<=	1000
Demand	DS-1 Demand	7	1	1	12.5									7	1	1	12.5										7	1	1	12.5																21	>=	21	
	DS-2 Demand					7	1	1	12.5																																						106	>=	106
	DS-3 Demand										7	1	1	12.5																																		170	>=

Table 10. Additional Materials Handling Equipment Costs “if loop” Calculations for Clear Routes Model

		Additional Materials Handling Equipment Costs "if loop" Calculations																																							
		Route Airfield to DS1				Route Airfield to DS2				Route Airfield to DS3				Route Beach to DS1				Route Beach to DS2				Route Beach to DS3				Route Urban to DS1				Route Urban to DS2				Route Urban to DS3							
		Airfield to DS1 via 7ton	Airfield to DS 1 via JLT V	Airfield to DS1 via HMMWV	Airfield to DS1 via LVSR	Airfield to DS2 via 7ton	Airfield to DS2 via JLT V	Airfield to DS2 via HMMWV	Airfield to DS2 via LVSR	Airfield to DS3 via 7 ton	Airfield to DS 3 via JLT V	Airfield to DS 3 via HMMWV	Airfield to DS 3 via LVSR	Beach to DS1 via 7 ton	Beach to DS1 via JLT V	Beach to DS1 via HMMWV	Beach to DS1 via LVSR	Beach to DS2 via 7 ton	Beach to DS2 via JLT V	Beach to DS2 via HMMWV	Beach to DS2 via LVSR	Beach to DS3 via 7ton	Beach to DS3 via JLT V	Beach to DS3 via HMMWV	Beach to DS3 via LVSR	Urban Center to DS1 via 7 ton	Urban Center to DS1 via JLT V	Urban Center to DS1 via HMMWV	Urban Center to DS1 via LVSR	Urban Center to DS2 via 7 ton	Urban Center to DS2 via JLT V	Urban Center to DS2 via HMMWV	Urban Center to DS2 via LVSR	Urban Center to DS3 via 7 ton	Urban Center to DS3 via JLT V	Urban Center to DS3 via HMMWV	Urban Center to DS3 via LVSR				
Solved Objective Function Values		0	0	0	0	0	0	0	0	18	0	20	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	40	0	0	0	0	0	0
Sum of all Vehicles on route		0				0				42				4				0				0				0				45				0							
Additional MHE Cost if any vic uses that route		\$0.00				\$0.00				\$0.00				\$0.00				\$0.00				\$0.00				\$0.00				\$0.00				\$0.00							

Table 12. Additional Materials Handling Equipment Costs “if loop” Calculations for Medium Impact Routes

		Additional Materials Handling Equipment Costs "if loop" Calculations																																							
		Route Airfield to DS1				Route Airfield to DS2				Route Airfield to DS3				Route Beach to DS1				Route Beach to DS2				Route Beach to DS3				Route Urban to DS1				Route Urban to DS2				Route Urban to DS3							
		Airfield to DS1 via 7ton	Airfield to DS 1 via JLT V	Airfield to DS1 via HMMWV	Airfield to DS1 via LVS R	Airfield to DS2 via 7ton	Airfield to DS2 via JLT V	Airfield to DS2 via HMMWV	Airfield to DS2 via LVS R	Airfield to DS3 via 7 ton	Airfield to DS 3 via JLT V	Airfield to DS 3 via HMMWV	Airfield to DS 3 via LVS R	Beach to DS1 via 7 ton	Beach to DS1 via JLT V	Beach to DS1 via HMMWV	Beach to DS1 via LVS R	Beach to DS2 via 7 ton	Beach to DS2 via JLT V	Beach to DS2 via HMMWV	Beach to DS2 via LVS R	Beach to DS3 via 7ton	Beach to DS3 via JLT V	Beach to DS3 via HMMWV	Beach to DS3 via LVS R	Urban Center to DS1 via 7 ton	Urban Center to DS1 via JLT V	Urban Center to DS1 via HMMWV	Urban Center to DS1 via LVS R	Urban Center to DS2 via 7 ton	Urban Center to DS2 via JLT V	Urban Center to DS2 via HMMWV	Urban Center to DS2 via LVS R	Urban Center to DS3 via 7 ton	Urban Center to DS3 via JLT V	Urban Center to DS3 via HMMWV	Urban Center to DS3 via LVS R				
Solved Objective Function Values		0	0	0	0	0	0	0	0	18	0	20	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	40	0	0	0	0	0	0	0	0	0	0
Sum of all Vehicles on Route		0				0				42				4				0				0				0				45				0							
Additional MHE Cost if any vic uses that route		\$0.00				\$0.00				\$256.58				\$256.58				\$0.00				\$0.00				\$0.00				\$256.58				\$0.00							

Table 14. Additional Materials Handling Equipment Costs “if loop” Calculations

		Additional Materials Handling Equipment Costs "if loop" Calculations																																							
		Route Airfield to DS1				Route Airfield to DS2				Route Airfield to DS3				Route Beach to DS1				Route Beach to DS2				Route Beach to DS3				Route Urban to DS1			Route Urban to DS2			Route Urban to DS3									
		Airfield to DS1 via 7 ton	Airfield to DS 1 via JLTV	Airfield to DS1 via HMMWV	Airfield to DS1 via LVSF	Airfield to DS2 via 7 ton	Airfield to DS2 via JLTV	Airfield to DS2 via HMMWV	Airfield to DS2 via LVSF	Airfield to DS3 via 7 ton	Airfield to DS 3 via JLTV	Airfield to DS 3 via HMMWV	Airfield to DS 3 via LVSF	Beach to DS1 via 7 ton	Beach to DS1 via JLTV	Beach to DS1 via HMMWV	Beach to DS1 via LVSF	Beach to DS2 via 7 ton	Beach to DS2 via JLTV	Beach to DS2 via HMMWV	Beach to DS2 via LVSF	Beach to DS3 via 7 ton	Beach to DS3 via JLTV	Beach to DS3 via HMMWV	Beach to DS3 via LVSF	Urban Center to DS1 via 7 ton	Urban Center to DS1 via JLTV	Urban Center to DS1 via HMMWV	Urban Center to DS1 via LVSF	Urban Center to DS2 via 7 ton	Urban Center to DS2 via JLTV	Urban Center to DS2 via HMMWV	Urban Center to DS2 via LVSF	Urban Center to DS3 via 7 ton	Urban Center to DS3 via JLTV	Urban Center to DS3 via HMMWV	Urban Center to DS3 via LVSF				
Solved Objective Function Values		0	0	0	0	0	0	0	0	18	0	20	4	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	40	0	0	0	0	0	0	0	0	0	0
Sum of all Vehicles on route		0				0				42				4				0				0				0			45			0									
Additional MHE Cost if any vic uses that route		\$0.00				\$0.00				\$457.38				\$457.38				\$0.00				\$0.00				\$0.00			\$457.38			\$0.00									

Table 16. Additional Materials Handling Equipment Costs “if loop” Calculations for Mixed Impact Routes #1

		Additional Materials Handling Equipment Costs "if loop" Calculations																																							
		Route Airfield to DS1				Route Airfield to DS2				Route Airfield to DS3				Route Beach to DS1				Route Beach to DS2				Route Beach to DS3				Route Urban to DS1				Route Urban to DS2				Route Urban to DS3							
		Airfield to DS1 via 7 ton	Airfield to DS1 via JLTV	Airfield to DS1 via HMMWV	Airfield to DS1 via LVSRR	Airfield to DS2 via 7 ton	Airfield to DS2 via JLTV	Airfield to DS2 via HMMWV	Airfield to DS2 via LVSRR	Airfield to DS3 via 7 ton	Airfield to DS3 via JLTV	Airfield to DS3 via HMMWV	Airfield to DS3 via LVSRR	Beach to DS1 via 7 ton	Beach to DS1 via JLTV	Beach to DS1 via HMMWV	Beach to DS1 via LVSRR	Beach to DS2 via 7 ton	Beach to DS2 via JLTV	Beach to DS2 via HMMWV	Beach to DS2 via LVSRR	Beach to DS3 via 7 ton	Beach to DS3 via JLTV	Beach to DS3 via HMMWV	Beach to DS3 via LVSRR	Urban Center to DS1 via 7 ton	Urban Center to DS1 via JLTV	Urban Center to DS1 via HMMWV	Urban Center to DS1 via LVSRR	Urban Center to DS2 via 7 ton	Urban Center to DS2 via JLTV	Urban Center to DS2 via HMMWV	Urban Center to DS2 via LVSRR	Urban Center to DS3 via 7 ton	Urban Center to DS3 via JLTV	Urban Center to DS3 via HMMWV	Urban Center to DS3 via LVSRR				
Solved Objective Function Values		4	0	0	0	0	0	0	0	18	36	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	4	19	4	0	0	0	0
Sum of all Vehicles on route		4				0				55				0				0				0				0				32				0							
Additional MHE Cost if any vic uses that route		\$55.78				\$0.00				\$457.38				\$0.00				\$0.00				\$0.00				\$0.00				\$55.78				\$0.00							

Table 18. Additional Materials Handling Equipment Costs “if loop” Calculations for Mixed Impact Routes #2

		Additional Materials Handling Equipment Costs "if loop" Calculations																																							
		Route Airfield to DS1				Route Airfield to DS2				Route Airfield to DS3				Route Beach to DS1				Route Beach to DS2				Route Beach to DS3				Route Urban to DS1				Route Urban to DS2				Route Urban to DS3							
		Airfield to DS1 via 7 ton	Airfield to DS 1 via JLT.V	Airfield to DS1 via HMMWV	Airfield to DS1 via LVS.R	Airfield to DS2 via 7 ton	Airfield to DS2 via JLT.V	Airfield to DS2 via HMMWV	Airfield to DS2 via LVS.R	Airfield to DS3 via 7 ton	Airfield to DS 3 via JLT.V	Airfield to DS 3 via HMMWV	Airfield to DS 3 via LVS.R	Beach to DS1 via 7 ton	Beach to DS1 via JLT.V	Beach to DS1 via HMMWV	Beach to DS1 via LVS.R	Beach to DS2 via 7 ton	Beach to DS2 via JLT.V	Beach to DS2 via HMMWV	Beach to DS2 via LVS.R	Beach to DS3 via 7 ton	Beach to DS3 via JLT.V	Beach to DS3 via HMMWV	Beach to DS3 via LVS.R	Urban Center to DS1 via 7 ton	Urban Center to DS1 via JLT.V	Urban Center to DS1 via HMMWV	Urban Center to DS1 via LVS.R	Urban Center to DS2 via 7 ton	Urban Center to DS2 via JLT.V	Urban Center to DS2 via HMMWV	Urban Center to DS2 via LVS.R	Urban Center to DS3 via 7 ton	Urban Center to DS3 via JLT.V	Urban Center to DS3 via HMMWV	Urban Center to DS3 via LVS.R				
Solved Objective Function Values		0	0	0	0	0	0	0	0	5	40	15	4	3	0	3	0	19	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sum of all Vehicles on route		0				0				64				6				21				0				0				0				0							
Additional MHE Cost if any vic uses that route		\$0.00				\$0.00				\$256.58				\$55.78				\$0.00				\$0.00				\$0.00				\$0.00				\$0.00							

Figure 12 provides an illustration of the quantity of vehicles that the model has assigned to use each different route. Despite changing route conditions, the model still favored many of the same routes even as the conditions changed.

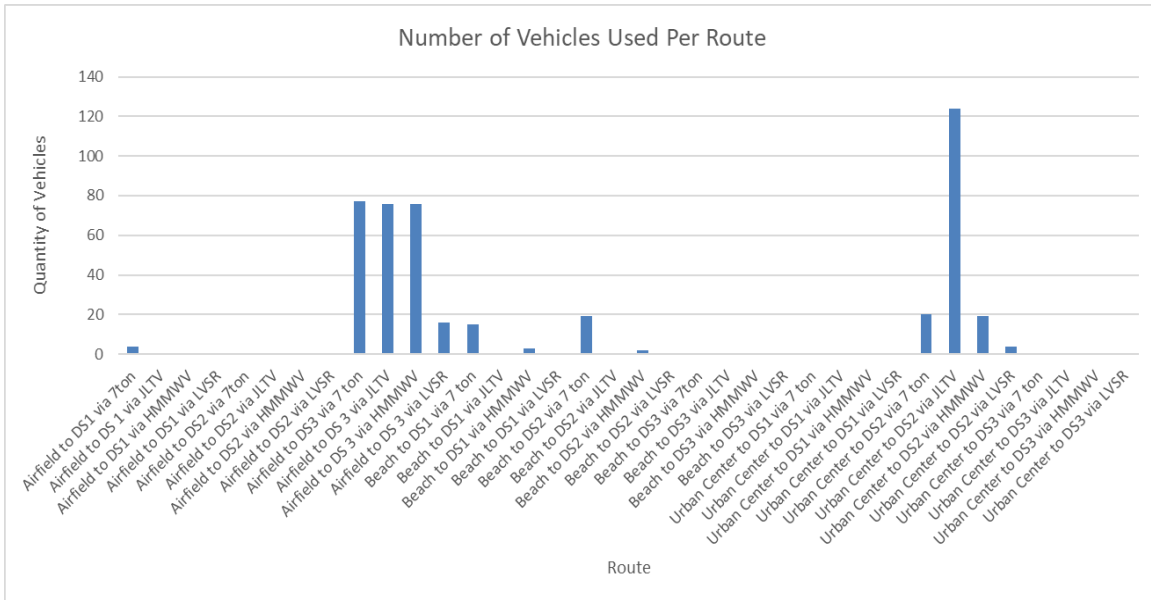


Figure 12. Number of Vehicles Used per Route

D. REPLANNING

In this model, the demand for supplies at all sites is too large to be met by the ground equipment in a single movement. This limitation forces the planners to work with the amount of ground transportation resources they have at that particular time to satisfy as much of the supply demand as possible. By following the model outputs, the planners slowly reduce the quantity of supplies needed at each site as ground assets move supplies daily. However, this process does not account for a changing situation on the ground. The conditions of roadways in the area have the potential to change from day to day as routes are cleared or to potentially become worse due to follow-on damage. The demand at each disaster site may increase as more people are displaced in the area. There may also be entirely new disaster sites that were not previously supported the day prior, but that now need to be included in the planning model. All these factors contribute to how the model

allocates vehicles to optimize the delivery of supplies to the required areas. For this reason, we recommend the model be rerun daily to allow planners to capture these changing requirements in the model and work to solve the transportation problem. Rerunning the model can also be referred to as replanning. This process is similar to the “Replanning” strategy that Özdamar et al. highlighted in their article “Emergency Logistics Planning in Natural Disasters” (Özdamar et al., 2004, pp. 224–225). The transportation model that we built finds the optimal solution given a set of conditions that are true at the start of the planning process. For the model to be continually used throughout a large disaster, it is necessary to rerun the model at regular intervals to determine the new optimal solution.

V. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The following paragraphs represent areas that future research should be directed towards to help build on the model that was created.

A. RECOMMENDATIONS

Prior to deploying each MEU goes through an extensive training pipeline to ensure that the Marines and equipment are ready to execute required missions. This training atmosphere is meant to simulate real situations and challenge the MEU to plan and execute missions successfully. These training situations represent an opportunity that could be used by mission planners to use the model to plan humanitarian operations. As the unit uses the model, they will be able to collect data to help refine the planning model for how long certain tasks took in a particular environment. For example, the unit may find that the model assumed it would take much longer to clear a particular route, but since the unit has training for this mission, they were more efficient than originally estimated. Therefore, the model might be refined to include a learning curve if a unit is more proficient in a certain type of operation.

B. AREAS FOR FUTURE STUDY

There are five improvements that are recommended to be implemented in the future to improve the effectiveness of the model.

1. This model uses a fixed cost to capture the additional cost of MHE equipment that is required to use routes that are not able to be traveled by normal vehicles. Just like there are a limited number of ground transportation assets there is also a limited number of MHE assets. This limitation means that if multiple routes need MHE support at the same time there will be a shortfall that will not be able to be meant. This could result in a certain disaster site not receiving any supplies via ground until a particular route is clear.

2. The Commander for the Marine Forces on the ground is likely to have a series of additional constraints that may be imposed for a safety, communication, or security concern. Some of these additional constraints could be that the smallest movement that can travel on any route is four vehicles or that a security vehicle must be on every movement. Constraints like these should be anticipated and added into the model so that planners can add or remove additional limitations easily.
3. Change the cargo being moved from short tons to pallets. This simple change can help provide additional information to planners if requirements are given in a different unit.
4. The model should be built to include the amount of personnel that will be required to operate all the vehicles and equipment in the model. This information will be useful to planners because the mission requires that supplies be delivered to specific locations, but to also sustain the force that is providing the supplies. This information can be expanded into projected fuel, food, and water consumption for the disaster relief force that will need to be supplied in addition to the supplies being moved to the disaster sites.
5. A large portion of the effectiveness of this model is classification of each route based on its trafficability. In this model this is an estimate that is provided by units on the ground. It is recommended that a more mathematical approach be used in this survey to determine the trafficability on the ground. For example, the unit on the ground should attempt to travel a route and determine the average number of trees or debris on the ground over the route, along with their approximate size. With this information planners can create a formula for how long it would take to clear the route. This additional calculation would allow the model to estimate the amount of time it takes to clear and travel a route, further improving the effectiveness of the model.
6. The Marine Corps and the U.S. Military will not usually be the only ones that respond to a disaster. It is possible for the host nation groups, volunteer

groups, or other nations to provide resources and supplies to disaster relief. For this reason, it is important the military is able to work with and support if needed the civilian force. This can be done by improving the ability to use this model with the addition of civilian resources. Information from other research shows that there are capabilities from the civilian side that can complement the military in disaster relief operations (Cameron, 2020). The inclusion of these capabilities will continue to make this model a better planning tool.

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APPENDIX

A. ALL ROUTES CLEAR INPUT DATA FOR MODEL

Table 19. All Clear Input Data for MTRV

Transportation Costs by Vehicle Type					
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)	MHE Cost
Truck, Cargo, 7 Ton	Airfield to DS1	Clear	24	\$ 13.39	\$0.00
	Airfield to DS2	Clear	30	\$ 16.73	\$0.00
	Airfield to DS3	Clear	10	\$ 5.58	\$0.00
	Beach to DS1	Clear	16	\$ 8.92	\$0.00
	Beach to DS2	Clear	21	\$ 11.71	\$0.00
	Beach to DS3	Clear	25	\$ 13.94	\$0.00
	Urban Center to DS1	Clear	20	\$ 11.16	\$0.00
	Urban Center to DS2	Clear	18	\$ 10.04	\$0.00
	Urban Center to DS3	Clear	22	\$ 12.27	\$0.00

Table 20. All Clear Input Data for JLTV

Transportation Costs by Vehicle Type				
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)
JLTV	Airfield to DS1	Clear	24	\$ 4.82
	Airfield to DS2	Clear	30	\$ 6.02
	Airfield to DS3	Clear	10	\$ 2.01
	Beach to DS1	Clear	16	\$ 3.21
	Beach to DS2	Clear	21	\$ 4.22
	Beach to DS3	Clear	25	\$ 5.02
	Urban Center to DS1	Clear	20	\$ 4.02
	Urban Center to DS2	Clear	18	\$ 3.61
	Urban Center to DS3	Clear	22	\$ 4.42

Table 21. All Clear Input Data for HMMWV

Transportation Costs by Vehicle Type				
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)
HMMWV	Airfield to DS1	Clear	24	\$ 5.48
	Airfield to DS2	Clear	30	\$ 6.85
	Airfield to DS3	Clear	10	\$ 2.28
	Beach to DS1	Clear	16	\$ 3.65
	Beach to DS2	Clear	21	\$ 4.79
	Beach to DS3	Clear	25	\$ 5.70
	Urban Center to DS1	Clear	20	\$ 4.56
	Urban Center to DS2	Clear	18	\$ 4.11
	Urban Center to DS3	Clear	22	\$ 5.02

Table 22. All Clear Input Data for LVSR

Transportation Costs by Vehicle Type				
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)
LVSR	Airfield to DS1	Clear	24	\$ 30.12
	Airfield to DS2	Clear	30	\$ 37.65
	Airfield to DS3	Clear	10	\$ 12.55
	Beach to DS1	Clear	16	\$ 20.08
	Beach to DS2	Clear	21	\$ 26.36
	Beach to DS3	Clear	25	\$ 31.38
	Urban Center to DS1	Clear	20	\$ 25.10
	Urban Center to DS2	Clear	18	\$ 22.59
	Urban Center to DS3	Clear	22	\$ 27.61

B. ALL ROUTES MEDIUM INPUT DATA

Table 23. All Routes Medium Input Data for MTVR

Transportation Costs by Vehicle Type					
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)	MHE Cost
Truck, Cargo, 7 Ton	Airfield to DS1	Med Impact	24	\$ 26.77	\$256.58
	Airfield to DS2	Med Impact	30	\$ 33.47	\$256.58
	Airfield to DS3	Med Impact	10	\$ 11.16	\$256.58
	Beach to DS1	Med Impact	16	\$ 17.85	\$256.58
	Beach to DS2	Med Impact	21	\$ 23.43	\$256.58
	Beach to DS3	Med Impact	25	\$ 27.89	\$256.58
	Urban Center to DS1	Med Impact	20	\$ 22.31	\$256.58
	Urban Center to DS2	Med Impact	18	\$ 20.08	\$256.58
	Urban Center to DS3	Med Impact	22	\$ 24.54	\$256.58

Table 24. All Routes Medium Input Data for JLTV

Transportation Costs by Vehicle Type				
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)
JLTV	Airfield to DS1	Med Impact	24	\$ 9.64
	Airfield to DS2	Med Impact	30	\$ 12.05
	Airfield to DS3	Med Impact	10	\$ 4.02
	Beach to DS1	Med Impact	16	\$ 6.43
	Beach to DS2	Med Impact	21	\$ 8.43
	Beach to DS3	Med Impact	25	\$ 10.04
	Urban Center to DS1	Med Impact	20	\$ 8.03
	Urban Center to DS2	Med Impact	18	\$ 7.23
	Urban Center to DS3	Med Impact	22	\$ 8.84

Table 25. All Routes Medium Input Data for HMMWV

Transportation Costs by Vehicle Type				
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)
HMMWV	Airfield to DS1	Med Impact	24	\$ 10.95
	Airfield to DS2	Med Impact	30	\$ 13.69
	Airfield to DS3	Med Impact	10	\$ 4.56
	Beach to DS1	Med Impact	16	\$ 7.30
	Beach to DS2	Med Impact	21	\$ 9.58
	Beach to DS3	Med Impact	25	\$ 11.41
	Urban Center to DS1	Med Impact	20	\$ 9.13
	Urban Center to DS2	Med Impact	18	\$ 8.21
	Urban Center to DS3	Med Impact	22	\$ 10.04

Table 26. All Routes Medium Input Data for LVSR

Transportation Costs by Vehicle Type				
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)
LVSR	Airfield to DS1	Med Impact	24	\$ 60.24
	Airfield to DS2	Med Impact	30	\$ 75.30
	Airfield to DS3	Med Impact	10	\$ 25.10
	Beach to DS1	Med Impact	16	\$ 40.16
	Beach to DS2	Med Impact	21	\$ 52.71
	Beach to DS3	Med Impact	25	\$ 62.75
	Urban Center to DS1	Med Impact	20	\$ 50.20
	Urban Center to DS2	Med Impact	18	\$ 45.18
	Urban Center to DS3	Med Impact	22	\$ 55.22

C. ALL ROUTES HIGH INPUT DATA

Table 27. All Routes High Input Data for MTRV

Transportation Costs by Vehicle Type					
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)	MHE Cost
Truck, Cargo, 7 Ton	Airfield to DS1	High Impact	24	\$ 40.16	\$457.38
	Airfield to DS2	High Impact	30	\$ 50.20	\$457.38
	Airfield to DS3	High Impact	10	\$ 16.73	\$457.38
	Beach to DS1	High Impact	16	\$ 26.77	\$457.38
	Beach to DS2	High Impact	21	\$ 35.14	\$457.38
	Beach to DS3	High Impact	25	\$ 41.83	\$457.38
	Urban Center to DS1	High Impact	20	\$ 33.47	\$457.38
	Urban Center to DS2	High Impact	18	\$ 30.12	\$457.38
	Urban Center to DS3	High Impact	22	\$ 36.81	\$457.38

Table 28. All Routes High Input Data for JLTV

Transportation Costs by Vehicle Type				
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)
JLTV	Airfield to DS1	High Impact	24	\$ 14.46
	Airfield to DS2	High Impact	30	\$ 18.07
	Airfield to DS3	High Impact	10	\$ 6.02
	Beach to DS1	High Impact	16	\$ 9.64
	Beach to DS2	High Impact	21	\$ 12.65
	Beach to DS3	High Impact	25	\$ 15.06
	Urban Center to DS1	High Impact	20	\$ 12.05
	Urban Center to DS2	High Impact	18	\$ 10.84
	Urban Center to DS3	High Impact	22	\$ 13.25

Table 29. All Routes High Input Data for HMMWV

Transportation Costs by Vehicle Type				
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)
HMMWV	Airfield to DS1	High Impact	24	\$ 16.43
	Airfield to DS2	High Impact	30	\$ 20.54
	Airfield to DS3	High Impact	10	\$ 6.85
	Beach to DS1	High Impact	16	\$ 10.95
	Beach to DS2	High Impact	21	\$ 14.38
	Beach to DS3	High Impact	25	\$ 17.11
	Urban Center to DS1	High Impact	20	\$ 13.69
	Urban Center to DS2	High Impact	18	\$ 12.32
	Urban Center to DS3	High Impact	22	\$ 15.06

Table 30. All Routes High Input Data for LVS

Transportation Costs by Vehicle Type				
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)
LVS	Airfield to DS1	High Impact	24	\$ 90.36
	Airfield to DS2	High Impact	30	\$ 112.95
	Airfield to DS3	High Impact	10	\$ 37.65
	Beach to DS1	High Impact	16	\$ 60.24
	Beach to DS2	High Impact	21	\$ 79.07
	Beach to DS3	High Impact	25	\$ 94.13
	Urban Center to DS1	High Impact	20	\$ 75.30
	Urban Center to DS2	High Impact	18	\$ 67.77
	Urban Center to DS3	High Impact	22	\$ 82.83

D. MIXED ROUTES ITERATION #1 INPUT DATA

Table 31. Mixed Routes Iteration #1 Input Data for MTRV

Transportation Costs by Vehicle Type					
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)	MHE Cost
Truck, Cargo, 7 Ton	Airfield to DS1	Low Impact	24	\$ 20.08	\$55.78
	Airfield to DS2	Med Impact	30	\$ 33.47	\$256.58
	Airfield to DS3	High Impact	10	\$ 16.73	\$457.38
	Beach to DS1	Impassable	16	\$ 892.44	\$0.00
	Beach to DS2	Med Impact	21	\$ 23.43	\$256.58
	Beach to DS3	Low Impact	25	\$ 20.92	\$55.78
	Urban Center to DS1	High Impact	20	\$ 33.47	\$457.38
	Urban Center to DS2	Low Impact	18	\$ 15.06	\$55.78
	Urban Center to DS3	Med Impact	22	\$ 24.54	\$256.58

Table 32. Mixed Routes Iteration #1 Input Data for JLTV

Transportation Costs by Vehicle Type				
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)
JLTV	Airfield to DS1	Low Impact	24	\$ 7.23
	Airfield to DS2	Med Impact	30	\$ 12.05
	Airfield to DS3	High Impact	10	\$ 6.02
	Beach to DS1	Impassable	16	\$ 321.28
	Beach to DS2	Med Impact	21	\$ 8.43
	Beach to DS3	Low Impact	25	\$ 7.53
	Urban Center to DS1	High Impact	20	\$ 12.05
	Urban Center to DS2	Low Impact	18	\$ 5.42
	Urban Center to DS3	Med Impact	22	\$ 8.84

Table 33. Mixed Routes Iteration #1 Input Data for HMMWV

Transportation Costs by Vehicle Type				
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)
HMMWV	Airfield to DS1	Low Impact	24	\$ 8.21
	Airfield to DS2	Med Impact	30	\$ 13.69
	Airfield to DS3	High Impact	10	\$ 6.85
	Beach to DS1	Impassable	16	\$ 365.09
	Beach to DS2	Med Impact	21	\$ 9.58
	Beach to DS3	Low Impact	25	\$ 8.56
	Urban Center to DS1	High Impact	20	\$ 13.69
	Urban Center to DS2	Low Impact	18	\$ 6.16
	Urban Center to DS3	Med Impact	22	\$ 10.04

Table 34. Mixed Routes Iteration #1 Input Data for LVSr

Transportation Costs by Vehicle Type				
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)
LVSr	Airfield to DS1	Low Impact	24	\$ 45.18
	Airfield to DS2	Med Impact	30	\$ 75.30
	Airfield to DS3	High Impact	10	\$ 37.65
	Beach to DS1	Impassable	16	\$ 2,008.00
	Beach to DS2	Med Impact	21	\$ 52.71
	Beach to DS3	Low Impact	25	\$ 47.06
	Urban Center to DS1	High Impact	20	\$ 75.30
	Urban Center to DS2	Low Impact	18	\$ 33.89
	Urban Center to DS3	Med Impact	22	\$ 55.22

E. MIXED ROUTES ITERATION #2 INPUT DATA

Table 35. Mixed Routes Iteration #2 Input Data for MTRV

Transportation Costs by Vehicle Type					
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)	MHE Cost
Truck, Cargo, 7 Ton	Airfield to DS1	Impassable	24	\$ 1,338.67	\$0.00
	Airfield to DS2	High Impact	30	\$ 50.20	\$457.38
	Airfield to DS3	Med Impact	10	\$ 11.16	\$256.58
	Beach to DS1	Low Impact	16	\$ 13.39	\$55.78
	Beach to DS2	Clear	21	\$ 11.71	\$0.00
	Beach to DS3	Low Impact	25	\$ 20.92	\$55.78
	Urban Center to DS1	Med Impact	20	\$ 22.31	\$256.58
	Urban Center to DS2	Med Impact	18	\$ 20.08	\$256.58
	Urban Center to DS3	High Impact	22	\$ 36.81	\$457.38

Table 36. Mixed Routes Iteration #2 Input Data for JLTV

Transportation Costs by Vehicle Type				
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)
JLTV	Airfield to DS1	Impassable	24	\$ 481.92
	Airfield to DS2	High Impact	30	\$ 18.07
	Airfield to DS3	Med Impact	10	\$ 4.02
	Beach to DS1	Low Impact	16	\$ 4.82
	Beach to DS2	Clear	21	\$ 4.22
	Beach to DS3	Low Impact	25	\$ 7.53
	Urban Center to DS1	Med Impact	20	\$ 8.03
	Urban Center to DS2	Med Impact	18	\$ 7.23
	Urban Center to DS3	High Impact	22	\$ 13.25

Table 37. Mixed Routes Iteration #2 Input Data for HMMWV

Transportation Costs by Vehicle Type				
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)
HMMWV	Airfield to DS1	Impassable	24	\$ 547.64
	Airfield to DS2	High Impact	30	\$ 20.54
	Airfield to DS3	Med Impact	10	\$ 4.56
	Beach to DS1	Low Impact	16	\$ 5.48
	Beach to DS2	Clear	21	\$ 4.79
	Beach to DS3	Low Impact	25	\$ 8.56
	Urban Center to DS1	Med Impact	20	\$ 9.13
	Urban Center to DS2	Med Impact	18	\$ 8.21
	Urban Center to DS3	High Impact	22	\$ 15.06

Table 38. Mixed Routes Iteration #2 Input Data for LVSR

Transportation Costs by Vehicle Type				
Equipment	Name	Route Condition	Distance (miles)	Adjusted Daily Cost (\$)
LVSR	Airfield to DS1	Impassable	24	\$ 3,012.00
	Airfield to DS2	High Impact	30	\$ 112.95
	Airfield to DS3	Med Impact	10	\$ 25.10
	Beach to DS1	Low Impact	16	\$ 30.12
	Beach to DS2	Clear	21	\$ 26.36
	Beach to DS3	Low Impact	25	\$ 47.06
	Urban Center to DS1	Med Impact	20	\$ 50.20
	Urban Center to DS2	Med Impact	18	\$ 45.18
	Urban Center to DS3	High Impact	22	\$ 82.83

F. EQUATIONS AND CALCULATIONS

The following sections provide a detailed breakdown of the equations introduced in Chapter III that were used to solve the model.

1. Weighted Demand Calculations

$$DS1 \text{ Adjusted Demand Tonnage} = 7.14\% \times (189 + 102 + 44 + 50) \text{ tons} = 27 \text{ short tons} \quad (8)$$

$$DS2 \text{ Weighted Demand} = \frac{500}{1400} = 35.71\% \quad (9)$$

$$DS2 \text{ Single Movement Demand} = 35.71\% \times (189 + 102 + 44 + 50) \text{ tons} = 137 \text{ short tons} \quad (10)$$

$$DS3 \text{ Weighted Demand} = \frac{800}{1400} = 57.14\% \quad (11)$$

$$DS3 \text{ Single Movement Demand} = 57.14\% \times (189 + 102 + 44 + 50) \text{ tons} = 220 \text{ short tons} \quad (12)$$

2. Constraints

Maximum tonnage of supplies to disaster site by vehicle-type subject to vehicle costs.

$$\sum_d^D \sum_v^V Q_{sdv} C_v \leq \text{Supply}_s \quad \forall S \quad (13)$$

Minimum tonnage of supplies from source by vehicle-type subject to vehicle costs.

$$\sum_s^S \sum_v^V Q_{sdv} C_v \geq \text{Demand}_d \quad \forall D \quad (14)$$

Ensures that the program only delivers solutions that are integers and not fractions.

$$Q_{sdv} \text{ are integers} \quad (15)$$

Equations 16–18 give the longhand versions of Equations 13–15, substituted with variables.

$$7X_{A1} + 2.55Y_{A1} + 2.2Z_{A1} + 12.5W_{A1} + 7X_{B1} + 2.55Y_{B1} + 2.2Z_{B1} + 12.5W_{B1} + 7X_{U1} + 2.55Y_{U1} + 2.2Z_{U1} + 12.5W_{U1} \geq 27 \text{ (DS1 Adjusted Tonnage Demand)} \quad (16)$$

$$7X_{A2} + 2.55Y_{A2} + 2.2Z_{A2} + 12.5W_{A2} + 7X_{B2} + 2.55Y_{B2} + 2.2Z_{B2} + 12.5W_{B2} + 7X_{U2} + 2.55Y_{U2} + 2.2Z_{U2} + 12.5W_{U2} \geq 137 \text{ (DS2 Adjusted tonnage Demand)} \quad (17)$$

$$7X_{A3} + 2.55Y_{A3} + 2.2Z_{A3} + 12.5W_{A3} + 7X_{B3} + 2.55Y_{B3} + 2.2Z_{B3} + 12.5W_{B3} + 7X_{U3} + 2.55Y_{U3} + 2.2Z_{U3} + 12.5W_{U3} \geq 220 \text{ (DS3 Adjusted tonnage Demand)} \quad (18)$$

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