Optimization-Based Allocation of Force Protection Resources in an Asymmetric Environment

by

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ABSTRACT

More than four years after the end of major combat operations in the 2003 Iraq War, the United States military continues to sustain casualties at rates higher than those during the ground campaign. Combat service support soldiers conducting daily convoy operations on the Iraqi road network account for a large number of these casualties. One reason for this is the threat's affinity to targeting soft, vulnerable, high-payoff targets through the use of roadside bombs, otherwise known as improvised explosive devices. This enemy tactic is characteristic of asymmetric warfare, in which a lesser opponent opposes a force far superior in numbers, equipment, and technology. In an asymmetric operating environment, threats blend in with the local populace making them hard to detect and are easily capable of multi-directional attacks; absent are the linear battlefields of past wars where logistical soldiers operated in the relative safety of the rear battlefield.

This thesis explores a mathematical approach to decide how to use available resources to best protect logistical convoys. To achieve this we first model the threat using probabilistic models and identify input data requirements associated with the operating environment and other relevant factors. Second, we identify a set of force protection resources and model their counter-effects on the threat. Next, we develop a binary integer program to optimally allocate the force protection resources to a set of planned logistical convoys. Our model uses an algorithm that assigns resources to either fixed areas or individual convoys in a way that minimizes overall threat effects to the convoys. The algorithm provides lower-risk plans yielding a lower expected number of casualties.

We propose integrating this force protection algorithm in conjunction with convoy planning software that optimally builds and routes convoys based on minimizing exposure to the threat to achieve even better plans. We test the performance of a system that accomplishes this by comparing its resulting plans to human-generated plans in a controlled experiment. Additionally, we conduct Monte Carlo simulations to statistically analyze the system's performance. We find that the system produces lower-risk plans in less time than human planners. We describe future development of this methodology to reducing soldier casualties, and a proposed approach for its integration into existing Army systems and processes.

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Publication of this thesis does not constitute approval by Draper or the sponsoring agency of the findings herein. It is published for the exchange and stimulation of ideas.

Finally, as an active duty officer in the Army, I am required to acknowledge that the views expressed in this thesis are mine and do not reflect the official policy or position of the United States Army, the Department of Defense, or the United States Government.

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1 Introduction

In this thesis we describe a technical approach to reducing soldier casualties in the Global War on Terrorism. Furthermore, we propose a means for integrating this approach into existing systems and processes to enhance decision support of military planning. This chapter describes the motivation behind the research, the specifics of the problem we address, and provides a synopsis of the approach and experimentation that follows.

1.1 Research Motivation

In the four years since the end of major ground conflict in Iraq was announced by President Bush on May 1, 2003, the United States military has sustained on average 67 fatalities and accrued 503 wounded (that are not returned to duty within 72 hours) per month [10]. These numbers are high considering the ground war has long since ended, and the U.S. has the best equipped and most advanced military in the world. This thesis isolates and analyzes a specific component of U.S. military operations, force protection of Army logistical convoys, and describes a technical approach that addresses certain aspects relating to this component. The purpose of this approach is to optimize the allocation of available force protection resources in order to decrease the number of casualties sustained from logistical convoy operations.

In Iraq, a major contributor to the high casualty rates is insurgents' employment of improvised explosive devices along Iraqi roadways to target U.S. military vehicles and convoys.

The military logs hundreds of millions of miles annually in Iraq in support of Operation Iraqi Freedom [3]. One approach to reducing casualties due to roadside ambushes is to replace ground resupply with other means such as aerial resupply. However, it would be unavoidable to do away with ground transport altogether because of the limiting capacity of air transport assets, the lack of improved airstrips at forward operating bases, and the considerable quantities of supplies that must be moved daily to support a deployed military force.

Many military analysts and professional soldiers characterize the post-ground war threat and operating environment in Iraq as asymmetric warfare. In this type of warfare, an inferior opponent, in terms of size and equipment, utilizes adaptive tactics aimed at countering this imbalance while exploiting the weaknesses of the stronger force [7]. This style is preferred by weaker opponents due to its relative effectiveness against conventional forces and tactics. We describe asymmetric warfare in greater detail in Chapter 2.

As long as the U.S. military is engaged abroad in fighting the Global War on Terrorism, we can expect to face an asymmetric threat. U.S. forces deployed to foreign lands will always require a continuous flow of resupply to sustain operations. Most of this demand must be serviced by soldiers physically transporting these supplies in trucks along foreign roadways. This situation greatly affects the U.S. Army combat service support soldier, who is particularly susceptible to becoming a casualty from a roadside ambush due to their frequent road travel and vulnerability compared to combat forces

Given the state of world affairs, it is likely the U.S. Army, referred to as the Army from here on, will be fighting an asymmetric fight, in one form or another, in the foreseeable future. Consequently, the problem of high casualty rates for combat service support soldiers will also remain. The approach described in this thesis enables automated decision support to optimize force protection of Army logistical convoy planning, which in return will lower combat service support causality rates. Therefore, our research into a technical approach that supports mitigation of the effects from asymmetric warfare is extremely relevant for the U.S. soldier and military as a whole.

As presented, the intended benefactor of the approach is the Army corps and divisional transportation units, but the approach can benefit other Army branches, services and/or echelons of the military.

1.2 Problem Statement

The operational problem we address is that of high casualty rates for Army combat service support soldiers operating in Iraq and elsewhere in the world, from the effects of threat ambushes. Good intelligence, availability of force protection resources, and experienced decision making can help decrease these rates, but unfortunately, these components are not always available or in force.

In traditional warfare, combat forces execute decisive operations and therefore receive the preponderance of resources and support. Combat service support units exist to provide these resources and support to combat forces. However, a main function of contingency operations is supplying the entire force through routine logistical convoy operations on the roadways. These logistical convoys are subjected to the same risks and threats as maneuver forces, yet they are often less equipped and less trained to handle the types of threats they encounter on the highway. Home-station training of combat service support soldiers has traditionally focused on the aspects of logistics rather than war fighting. Although the Global War on Terror has ignited changes to home-station training for logisticians that is more warrior-focused, there is still a great susceptibility to risk for these combat service support soldiers [3].

This vulnerability has not gone unnoticed by the military as vast resources and procedural changes have been vested to mitigate this risk to combat service support soldiers since the end of the ground war. These changes include: adding more armor to logistical trucks, providing more force protection resources, and changing the focus of training and how support units prepare for a rotation. While great strides have been made in this direction, even more can be done to lower the casualty rates of combat service support soldiers. Money and time often constrain the Army's ability to provide some of these types of protection, but there is another approach which can complement the current effort to protect these soldiers. This alternate approach is to employ human-system decision support tools to assist in developing lower-risk logistical convoy plans.

1.3 Technical Approach

We take an operations research approach to addressing the high number of combat service support casualties. The Institute for Operations Research and Management Science defines "operations research (O.R.) as the discipline of applying advanced analytical methods to help make better decisions" [1]. A goal of operations research is to help the decision maker make the best possible decision by "seeking to understand and structure complex situations, and to utilize this understanding to predict system behavior and improve system performance" [11]. To achieve this goal, the operations research analyst develops mathematical models and applies analytical methods to quantify the results of systems and processes in effect.

An operations research approach is appropriate for this problem because current Army systems and processes involved in planning logistical convoys are complex and large-scale. Furthermore, the process is time consuming, it lacks global synchronization of assets across the area of operations, it places little emphasis on intelligence and force protection considerations, and it produces plans that might be feasible but are likely to fail during execution. Currently, the Army planning process for logistical convoys is decentralized in that plans are developed at the lowest levels. This method of decentralized planning does not capitalize on the advantages gained by applying operations research techniques that utilize global optimization to produce better solutions. Furthermore, we will see that the disjointed nature of the supply and transportation functions in the Army impose additional layers of coordination and planning that detracts from the planners' ability to develop and analyze multiple course of actions or plans.

Current technology-based systems ease some of the burdens of the process through database sharing, web-based collaboration tools, and near-real time delivery of reports and request forms. However, even with these tools, the process of planning and developing logistical convoys still requires a great deal of human effort in the form of entry, manipulation, and analysis of the relevant data and information. The automated systems in use today do not provide an algorithmic approach for risk-based optimized planning, which will produce better plans in less time. The operations research approach can produce, relatively quickly, multiple plans based on user-defined preferences and priorities. Planning staffs can then use the time saved from automating part of the process to compare and contrast the multiple plans generated. This enables the staff to present multiple, detailed courses of action to the commander, resulting in better informed decisions and plans.

Throughout the thesis some of the research and analysis on the processes that we discuss are not directly cited from military doctrine but from a compilation of discussions and interviews with active and former military personnel with experience in the military logistics domain.

1.4 Experimentation

Although the motivation for the thesis is the high casualty rates of combat service support soldiers in Iraq, we apply the approach in this thesis to a notional Army corps operating in a notional environment. We build a scenario and populate it with reasonable data so we can use our model to generate a force protection plan that lowers the risk of a given set of convoys. We set up two experiments to test the performance of our model. The first experiment focuses on the human aspect of planning and compares the performance of a series of human-generated plans to that of the plans generated by our model. In the second experiment, we conduct Monte Carlo simulation to generate a large number of sample plans on three variants of our model. We use these samples to statistically analyze and compare the variants.

1.5 Thesis Organization

In Chapter 2 we provide an overview of military logistics with respect to an Army corps, the operating environment, and the planning process. This gives us the context for understanding how combat service support units integrate with and support combat forces. We also list contributing factors to the high casualty rates of combat service support soldiers.

In Chapter 3 we take a closer look at the combat service support function of the Army and analyze the distribution management planning process. We describe the inputs into the distribution management process, examine the process itself, and review the desired outputs. Finally, we establish links between the contributing factors and the distribution management process.

In Chapter 4 we outline the technical approach, operating environment, proposed threat model, data structure, and decision variables. This chapter concludes with a detailed formulation of the mathematical model we use in the experiments that address the problem.

In Chapter 5 we describe the designs for our two experiments, we list the metrics we use in our analysis, and we present our results and conclusions from the analysis.

In Chapter 6 we discuss directions for future research and describe how our approach and model can integrate into existing Army systems and processes.

In Chapter 7 we conclude the thesis by reviewing the problem and summarizing the approach, experimentation, and findings.

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2 Operational Overview

The goal of this chapter is to describe briefly military logistics in the context of the Army, contemporary operating environments, and Army staffs and planning processes. The chapter ends with a non-exhaustive list and brief explanation of some of the contributing factors to high casualty rates for combat service support soldiers. This operational overview will provide the framework necessary for understanding the functional analysis we perform in Chapter 3 as well as the modeling approach we take in Chapter 4 to mitigate these high casualty rates. Additionally, we use the background information from this chapter to build an operational scenario in which to perform experiments in order to draw conclusions about the modeling approach.

2.1 The Army

This section provides a basic understanding of a few of the combat service support branches of the Army and how they integrate and function within an Army corps.

2.1.1 Organizational Structure

A typical configuration of an Army corps organized for combat or contingency operations has two main types of units. The first type is *combat*: units that are responsible for actual combat or executing the primary operational mission. The second type is *support*: units that are responsible for directly or indirectly supporting the combat forces in the execution of the primary mission. In addition to specialized support units in the organizational structure, there are smaller support elements intermixed with and subordinate to combat units that facilitate the coordination and interaction with other support units and echelons. Furthermore, each echelon at and above the level of battalion has a staff that consists of support personnel to further ensure timely and effective support to the combat units. Figure 2-1 depicts a simplified task organization (TASKO) of an Army corps, down to its combat brigades and support battalions. At the time of publication of this thesis, the Army was undergoing transformation where emergent doctrine has sustainment brigades (SUSs) and combat sustainment support battalions (CSSBs) replacing the traditional corps support command (COSCOM) and division support commands (DISCOMs).

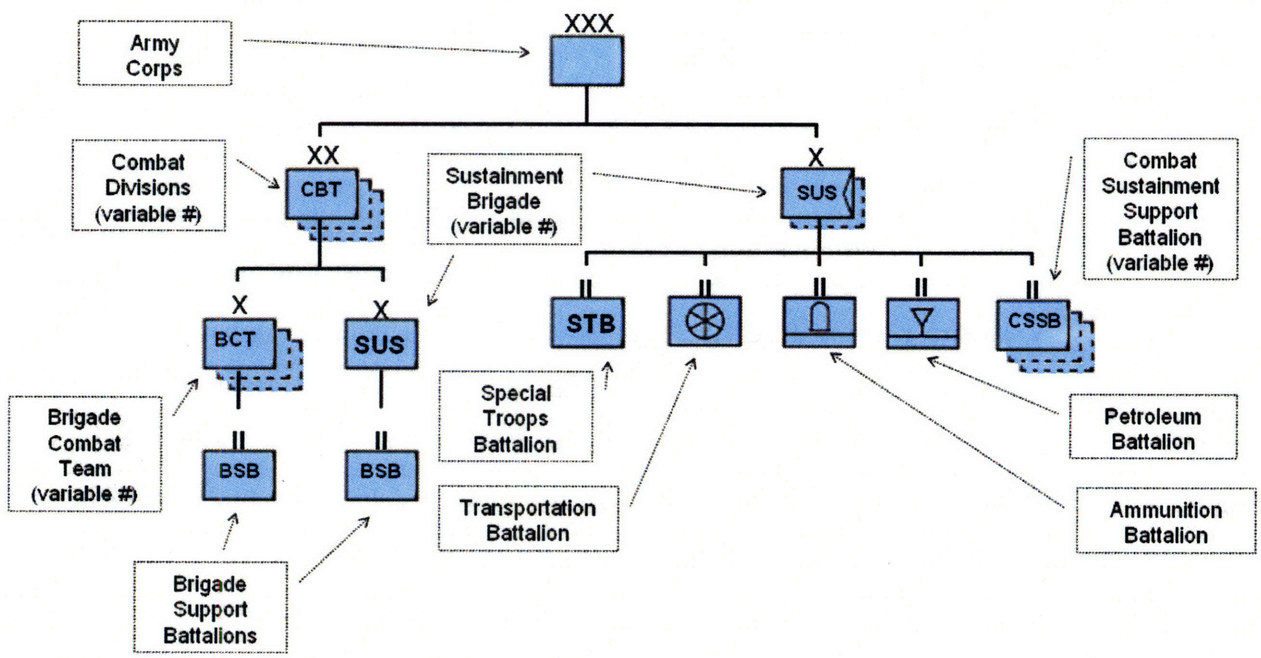

Figure 2-1: Notional task organization of an Army corps

The newly formed SUSs and CSSBs consolidate many of the support functions previously handled by separate entities subordinate to the old COSCOM and DISCOM. The SUS and CSSB can support a broader range of mission types and accommodate a wider range of force sizes than the former structure could. Additionally, brigade support battalions (BSBs), located at remote bases throughout the area of operations (AO), facilitate the interaction and flow of supplies between the SUS and combat brigades. This results in increased flexibility and agility for combat service support operations, an attribute of the Army's current transformation into a modular force.

2.1.2 Combat Service Support

The support function we reference in the previous section is referred to in military doctrine as combat service support (CSS). As mentioned in Chapter 1, the problem we address is high casualty rates for CSS soldiers performing logistics functions in hostile environments. We now describe the scope of CSS duties and how CSS soldiers interact with combat forces and adapt to the environment in which they are conducting their support missions. The Department of Defense (DoD) defines combat service support as:

> The essential capabilities, functions, activities, and tasks necessary to sustain all elements of operating forces in theater at all levels of war...it includes but is not limited to that support rendered by service forces in ensuring the aspects of supply, maintenance, transportation, health services, and other services required by aviation and ground combat troops to permit those units to accomplish their missions in combat. Combat service support encompasses those activities at all levels of war that produce sustainment to all operating forces on the battlefield [15].

A CSS soldier is one that performs any of the service functions listed above. CSS soldiers come from a number of branches of the Army, e.g., the Chaplain, Finance, Medical, Ordnance, Quartermaster, and Transportation branches. The CSS branches that are of interest for this thesis include Quartermaster, Ordnance, and in particular the Transportation branch. These three branches jointly supply the force with the necessary fuel, ammunition, sustenance, and other essential supplies necessary for combat units to sustain operations and successfully achieve the operational mission. Most of these supplies are managed and processed by quartermaster and ordnance units and are delivered by transportation units. Additionally, specialized petroleum and ammunition units control their own transport trucks in order to oversee the special handling and delivery of their respective commodities. In Chapter 3 we will examine the process of requesting, planning, and synchronizing the utilization of transportation assets for the delivery of supplies to combat units. During continuous military operations, large quantities of supplies are delivered across the AO on a regular basis in order to sustain the force over extended periods of time.

2.1.2.1 Sustainment Brigade

The SUS consolidates selected functions previously performed by corps and division support commands into a single operational echelon. One of the new benefits of the SUS is the commander's ability to add and remove subordinate CSS units to meet the requirements of the particular mission at hand. The SUS can have up to three specialized battalions (transportation, ammunition, and petroleum) to handle high demand commodities, as well as a variable number, usually one to three, of CSSBs. One of the supporting tasks of the SUS is to monitor and direct the distribution of all supplies and services within its AO. To accomplish this task, the SUS is normally centrally located or positioned at a logistics support area (LSA) along a main supply route (MSR) and collocated with its subordinate CSS battalions.

For each FOB within a division's AO there is a BSB that provides the CSS linkage for that base to the supporting SUS. Each BSB will have a variable number of field service companies (FSCs) that are further assigned to support the various maneuver battalions. All of these units must communicate and coordinate with one another in order to supply the combat forces. The units accomplish this through the use of staffs configured to handle different lanes of responsibility. We discuss staff composition in greater detail in Section 2.3.1.

2.1.2.2 Transportation Assets

The majority of the transportation assets for a corps are found within the SUS transportation battalion. To facilitate movement of hazardous classes of supplies that require special handling, the SUS also has specialized ammunition and petroleum battalions that solely manage and transport their respective commodities. These units utilize various medium and heavy trucks, e.g., tractor and semi-trailer, 5,000 gallon tanker, palletized loading system (PLS), and heavy equipment and truck transport (HETT) trucks. Furthermore, to support small-scale shipments and provide greater flexibility to the combat units, there are truck companies subordinate to the combat sustainment support battalions, and a multitude of tactical transport trucks assigned to combat units. Each type of truck has one or more specified purposes, constrained by the physical carrying capacities of that truck. Each type of transportation unit is authorized a specified number of these trucks and must maintain them to operational standards to remain available for resupply operations.

2.1.2.3 Classes of Supply

The Army classifies supplies into 10 major classes and labels them using Roman numerals I-X [19]. In this thesis we handle the transportation of these classes from one base to another within the AO. With respect to truck transport, we can further sub-categorize these supplies by the type of trucks required to move them. Therefore, we will group the supplies based upon the chart in Table 2-1.

Category	Classes of Supply	Special Handling Requirements	Types of trucks
Petroleum	III	Must be transported in tankers designed for petroleum	Tanker
Ammunition	V	Cannot be transported on same truck as any other class of supply	Tractor-trailer, PLS, tactical truck
Water	I (water)	Must be transported in water tanks	Water tanker, PLS
General Cargo	I, II, IV, VI, VIII, IX, X	Can be shipped either break-bulk or in containers	Tractor-trailer, PLS, tactical truck
Combat Vehicles	VII	Must be transported using HETTs	HETT

Table 2-1: Classes of supply

2.1.2.4 Transportation Request Procedures

The purpose of a transportation request (TR) is to request transportation of supplies that a sustainment supply unit releases for shipment. Figure 2-2 [16] shows the flow of a TR and how that request transforms into a transportation movement release (TMR). The process begins with a supply unit, or customer, submitting a TR to its servicing SUS and movement control team (MCT) who will review the request and determine the mode of transportation. One or more MCTs, usually collocated with SUS, can be assigned by the theater movement control battalion (MCB) to assist and facilitate corps movement operations. According to the flow chart, there are four possible modes to use; however, in this thesis we only concern ourselves with the motor transport mode.

After selecting the mode, the MCT generates a TMR and assigns a TMR number. Advance shipping notification is sent to interested parties while the mode operator receives commitment from the original MCT. The mode operator requests highway clearances from the appropriate MCT and then commits assets. The transportation assets are sent to the shipper who then releases the cargo to the transport unit, which ships the cargo to its designated receiver. All units and appropriate staff sections then submit a closure report detailing the specifics of the completed shipment [16].

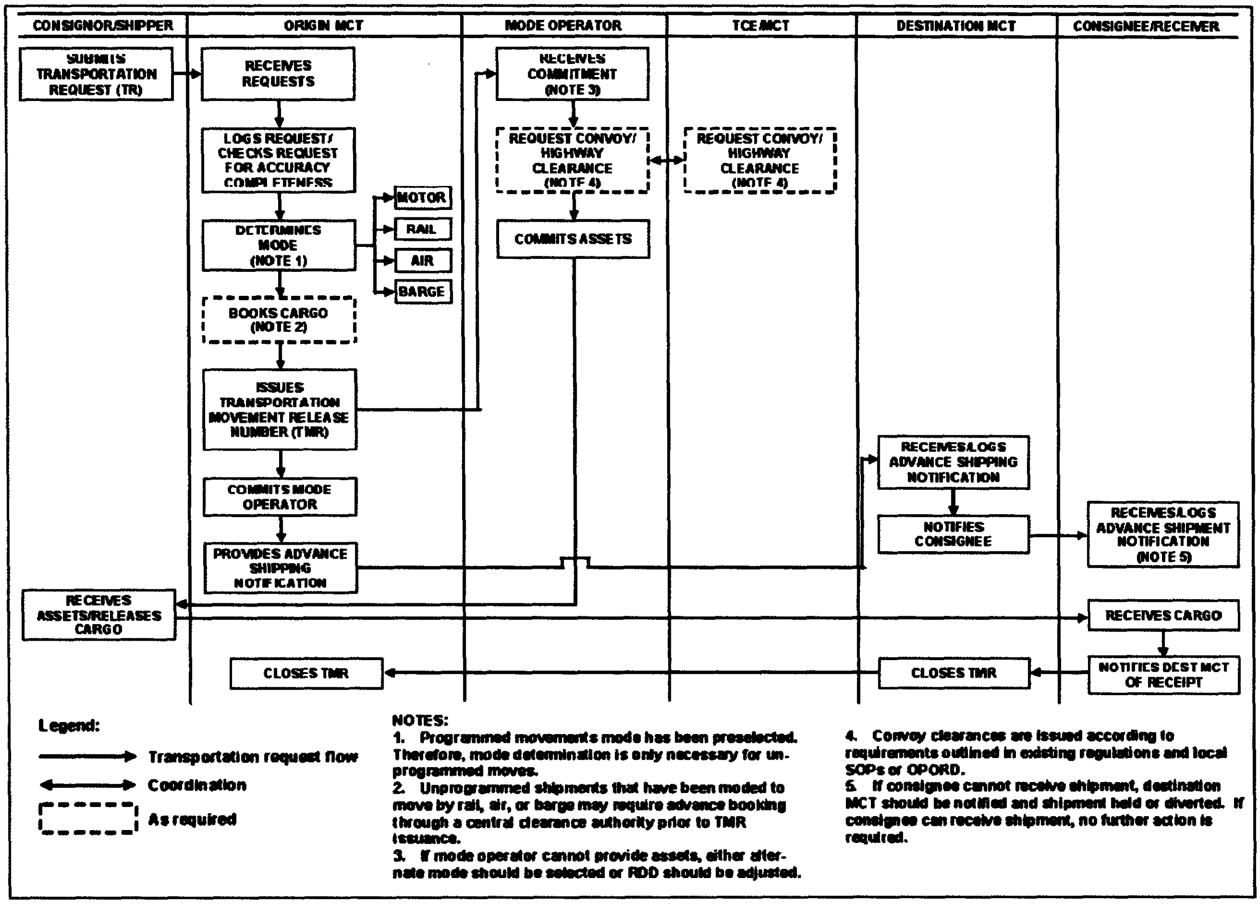

Figure 2-2: Transportation request procedures

The development of a TMR is a separate process altogether. The TMR is built by Army logistics planners based on supply requisitions and availability of transportation assets. Building the TMR is a manual process that planners perform using web-based applications. Each TMR is typically built independently of the others, and therefore, the routes and movement times selected do not take into account those of other TMRs. This form of independent planning and lack of synchronization is a possible contributing factor to high casualty rates of CSS soldiers. We will explain this and other possible contributing factors at the end of this chapter.

In Figure 2-3 [16] we highlight the relevant information from a sample TMR format that we use in our model approach. This information includes priorities, delivery dates, classes of supplies, and locations of origin and destination for the cargo [16].

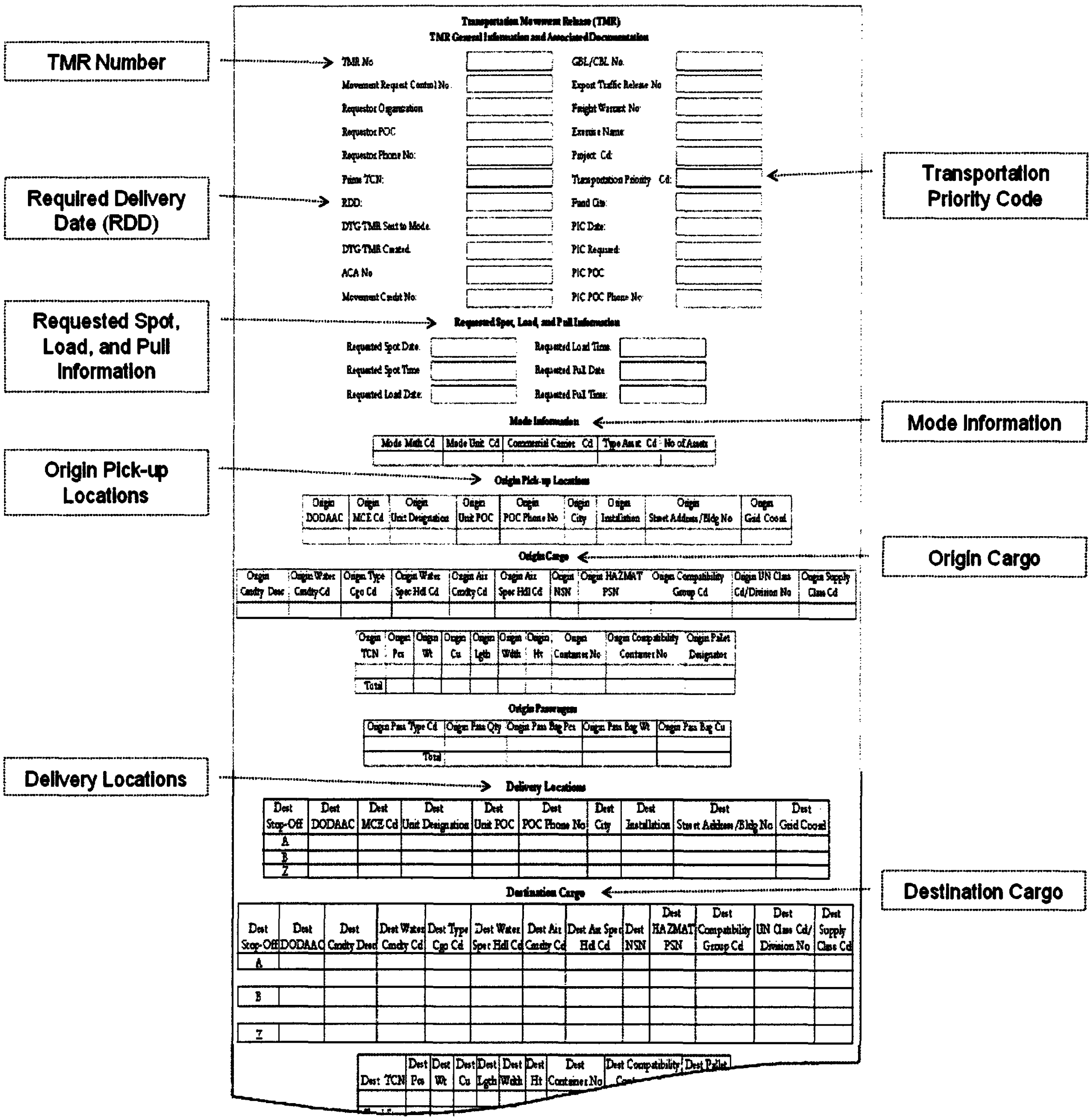

Figure 2-3: Sample transportation movement release

The receipt of a TMR initializes the distribution management (DM) process. This is a four-phase process we describe in detail and analyze in Chapter 3. We propose that integrating and implementing our approach into the existing systems and sub-processes, which comprise the DM process, will address the problem discussed in Chapter 1 and reduce CSS soldier casualties.

2.1.2.5 Movement Control Teams

The movement control battalion, a theater asset, consists of a staff headquarters and a variable number of movement control teams. The MCB positions its subordinate MCTs throughout the AO to extend its control at critical nodes and operating units. The MCT operates most efficiently when collocated with the SUS as it can then conduct direct coordination with corps/division transportation planners or augment movement support operations where necessary in the division AOs. The MCTs assist in tracking the movement of all convoys once a plan enters the execution phase. MCTs also play a critical role throughout the DM process, especially in rerouting unsupported TMRs.

2.1.2.6 Force Protection Considerations

An important component of resupply operations is force protection of logistical convoys. Force protection can take many forms, from passive protective measures, such as increased armor around the cabs of the transport trucks, to overt measures, such as increasing firepower by integrating guntrucks, armor protected ground vehicles with a mounted light to medium machine-gun aboard, into convoys. Figure 2-4 [22] depicts an example of a guntruck.

Figure 2-4: Example guntruck

Army transportation units will typically have a set number of guntrucks organic to its organization that they man internally with their own personnel. The reason for having organic guntrucks is to ease the confusion and complexity brought about by constant link-ups between transport units and special security units that would otherwise be required if transport units did not have their own guntrucks. There are often procedural rules set by the command that dictate protection requirements for convoys such as meeting a minimum guntruck to transport truck ratio before a convoy can go off base. However, despite having organic guntrucks, a unit may still come up short satisfying the minimum guntruck to transport truck ratio. In a situation as this, the transportation unit would request guntruck augmentation through its higher headquarters, which is fulfilled from specialized security units.

Other protection methods include, but are not limited to: armed-helicopter escort, electronic warfare (EW), and the implementation of new tactics, techniques, and procedures (TTPs). Examples of new TTPs are limiting the number of vehicles in a convoy, managing the spacing of vehicles, or adjusting vehicle speeds. Typically, logistic convoys use a combination of TTPs, on-board EW equipment, and an integration of organic guntrucks. Integrating force protection resources (FPRs) into a plan and developing a plan with protection as a focal point is essential to protecting equipment and soldiers in the contemporary operating environment.

2.2 External Considerations

This section covers three factors outside the control of Army units when deployed to a new theater conducting contingency operations. These factors are the contemporary operating environment, the threat, and the host country's infrastructure.

2.2.1 Contemporary Operating Environment

Wars and conflicts today are fought very differently from those of our forefathers. In most of the major wars prior to Vietnam, there are two major characteristics that are not found in the majority of contemporary conflicts: those are opposing armies of comparable size and organization, and distinct lines of separation between opposing armies. According to the Center for Army Lessons Learned (CALL):

> The contemporary operational environment (COE) is the overall operational environment that exists today and in the near future (out to the year 2020). The range of threats during this period extends from smaller, lower-technology opponents using more adaptive, asymmetric methods to larger, modernized forces able to engage deployed U.S. forces in more conventional, symmetrical ways. In some possible conflicts (or in multiple, concurrent conflicts), a combination of these types of threats could be especially problematic [7].

This means that U.S. forces operating on foreign territory, whether conducting combat operations, contingency operations, or operations other than war, will likely be dealing with an insurgent-like threat carrying out asymmetric warfare. "Asymmetry is a condition of ... military imbalance that exists when there is a disparity in comparative strengths and weaknesses. In the context of the COE, asymmetry means an adaptive approach to avoid or counter U.S. strengths without attempting to oppose them directly, while seeking to exploit weaknesses" [7].

2.2.2 Threat

In a COE, the threat will not take on the form or structure of conventional armies nor will it have access to conventional weapon systems such as tanks and artillery pieces. The threat will most likely operate in small cells, under decentralized command and control, and will utilize whatever weapons they can obtain in ways that will counteract the strengths of U.S. forces.

The cheapest and easiest weapon for such an asymmetric threat is to take readily available and inexpensive conventional munitions and modify them so they can be employed separately from their intended conventional weapon system. For example, an artillery round can be used as a bomb by hard-wiring the detonator such that the detonation can be controlled manually. This improvised bomb can now be placed at an ambush site and allow a triggerman to hide until the intended target moves into the bomb's kill zone. Such a device is called an improvised explosive device (IED). An IED, depicted in Figure 2-5 [22], can take on forms limited only by the imagination of the bomb-maker, resulting in infinite variations on the size, means of detonation, and method of employment. This poses great difficulty and numerous problems for U.S. forces trying to counter the threat and protect themselves from these devices.

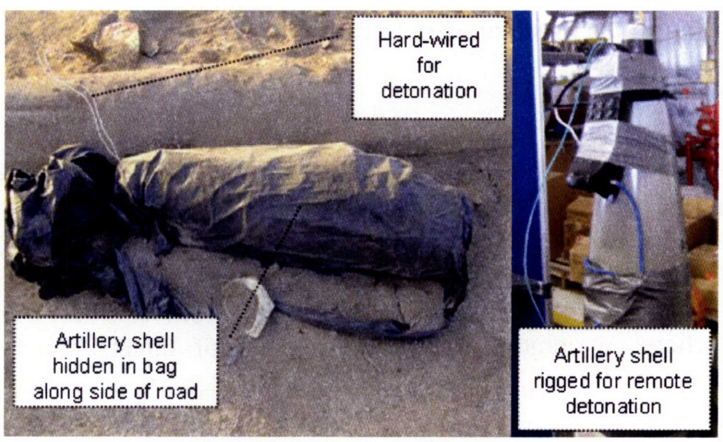

Figure 2-5: Examples of improvised explosive

Due to its significant disadvantage in military force, the asymmetric threat will attempt to target the most vulnerable components that yield the greatest return for their efforts. This means the threat will choose locations where the risk of retaliation is less prevalent and will direct their efforts at softer vehicles that have less armor and lighter weapon systems. Logistical convoys, constantly moving supplies between bases around the battlefield, are thus prime targets of the threat. These logistic vehicles typically have less armor, smaller weapon systems if any, and are carrying cargo considered high-payoff to the threat because said cargo will inevitably be used against the threat upon delivery. This is not to say that the threat will not target tanks and mechanized fighting vehicles if the opportunity presents itself, as hitting this type of target achieves other benefits for the threat.

2.2.3 Infrastructure

Another component of the COE is the physical environment and infrastructure of the country. The physical environment consists of the types of terrain, the climate, and accessibility to waterways. A country's infrastructure consists of ports, railways, airfields, road networks, and existing transportation assets and facilities. Critical to U.S. operations in a foreign country is the level and condition of the infrastructure; the more austere the environment and the worse the state of disrepair of its transportation networks, the longer it will take U.S. forces to achieve freedom of movement within the AO. Furthermore, the greater disrepair is the physical infrastructure of the host country, the more the U.S. will have to rely on ground convoys to move supplies around the battlefield.

2.3 Military Staffs and Planning Process

This section covers the organization of Army staffs and the planning process used by these staffs to plan combat and CSS operations. This section ends by describing some of the technological tools currently available to assist in the planning and tracking of military logistics.

2.3.1 Staff Structure

The commander of each of the units in the corps organizational structure has a dedicated staff organized to conduct the necessary coordination and the liaison required to synchronize the complex interdependencies and interrelationships existing within a corps. Each staff operates under the guidance of a chief of staff (CoS) or executive officer (XO), and has at a minimum a personnel (S1/G1), intelligence (S2/G2), operations (S3/G3), logistics (S4/G4), and communications (S6/G6) section. Staffs tend be larger at higher echelons of division and corps and will include special staff sections that perform specific functions and personal staff that directly advise the commanding general. Lower echelons, e.g., brigades and battalions, will have smaller staffs and fewer special sections. Figure 2-6 [19] depicts a typical staff structure;

for a complete explanation of staff organization and responsibilities refer to FM 6-0, Mission Command: Command and Control of Army Forces.

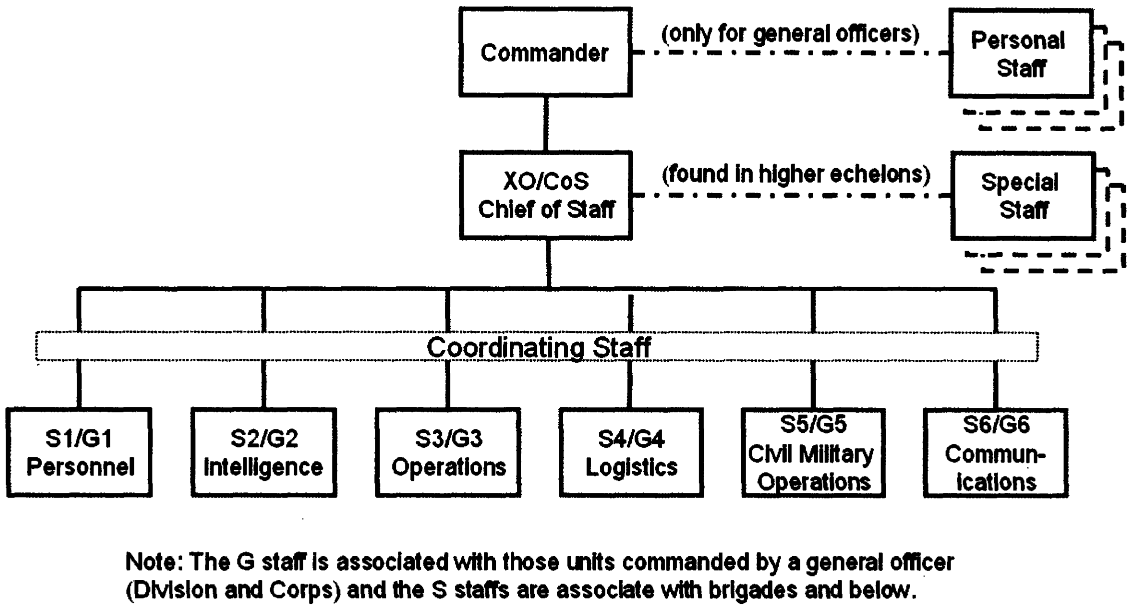

Figure 2-6: Generic staff structure

One of the many functions of a staff is to facilitate the command and control of a unit for the commander. Depending on the type of unit (combat or CSS) the missions can be entirely different. For example, the types of missions assigned to a combat unit, e.g., an infantry brigade or armor division, include defeating an enemy or maintaining security; whereas CSS units, e.g., petroleum or transportation battalions, are responsible for sustaining the combat units and force as a whole. While these units have entirely distinct missions and foci, there exists a common thread in the structure of their staffs that allows them to communicate and coordinate each other's needs effectively. The following is an example of how this common thread facilitates the flow of information and coordination across echelons and different types of units.

Example of Information Flow and Staff Coordination

The G4 of an armor division receives status reports from the S4 of all the subordinate brigades and consolidates them into one requisition report to send to the supporting SUS. Parallel to this, the supply companies subordinate to the CSSBs supporting the combat brigades send TRs to their respective SUS/MCT in order to request resources to move the necessary supplies. The SUS divides the requests by commodity and assigns the appropriate subordinate units to fill the requests and build convoys for delivery of the supplies. The MCT redirects the requests that they cannot handle to another SUS or the MCB.

The ammunition battalion staff devises a plan to fill all ammunition requests; the petroleum battalion staff plans for petroleum products; and the transportation battalion staff plans for moving all general supplies. These support staffs coordinate with one another to form heterogeneous convoys to deliver the necessary supplies to the combat units dispersed over multiple bases across the AO. Other essential staff coordination must occur concurrently for the successful execution of this divisional resupply. Some of this coordination includes verifying that the appropriate personnel are available for the resupply mission through S1/G1 sections, receiving the latest intelligence reports along the planned convoy routes from the S2/G2 sections, and requesting and receiving route clearances through MCTs controlling the movements along supply routes.

Crucial to timely and accurate resupply of combat forces is effective coordination and a common understanding or a common operating picture (COP) of the battlefield and friendly forces. Later in this chapter we describe how technology assists in the sharing of information, facilitating coordination, and providing the COP necessary for efficient operations.

2.3.2 Military Decision Making Process

Over the years, the Army has developed and refined a formal process to guide staffs during the planning stage of operations. The process is referred to as the military decision making process (MDMP) and is depicted in the Figure 2-7 [18] below, which outlines the role of the command and staff in this process. The process is thoroughly described in Army Field Manual 5-0, Army Planning and Orders Production.

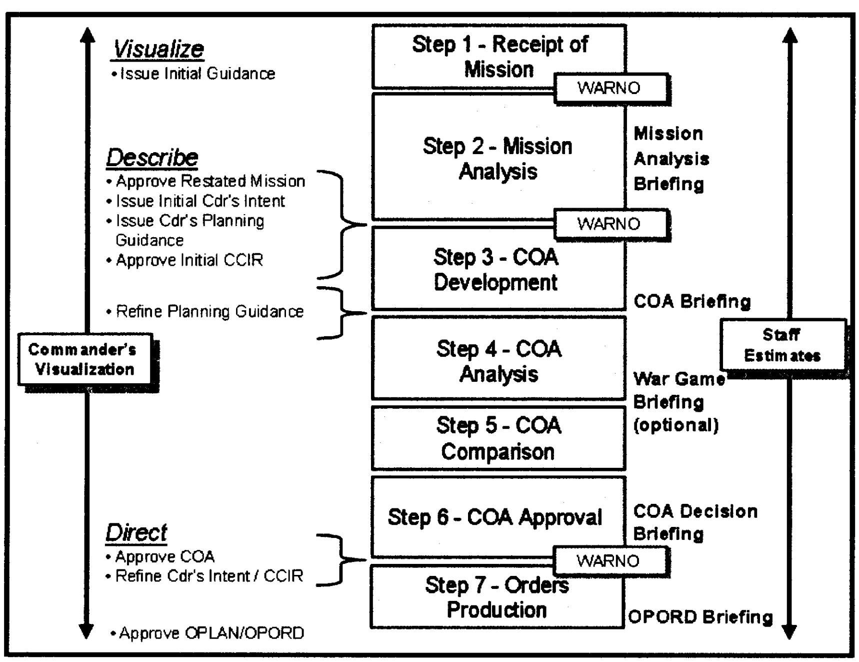

Figure 2-7: Role of the command and staff in the MDMP

At various points throughout the process, the commander has the opportunity to provide vision and guidance to the staff sections as illustrated on the left-hand side of the figure. The staff takes this guidance and uses it to develop and refine their respective estimates of the situation depicted on the right-hand side of the figure. During Step 3, course of action development, a number of plans are proposed and then analyzed and compared in the next two steps. This allows the staff to recommend the best plan or provide alternatives to the commander. The commander will then decide upon the best course of action (COA), and the staff will develop it in greater detail and publish it in an operations plan (OPLAN) or operations order (OPORD) for distribution to the subordinate commands for execution. After Steps 1, 2 and 7 of the MDMP, the staff prepares and disseminates warning orders (WARNO) to subordinate commanders so that they can begin their planning in parallel. With respect to CSS operations, a COA would be the distribution plan for a given execution period that includes a set of logistical convoys configured to distribute supplies across the AO.

The OPORD that results from the MDMP has a combat focus with supporting paragraphs and annexes describing the CSS plan that supports the combat units. Paragraph 4 (Service Support) and Annex I (Combat Service Support) of the OPORD contain all the CSS details necessary for supporting the combat mission. Due to the unique mission of CSS units, their planning process works a little differently, but nonetheless integrates and synchronizes with the overall operations order. Figure 2-8 [15] depicts how the CSS estimates, a result of the MDMP steps developed by the S4/G4 staff section, provide the basis for the logistic support of the OPORD that follows from the commander's guidance and higher command's mission.

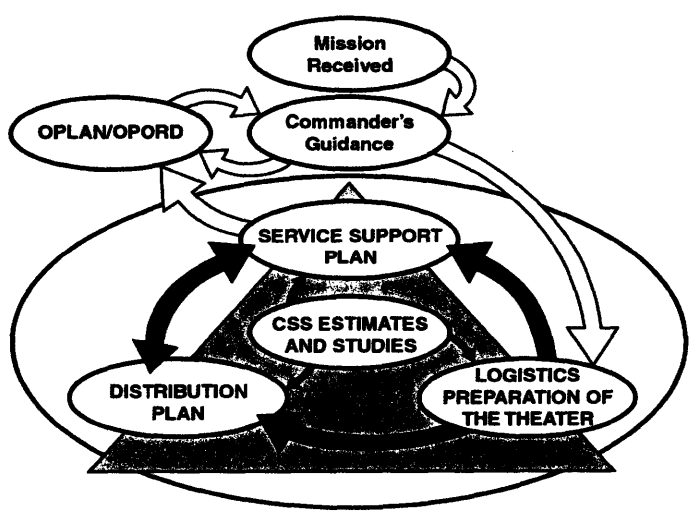

Figure 2-8: Planning for CSS that supports the mission

After the initial OPORD is published, day-to-day continuous operations are planned and executed off of fragmentary orders (FRAGO). A FRAGO will change, add, or delete information contained in the original OPORD or previous FRAGOs. Because military distribution occurs on a daily basis, the plans that outline the distribution movements for a given day are continuously developed, refined, and published in daily FRAGOs. This recurring planning process is known as the military distribution process. As a general rule of thumb, the Army applies a 1/3:2/3 rule to the MDMP. This rule states that command and staff take no more than one third of the available time until mission execution to plan and publish an OPORD or FRAGO. The subordinate units utilize the remaining two thirds of the time to prepare their personnel and equipment and to conduct necessary rehearsals required for mission success. Figure 2-9 illustrates the time breakdown of planning, preparation, and mission execution.

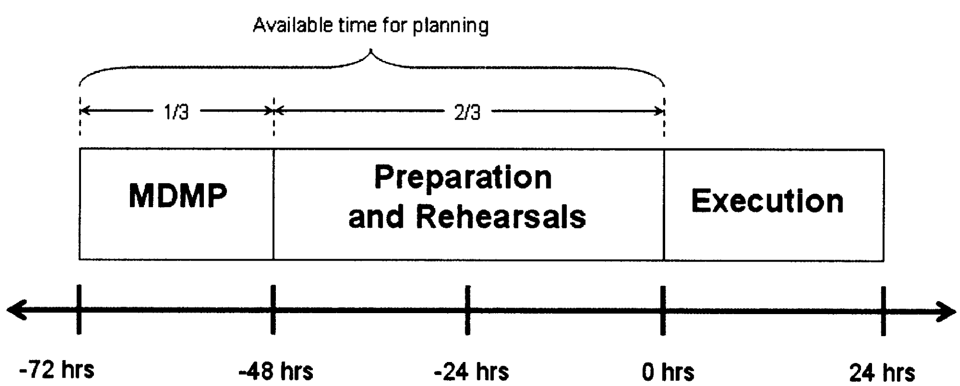

Figure 2-9: Mission planning and execution timeline

There are a few specific elements of the MDMP and resulting OPORD that are of interest to our research and approach. First is the intelligence preparation of the battlefield (IPB) that occurs during the Mission Analysis step of the MDMP. The S2/G2 staff section performs the IPB for that particular unit's AO prior to the unit's deployment to the theater. The IPB serves to describe the threat and how the environment will impact both the threat and friendly forces. This initial IPB is significant because it serves as the base for all future intelligence updates, to include updates given to transportation units prior to conducting a convoy.

The next two elements are a product of the CSS estimate generated during Step 2 as well. The first is the selection of the main supply routes (MSRs) and alternate supply routes (ASRs) within the AO. These are routes selected by CSS staff planners prior to a unit's deployment based on a thorough map reconnaissance and analysis of other geospatial products. Planners typically select major highways for the MSRs and ASRs because they are designed to withstand heavier traffic at higher speeds. Using MSR and ASRs during planning and executing of movements makes the planning process more efficient and greatly enhances command and control. The last element is the list of support priorities in the OPORD. There are two separate priority lists: priority of support to combat units and priority of support for the classes of supply. Factoring both priority lists into CSS planning aids the planning staff in prioritizing shipment of supplies to support the operational mission. Throughout the MDMP and mission execution, commanders and staff have access to a myriad of automated decision support tools to help build the plans and control the execution of the plans.

2.3.3 Technology-Based Support Tools

There are many technology-based tools currently in use and in development to assist in the planning process and command and control (C2) of military operations to include distribution management. Historically, the various branches of the Army developed automated systems and tools independently, resulting in disjoint systems and databases that often slowed down and hampered the planning processes. However, in the recent past, the Army has put great emphasis on synchronizing automated C2 systems such that they operate off one common operating picture (COP) from which all types of units can access relevant data among shared databases. The successful synchronization of these automated tools would remove redundancies and disconnects that have existed in the past.

This movement has resulted in the current Army Battlefield Command System (ABCS), which is comprised of all the Army C2 systems that feed off one another. The five systems at the corners of the pentagons in Figure 2-10 [13] are the C2 systems for all the primary Army functions on the battlefield. They are: Maneuver Control System (MCS); Forward Area Air Defense Command, Control, Computers, and Information (FAADC3I); Advanced Field Artillery Tactical Data System (AFATDS); All Source Analysis System (ASAS); and Battlefield Command Sustainment Support System (BCS3). In this thesis, we will focus on the BCS3 system which is the C2 system for CSS operations.

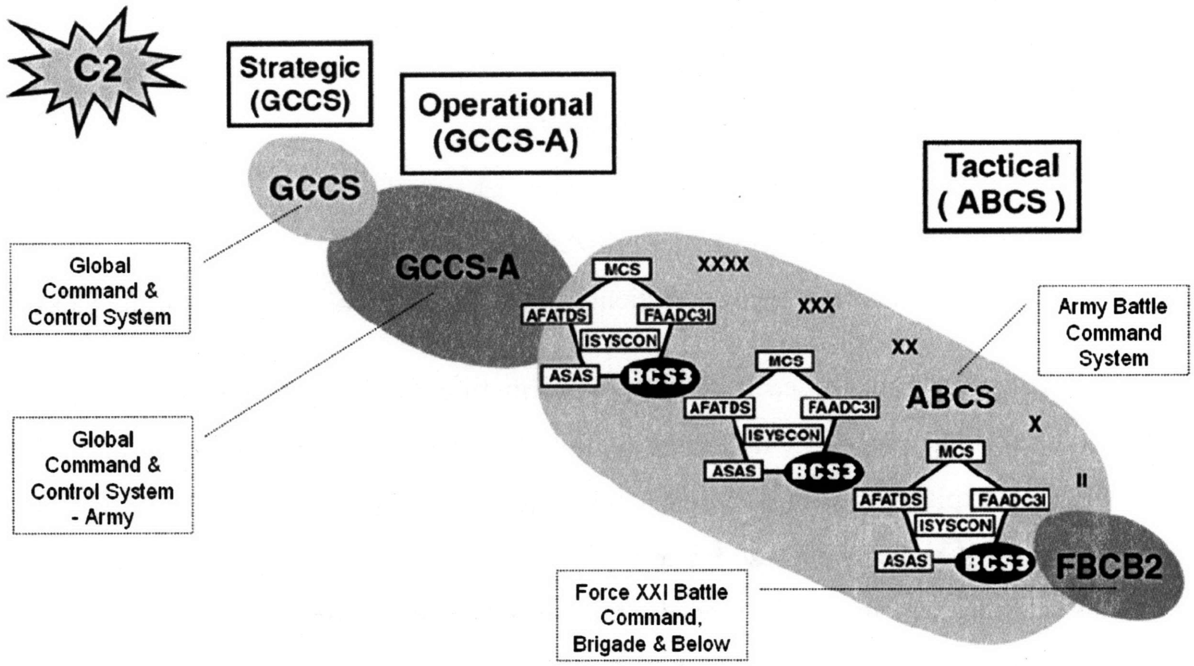

Figure 2-10: Army Battle Command System

BCS3 synchronizes all of the basic CSS functions into the logistics common operating picture (LCOP). The LCOP includes a map-based representation of all battlefield logistics data provided by tools such as the Movement Tracking System (MTS), in-transit visibility (ITV), radio-frequency identification devices (RFID), and Trans-Log Web (TLW). MTS is a vehicle-based GPS system that assists truck operators with navigation and command and control of a convoy. ITV uses interrogators across the battlefield to track the movement of RFID tags that are attached to shipping containers in order to provide commanders and staff visibility of supplies in the distribution network. Trans-Log Web, a component of BCS3, is a web-based system that facilitates the scheduling and de-confliction of convoy movements. We will further examine the functionality of some of these systems as they relate to the approaches we develop to reduce risk to CSS soldiers moving around the battlefield.

2.4 Contributing Factors to Problem

In the Army, a complex organization containing a multitude of interwoven systems and processes, it is hard to isolate and identify a single cause of the high casualty rates of CSS soldiers operating in a COE. In practice, there are likely numerous contributing factors. The following is a list of some possible contributing factors that we collected through personal interviews with and accounts by Army soldiers:

1. Unit convoys planned independently;
2. Too many unnecessary convoys on the roadways;
3. Movement of unit convoys not synchronized;
4. CSS planners do not have access to appropriate intelligence;
5. Force protection resources under utilized; and
6. DM process does not allow sufficient time to develop and analyze multiple COAs.

We will refer back to each of these contributing factors throughout the thesis and describe how existing processes fall short or fail to address these underlying issues. More importantly, we explain how the approach taken in our research specifically addresses and mitigates the negative effects of these factors.

One additional factor that can easily be overlooked is the constant rotation of units and individuals into a theater. Obviously, for operations lasting more than a year or two, it is important from a mental health standpoint to rotate soldiers out of combat to prevent "burn-out" from constant exposure to a high-stress, threat-laden environment. Taking this into account the Army has determined the appropriate length of time for a rotation is 12-15 months.

For a new unit rotating in to a theater, it can be considerably dangerous for the first 90 days. This is the time period in which a unit is adjusting to the environment and its mission. During this time, soldiers are more susceptible to the risks posed by the threat, and there is a higher probability of becoming a casualty. Every soldier and leader in the unit gains invaluable experience, over time, from operating in-theater, which reduces their susceptibility to becoming a casualty. After this approximate 3-month adjustment period, experience takes over, resulting in soldiers and units operating at high levels of efficiency with lower susceptibility to becoming casualties. Towards the end of a deployment, when a soldier or unit knows they will be returning home soon, there can be an increase in susceptibility as some complacency sets in and soldiers let their guard down. We plot the associated curve in Figure 2-11, which we term the deployment risk curve. We speculate that the basic shape remains the same whether for a unit or individual. Furthermore, we emphasize that the curve is not tied to actual data, but rather it is relative and used to illustrate how a soldier's experience, over time, affects his susceptibility to the risk.

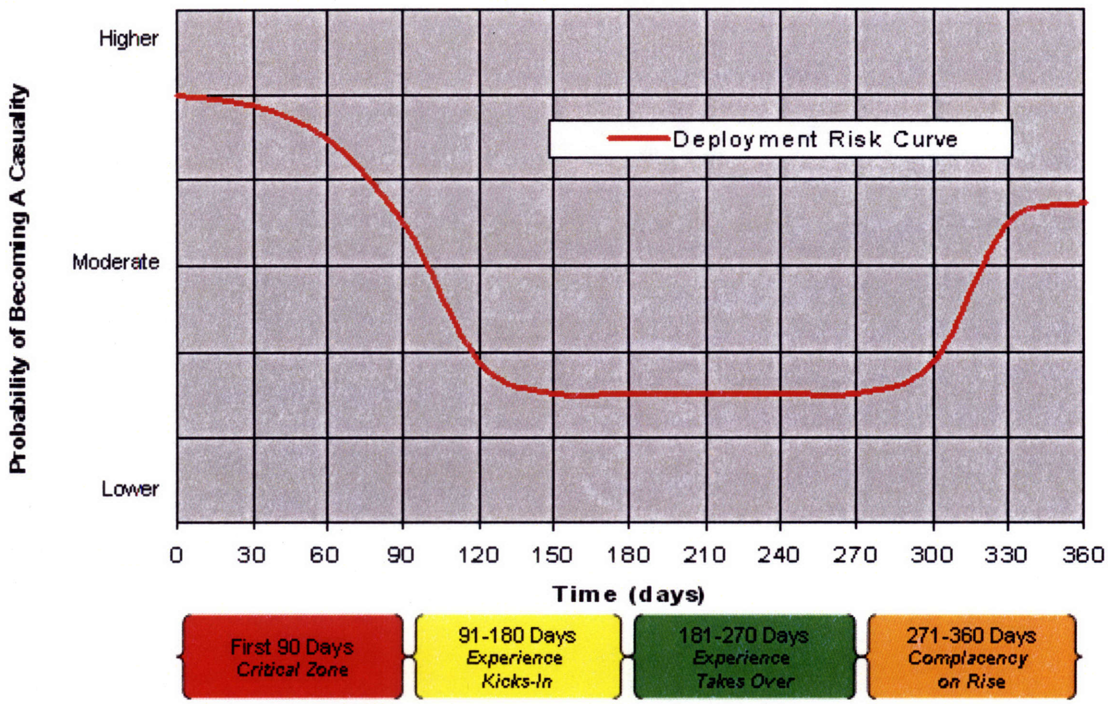

Figure 2-11: Deployment risk curve

A goal of our approach is to lower the deployment risk curve and flatten the high points at the beginning and end of a deployment. We propose that implementing our approach and associated model in the planning process will compensate for the lack of experience in the first 90 days as well as any complacency that might set in towards the end of a deployment.

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3 Distribution Management Process

As mentioned earlier, the Army is currently undergoing transformation, which means its organizational structures and processes are also undergoing change in real time; however, it often takes a couple of years for these changes to become transcribed and recorded into official published doctrine. Due to this fact, we base our functional analysis of the distribution management process partly on published doctrine and partly on the future direction of military logistics as described in the book *The Process of Military Distribution Management* by Lieutenant Colonel James H. Henderson, United States Army (Retired). Henderson wrote the book after his own recent experience in Operation Iraqi Freedom as an Army logistician.

3.1 Phases of Distribution Management

In his book, Henderson states that the "Distribution Management Process synchronizes critical supply and transportation assets to facilitate sustainment tracking and provide a Common Operating Picture (COP) of distribution flow in support of sustainment...of forces." The DM process is cyclical in nature, with a 72-96 hour period. Note that the period length may vary depending on the specific demands of the mission and the preferences of the planning staffs. There are four phases to the process: Planning and Allocation, Coordination and De-confliction, Validation, and Tracking. Figure 3-1 [8] illustrates the cycle of phases with time windows for their duration. The first three phases consist of planning and preparation for the fourth phase, which is tracking the movement of convoys as the plan is executed.

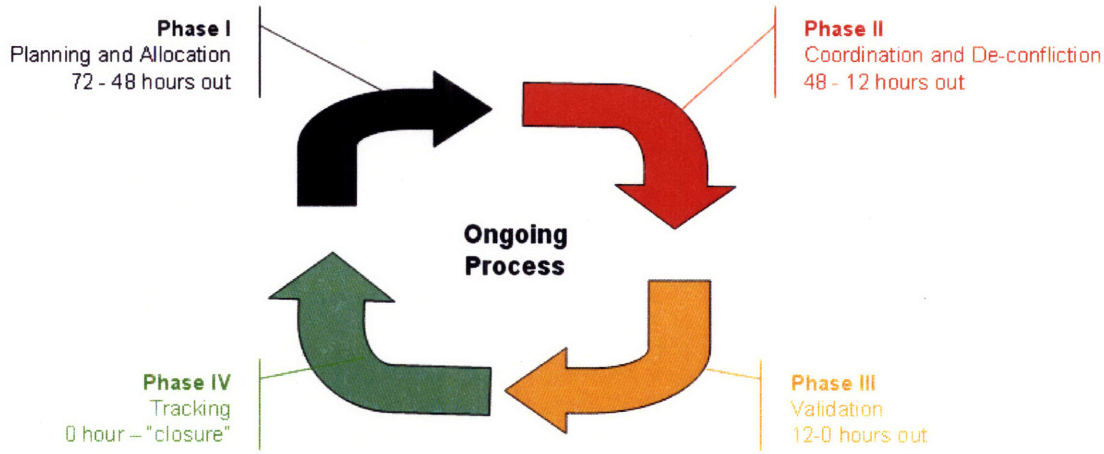


Figure 3-1: Distribution management process

The DM process is structured after the military decision making process, and each new plan the staff publishes is essentially a fragmentary order (FRAGO) for subordinate CSS units to execute. The DM process occurs in parallel with the MDMP (see Figure 2-7) of combat forces so that combat and CSS staffs can coordinate throughout the phases in order to develop support plans that satisfy the requirements for the overall mission. During indefinite military operations, the process of DM occurs continuously in overlapping cycles, so that at any given point in time, the staffs are developing or executing three or four concurrent plans each in different phases of the DM cycle.

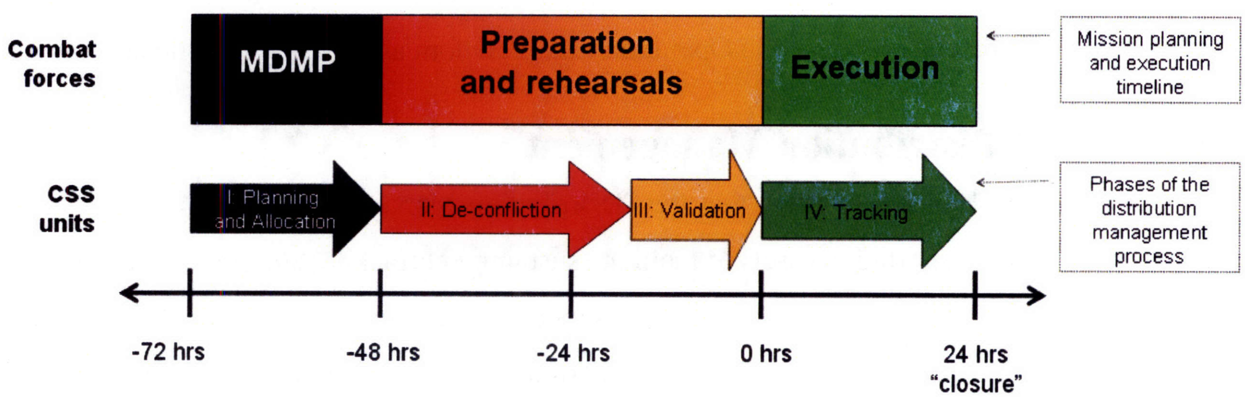


Figure 3-2: MDMP and DM process in parallel

3.1.1 Phase I: Planning and Allocation

The first phase, planning and allocation, occurs between 72 and 48 hours out from mission execution. This is in line with the 1/3:2/3 rule for planning operations discussed in

Section 2.3.2. The actual time frame can vary depending on whether distribution planning cycles occur over two, three, or four day time periods. The major input into this phase is the transportation movement release. The output of this phase is the first cut of the master distribution matrix accessible through the Battle Command Sustainment Support System.

The flow of information and decisions throughout this phase is illustrated in Figure 3-3 [8]. The phase initializes with customer requests for transportation of supplies. Customers include subordinate supply companies within the combat sustainment support battalion. The supply companies' requirements are generated from the demands of the combat brigades for which they provide logistical support, according to the task organization. The customer requests are sent to the movement control officer (MCO) at the divisional level and to a movement control team (MCT) at the corps level. The MCO is a special staff that links divisional transportation units to the customers. The requests originating at the MCO are forwarded to the supporting SUS.

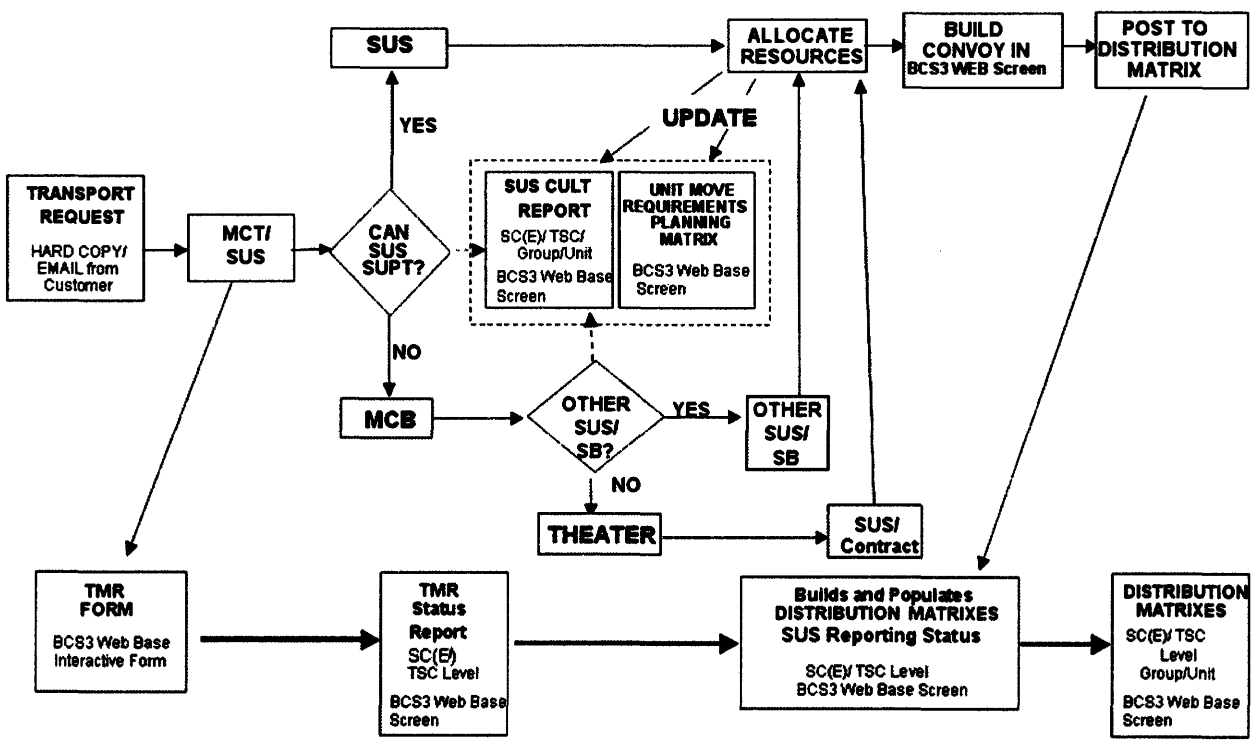


Figure 3-3: Phase I: Planning and Allocation

The SUS determines if they have the organic transportation assets to meet the movement requirements. If the SUS cannot support the move, then the MCT either tasks another SUS or forwards the request to its higher command, the MCB, who searches for theater-owned assets that can accommodate the move; otherwise, they contract out the request to the host nation or U.S. contractors. The SUS or other unit that accepts the TMR will allocate the appropriate transport resources and organic guntrucks and update the common user land transportation (CULT) report. The purpose of the CULT is to track all committed or unavailable assets and crews of all transportation units in the AO such that MCTs gain visibility of available assets for all units operating in the AO.

After allocating the necessary transportation resources, the SUS updates its unit move requirements planning matrix, also through BCS3, which assists in planning future cycles. The next step is to build the convoys according to set rules and procedures. Currently, this is a manual process in which staff planners look at aspects such as origin/destination of supplies, total number of transport trucks in the convoy, and transport-to-guntruck ratio for force protection. Once the convoy is formed, the information is posted to a distribution matrix available through BCS3. The web-based distribution matrix offers all units, combat and CSS, a logistics common operating picture (LCOP) that necessary parties can access and filter to view relevant distribution information.

3.1.2 Phase II: Coordination and De-confliction

The primary output of Phase I is a common working copy of the distribution matrix that portrays the set of transportation movements for an execution period of 24-hours. Each row in the matrix is a separate movement and the columns include the details of the movement. Each movement is a group of transport trucks configured in a single convoy for mutual protection and ease of command and control. In the asymmetric COE, these convoys are considered combat logistics patrols (CLP), a term coined by the 1st Infantry Division in the early stages of Operation Iraqi Freedom [3], because they are not exempt from the threats of IEDs and other ambushes along the roadways.

Throughout Phase II (Coordination and De-confliction) of the DM process, the distribution matrix is scrutinized through a series of daily board meetings held at various echelons of command. Figure 3-4 [8] shows the process flow for this phase. The joint distribution board (JDB) de-conflicts movements with joint forces, e.g., the Air Force or Marines, operating in the AO, while the distribution movement board (DMB) occurs at the corps level with participants that include SUS liaison officers (LNOs), MCB battle captain (BCPT), and other representatives from the MCB and the distribution management center (DMC). The DMC consolidates all CSS planning operations at the theater support command (TSC).

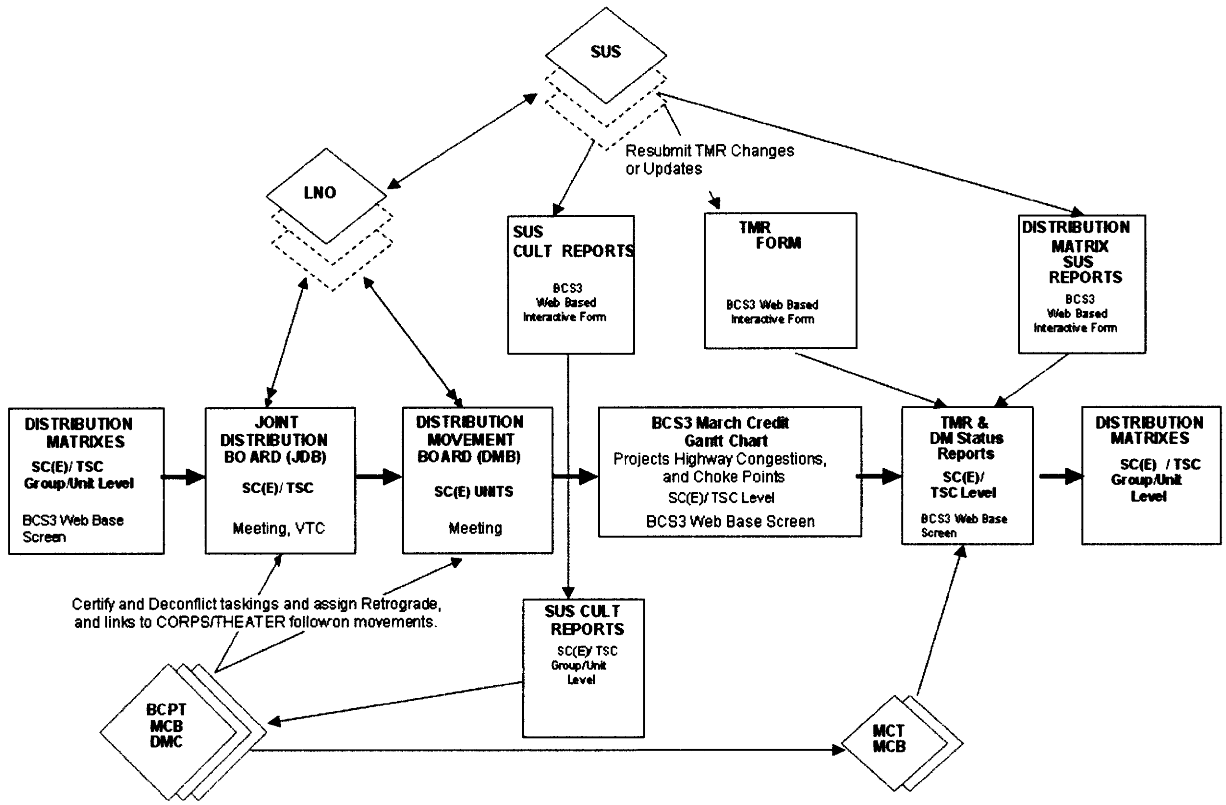


Figure 3-4: Phase II: Coordination and De-confliction

The purpose of the boards is to identify and correct discrepancies or conflicts that might prevent the execution of the TMRs included in the distribution matrix. If the board identifies a conflict, the LNOs forward the necessary information back to the planning staff of their respective SUS, who makes necessary adjustments and updates relevant TMRs and CULT reports. Approved movements receive march credits, an alpha-numeric code associated with an approved movement along a specific route and time window, that are added to the distribution matrix. The output from this phase is an updated distribution matrix containing all approved convoys.

3.1.3 Phase III: Validation

Once approved, the distribution matrix becomes the convoy plan to support the force over that 24-hour period. The distribution matrix is continually monitored throughout the validation phase by way of the daily boards depicted in Figure 3-5 [8]. Updates continue to occur as necessary to adjust for changes or the addition of high priority movements. Finally, during the evening prior to execution, all interested parties and LNOs conduct a final "hotwash" meeting that ensures all movements are a "go."

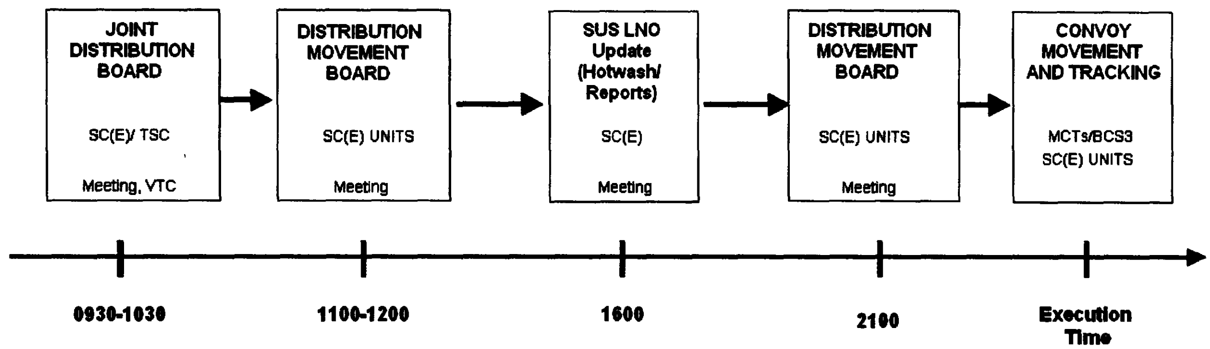


Figure 3-5: Phase III: Validation

Also occurring during this phase, is the preparation of the truck loads and configuration of the convoys. All supplies are loaded into appropriate trailers or onto pallets and pre-positioned for easy hookup to tractors or loading onto flat-bed trucks. This can be a time consuming process, so the earlier the supply units receive convoy configuration information, the more time they have to prepare for the movement. This phase leads into the execution period that, for the planners, consists of tracking all movements.

3.1.4 Phase IV: Tracking

During Phase IV (Tracking) the MCTs track all movements with assistance from automated tools and standard operating procedures. Figure 3-6 [8] depicts the functional flow for this phase. BCS3 provides a map centric view of convoys along the MSRs and ASRs and receives periodic updates via pre-positioned interrogators throughout the AO that collect data from radio frequency identification devices (RFIDs) attached to cargo. This allows concerned parties to track and verify that their respective cargo is inbound and on schedule as planned. Each convoy is given positive inbound clearance (PIC) once the MCT receives confirmation of arrival along the route. Should a threat encounter occur along the route, the convoy commander sends a "SPOT" report via radio or text message that describes the event and/or requests additional assistance.

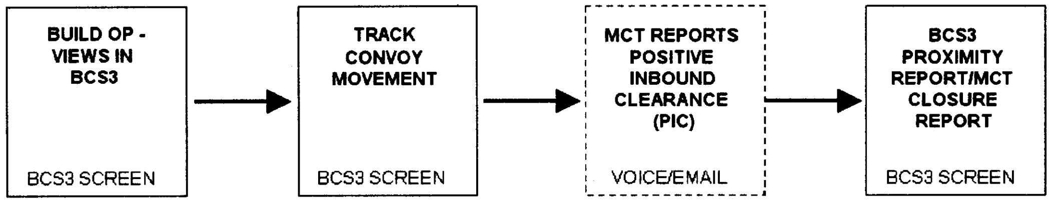


Figure 3-6: Phase IV: Tracking

The final step of this phase (and thus the entire DM cycle) is for convoys to submit a closure report when they return to their original base. The closure report, which includes mission completion times and ending operating strength, signifies the end of the convoy operation. The cycle ends when all scheduled convoys for a given 24-hour period have submitted their closure reports. Immediately afterwards, the planning staffs continue the DM process for future plans, at various phases in the cycle, while the operators (truck drivers) rest and prepare for the following day's mission.

3.2 Input-Output Model

Most systems can be modeled functionally using a simple input-output model in which material, data, or information flow into the system. The system processes these inputs accordingly based upon the system programming and produces a set of outputs in the desired form. Some systems may also produce unavoidable and undesirable residual effects as a result of the processes or by acting on the outputs. See Figure 3-7 for the generic functional form of the input-output model.

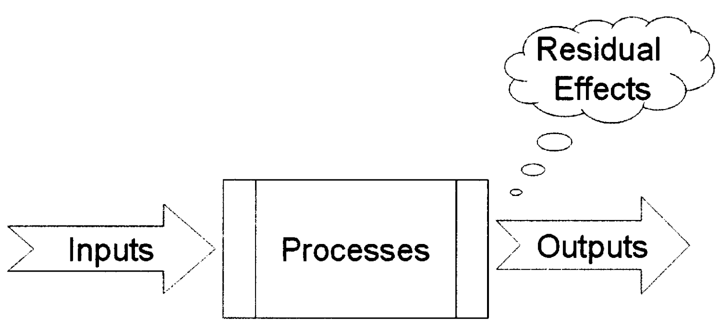


Figure 3-7: Input-output model

In the following sections we break down and analyze the Army's DM process in terms of the above input-output model. The purpose is to isolate the sub-processes that contribute to the undesired residual effects, notably high casualty rates for CSS soldiers, that occur as a result of executing the plans generated through the DM process. We then use what we learn from this functional analysis of the DM process to formulate a mathematical model and algorithmic approach that addresses the high casualty rates for CSS soldiers.

3.2.1 Inputs

The inputs for our model include quantitative and subjective data that we can collect and manipulate through various means, as well as user inputs (in the form of assumptions and estimates) for the data we cannot easily gather. Figure 3-8 lists the more significant data inputs to the model of the DM Process.

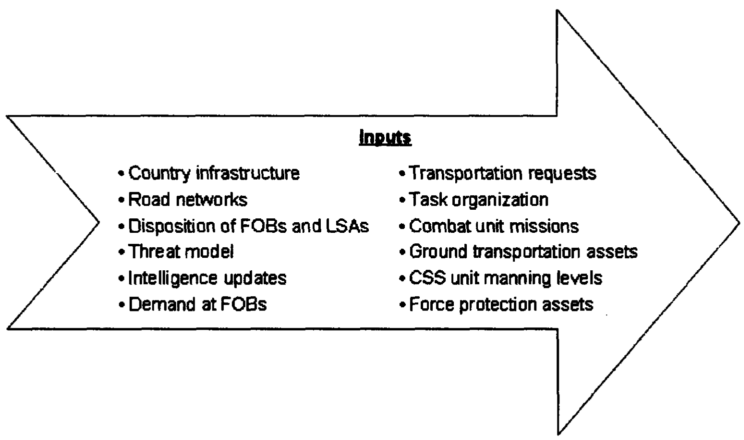


Figure 3-8: Model inputs

Under traditional military planning and operations, much of this data is collected through well established reporting mechanisms and stored in various shared and unshared databases and spreadsheets. Essential to generating the desired outputs of the system, while minimizing the residual effects, is establishing and implementing processes that efficiently search for, select, and manipulate the relevant data. This greatly enhances planners' abilities to use the data and information to develop good plans.

3.2.2 Processes

Distribution management (DM) consists of a series of sub-processes that lead to the common goal of generating an executable convoy plan to distribute supplies to combat forces across the AO. Some of these sub-processes include how to collect the data, use data for planning, implement the plan, and then track the execution of the plan. The processes listed in Figure 3-9 are a collection of significant sub-processes that access and utilize the inputs of the DM model in the creation of the convoy plan.

Processes	
• Military decision making process	•Allocation of FP resources
• Intelligence preparation of battlefield	• Populating distribution matrix
• Selection of initial MSRs and ASRs	• Distribution boards
• Military supply system	• Convoy building
• Distribution management	• Preparation of loads
• TMR initialization	• Unit reporting procedures
•Allocation of transportation assets	• Tracking

Figure 3-9: Model processes

The vast amount of virtual data and information available in the shared databases can be overwhelming for even the experienced staff planner. The contemporary Army staff officer is well versed with basic computer applications such as Microsoft Excel, which the staff officer uses to sort, manipulate, and generate reports on the relevant data available for his respective AO. Staff officers use these manually generated spreadsheets and reports to facilitate their respective planning portion of the overall staff planning effort. The drawback to this system is that changes to the data occur frequently and do not get updated on these static spreadsheets. This leads to planning with out of date and possibly inaccurate information that could result in the development of infeasible plans.

The employment of the Army Battle Command System (ABCS) attempts to bridge this gap by automating the collection, sharing, and accessibility to this data. However, even with these advances, the Army planner must still devote many man-hours in sorting through and deciding which data is relevant for his planning. Our approach follows the intent behind ABCS in collecting and sharing information and takes it a step further in the CSS C2 system. Our approach automates some of the manual tasks associated with CSS planning via algorithms designed to select and preprocess all relevant data in the development of optimized COAs.

3.2.3 Outputs

The primary output of the DM model is the distribution matrix, which in essence is the convoy plan. The process also produces the LCOP that facilitates future planning and provides commanders and staff with the ability to track the movements of plans in the execution phase. Figure 3-10 lists the outputs from this model. The model outputs comprise the CSS course of action for supporting the mission of combat forces. In practice, the COA would be included in the next published FRAGO for implementation and execution.

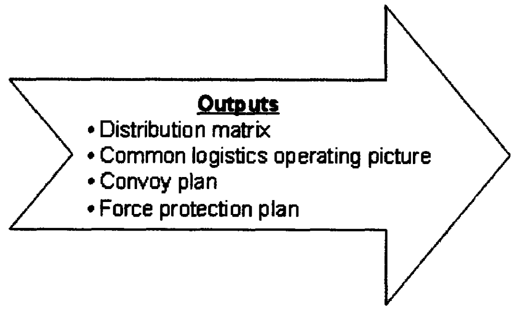


Figure 3-10: Model outputs

Note that traditionally the force protection plan, listed last in the outputs above, would not be a driving factor in the CSS plan. However, we suggest greater emphasis on this facet of convoy planning and operations will lead to better distribution plans with fewer casualties.

3.2.4 Residual Effects

It is impossible for military staffs to produce plans for a threat-laden environment that perfectly counters the threat and results in zero casualties. The realities of operating in a COE and facing an asymmetric threat are that the threat will attack vulnerable forces. Transport trucks and logistical convoys are considerably more vulnerable than combat forces, so no matter how good the plan, once the trucks are on the roads, they are sure to sustain some casualties as a result of threat ambushes. Other negative effects of these ambushes, as depicted in Figure 3-11, include damaged trucks and supplies, missed delivery timelines, and failed deliveries. Some of these residual effects require the inclusion of additional transport assets in future plans to redeliver supplies that did not get delivered to their destinations.

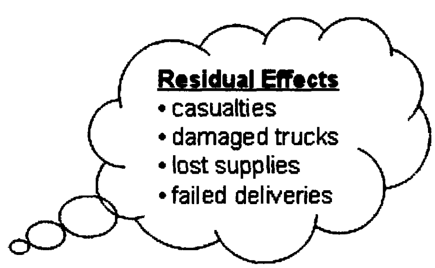


Figure 3-11: Model residual effects

We acknowledge that we can not completely eliminate CSS soldier casualties, so the emphasis should be on minimizing these casualties by mitigating the effects from threat ambushes. This goal is not possible unless it becomes a priority within the mind-frame of commanders and is aggressively addressed throughout the planning process.

3.3 Distribution Management Process and the Contributing Factors

Well-planned force protection for logistical convoys indirectly and directly addresses all of the contributing factors to the high casualty rates of CSS soldiers as discussed in Section 2.4. The residual effects explained in the previous section result from the underlying factors that are interwoven into the sub-processes discussed previously in this chapter. We end this chapter by isolating each of the contributing factors already identified and discuss how they relate to the processes that result in high casualty rates of CSS soldiers.

1. Unit convoys planned independently:

This situation arises from the multitude of transportation units segmented by the task organization (TASKO) and TR procedures. When a unit submits a TR, it is not automatically cross-referenced with any other TR having similar parameters, e.g., the same origin and destination. The amount of time and effort it would take a unit to try to find another unit traveling a like route would detract from other essential planning tasks. Independent planning efforts also preclude the effective use of scarce force protection resources that could be shared among units planning together. Thus, when a transportation unit receives a TMR, they build and configure their convoys without coordinating with other transportation units.

2. Too many unnecessary trucks and convoys on the roadways:

This is an indirect result of the previous factor. It is possible to have multiple smaller convoys of 5-10 trucks departing from the same LSA and delivering supplies to the same FOB, or at least traveling in the same direction. Furthermore, the transport trucks that are a part of these convoys might not be filled to capacity. Therefore, we can reduce the number of convoys on the road by consolidating smaller convoys and partial truck loads.

3. Movement of unit convoys not synchronized:

The process of granting march credits for approved TMRs does not seek to optimize or synchronize the flow of convoys along the MSRs and ASRs. MCTs merely check whether the route is open, that the host-nation has granted U.S. forces permission to use the route, and if the size of the movement for the TMR remains within the capacity limitations of the route. This does not insure the level of synchronization necessary to avoid and minimize exposure to the threat. A better approach is a system that considers the threat situation and all convoys requiring movement over a specified period when assigning routes and time windows for movement.

4. CSS planners do not have access to appropriate intelligence:

CSS units all have intelligence officers (S2/G2) that advise planners on the threat situation. Threat briefs or updates are usually generic in nature due to the large areas over which convoys operate. Additionally, CSS planners receive updates on times and locations of the most recent *threat events. While this sort of intelligence is good to know, it does not necessarily help the CSS staff officer effectively develop a plan that avoids or mitigates the effects of threat ambushes. What CSS planners really require are threat models that serve to predict threat activity along roadways. If the threat is properly modeled with respect to the road network, then the proposed algorithmic approach can process these models and factor them into convoy plan generation and optimized allocation of FPRs.*

5. Force protection resources under utilized:

The first issue at hand is that combat forces always receive priority of resources and support, including the use of FPRs. Therefore, a concerted effort on the part of the command must be made to dedicate a certain proportion of these scarce resources to CSS operations, giving CSS planners direct control over their employment. Second, many of the FPRs available are not readily known by CSS planners or they do not know the process for requesting them. Thus, the unit with proactive planners, familiar with the system, will work the system to procure those FPRs, even though that unit might not be the unit in greatest need of the resources.

DM process does not allow time necessary to develop and analyze multiple COAs:

The 1:3/2:3 guideline for planning operations usually limits both combat and CSS units in the level of detail for their planning. In practice, due to limited planning time, most staffs will develop one COA in great detail and refine it, as necessary, based on the commander's guidance. However, the MDMP clearly recommends developing two or more COAs, concurrently, so that the commander has more than one option to select from.

Staffs spend too much time on the manual steps involved in searching through and preparing the data to support the planning effort. An automated process could save this time in addition to quickly generating two or more potentially better COAs. Planners could then use the time saved in the process to compare and analyze the multiple COAs to determine the strengths and weaknesses of each. The staff could then present this analysis to the commander, giving that commander more options and flexibility to accomplish the mission.

At this point, we have described the operational problem; presented an overview of the Army, specifically distribution management and CSS operations; and defined asymmetric threat and the contemporary operating environment. All of this provides context for the remainder of this thesis in which we describe and apply the technical approach to addressing the problem in a series of experiments from which we draw our conclusions.

4 Modeling Approach and Formulation

This chapter describes the operations research modeling technique we use to address the problem of high casualty rates of combat service support soldiers operating in a contemporary operating environment. We explain the model, the associated data structures, and the decision variables that the model utilizes. Additionally, we describe some of the elements of the specific scenario, as they relate to the model parameters, that we use in conducting the experiments described in Chapter 5. Finally, we end the chapter by presenting a complete formulation to the mathematical model we use for optimally allocating force protection resources to the convoy plans.

4.1 Modeling Approach

In Chapter 1, we described the operations research discipline and its focus on using a technical approach to derive a best or better solution to a problem, rather than a more traditional qualitative approach to problem solving. In this thesis, our goal is to reduce the high casualty rate for CSS soldiers. One approach is to minimize the expected number of casualties of a plan during the COA development phase of the planning process. To achieve this we use a linear programming (LP) optimization approach in the modeling of the problem space, with the objective of minimizing the expected number of casualties while satisfying the logistical demands and other associated constraints.

To enhance the distribution management process we outlined in Chapter 3, we propose the inclusion of deliberate force protection planning into the process. This inclusion will assist planners in developing lower-risk convoy plans. We identified in Chapter 2 that logistic convoys are soft targets that are inherently vulnerable to threat attacks; therefore, it follows that the Army needs to dedicate a portion of available force protection resources specifically to logistical convoys. In our problem description, there are two distinct but related problems; the first is how to configure the convoys and the second is how to best utilize FPRs. To achieve this effect, we decompose the model into two modules (Figure 4-1) that sequentially solve these two problems by using the outputs from the first module as inputs into the second module. The first module, the Scheduling and Routing Module (SRMOD), generates the convoy plan: this entails determining the supplies to move, what types of trucks to use, the composition of the convoys, and the scheduling and routing of all convoys. The second module, the Force Protection Resource Allocation Model (FPRAM), assigns the available FPRs to the convoy plan generated from the preceding module. The resulting output from the second module is the overall convoy plan with integrated FPRs, which produces the lowest expected number of causalities.

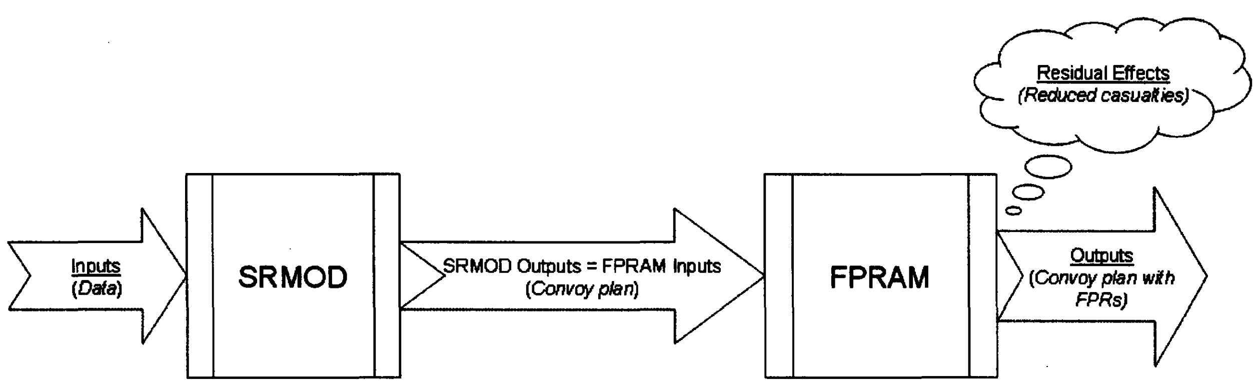


Figure 4-1: Model decomposition

It is important to note that the focus for this thesis is the FPRAM which relies on the output of the SRMOD. The SRMOD formulation is a result of internal research conducted by the technical staff at the Charles Stark Draper Laboratory, Inc. in Cambridge, Massachusetts, developed in conjunction with this thesis. We discuss briefly the basic components of the SRMOD in order to give context to the FPRAM developed for this thesis.

4.1.1.1 Scheduling and Routing Module

The SRMOD utilizes a few variants of standard network flow problems, which are incorporated into a sequence of functions designed to improve the computational efficiency of this potentially large-scale problem. Figure 4-2 illustrates the flow of data and the ordering of the internal functions of the SRMOD.

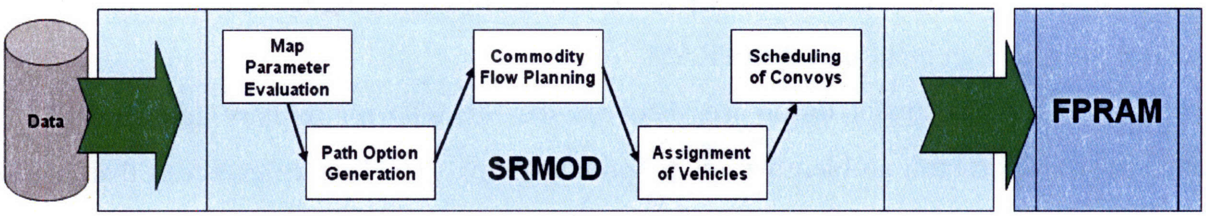


Figure 4-2: SRMOD internal functions

The first function, *Map Parameter Evaluation*, takes static map data along with results from the execution of recent plans to estimate the risks and travel times along each road segment. The *Path Option Generation* function first runs a modified version of the Dijkstra all-pairs shortest path algorithm [27]: for each pair of terminal bases it computes the lowest risk path that does not make any intermediate stops at other terminal bases. This function can also be set to compute the shortest distance path. For each supply base and subset of demand bases, this function then computes the shortest tour that starts at the supply base and visits exactly those demand bases via a modified traveling salesman problem algorithm [2]. This tour is termed a *path option*. Each path option represents a feasible and low-risk route that visits a desired set of FOBs from a given LSA. Path options generalize the concept of main supply routes and alternate supply routes by efficiently linking desired sets of bases. The C*ommodity Flow Planning* function is a standard multi-commodity flow problem that uses the various types of supplies (petroleum, ammunition, water, etc.) as its origin nodes and the FOBs as its destination nodes. In this multi-commodity flow, the origins are connected to the destinations via the possible path options output from the Path Option Generation function. The flow of supplies is measured in units of a generic "truck-unit," e.g., one "truck-unit" of petroleum is a standardized 5000 gallon tanker [4].

The next function, *Assignment of Vehicles,* uses an ad-hoc heuristic approach to match the actual truck fleet to the flows computed by the previous function. This assignment of trucks takes into consideration that certain trucks can only transport specific commodities; that trucks can either max out capacity in terms of gross weight or in terms of cubic volume; and that different types of trucks may have an actual capacity slightly larger or smaller than a "truck-unit." This function also assigns organic guntrucks to the flows to meet the required transport to guntruck ratio set by commanders. The last function of the SRMOD is the *Scheduling of Convoys* which estimates enroute times of departures and arrivals for the trucks traveling together in a convoy [4]. The resulting plan of all convoys traveling for that day is the convoy plan that we use as an input into the FPRAM.

There are two major differences between the SRMOD for military application and a traditional transportation problem within the private-sector. The first difference is that military transportation typically groups multiple vehicles into a single cohesive convoy. Private-sector transportation usually plans for and dispatches each truck independent of others. The second major difference is that private-sector transportation problems typically aim to minimize travel distance or cost, whereas the SRMOD aims to reduce casualties by minimizing risk to soldiers using the threat model we describe later in this chapter.

We do not examine the SRMOD any further than is presented in this section: the focus of this thesis is the optimal allocation of FPRs. However, we recognize that optimally solving the SRMOD in itself contributes to the reduction of casualties. Two ways in which this occurs is through selecting better routes for the convoys with respect to the threat along the road network and limiting the number of trucks on the roads by improving the utilization of trucks and truck capacities. Both of these reduce CSS soldiers' exposure to the threat.

4.1.1.2 Force Protection Resource Allocation Model

The second problem is how to allocate available FPRs to the set of convoys output from SRMOD. We refer to this problem as the *Force Protection Resource Allocation Model.* We model this problem with a set of scarce FPRs that traditionally are allocated to combat forces in the execution of their missions before being considered for supporting CSS units. Typically in CSS planning, unit planners build convoys independently of other units and will request FPRs from their higher commands to protect their convoys. Higher command constantly faces the problem of which units to assign the resources to as they often do not have enough resources to satisfy all the requests from subordinate units. Therefore, a critical assumption we make for our model is that a small portion of the FPRs are dedicated specifically to CSS operations, allowing CSS planners to build plans knowing that they will have at least some dedicated FPRs to work into the plan. Using optimization-based resource allocation resolves this issue by examining the problem globally and allocating the FPRs where they have the greatest effect on the threat.

Our mathematical model takes advantage of LP optimization which seeks to minimize a value-oriented objective function subject to a set of constraints. The specific form of linear programming we use in solving the FPRAM is binary integer programming (BIP). In BIP the decision variables take on values of either 0 or 1: a value of 1 represents a decision to activate or use a variable, whereas a value of 0 deactivates or turns off a variable [9]. We use BIP to model the FPRAM because the decisions we are making involve whether or not to use an FPR in particular areas or assigned to specific convoys. The FPRs are individual assets that cannot be divided into fractional parts.

4.2 Model Building Blocks

This section serves two purposes. It provides a detailed description of all the parameters and decision variables we use in the FPRAM. It also illustrates how we take the inputs of the physical world and processes and convert them into measurable data we can use in forming a mathematical representation of the problem. The main building blocks for the FPRAM include the graphical network of AO, threat model, convoy plans, and available FPRs. In addition we introduce the concept of composite strategy variables which allow the algorithm to account for certain nonlinearities associated with FPRs. These building blocks comprise the data sets, parameters, and decision variables that the FPRAM accesses and utilizes when computing the optimal allocation of FPRs to the convoy plan.

4.2.1 Graphical Network

The data we collect from the physical environment to use in the FPRAM includes characteristics about the road network. Figure 4-3 [23] below displays the actual geographical area along with certain operational graphics we will use in our modeling and experimentation. This map and others presented in this thesis are screenshots taken from Google Earth, Version 3.0, developed by ©Google. The actual terrain is that of the state of Utah, but for this thesis it represents a notional country and operating environment for Army forces on a scale smaller than that of Operation Iraqi Freedom.

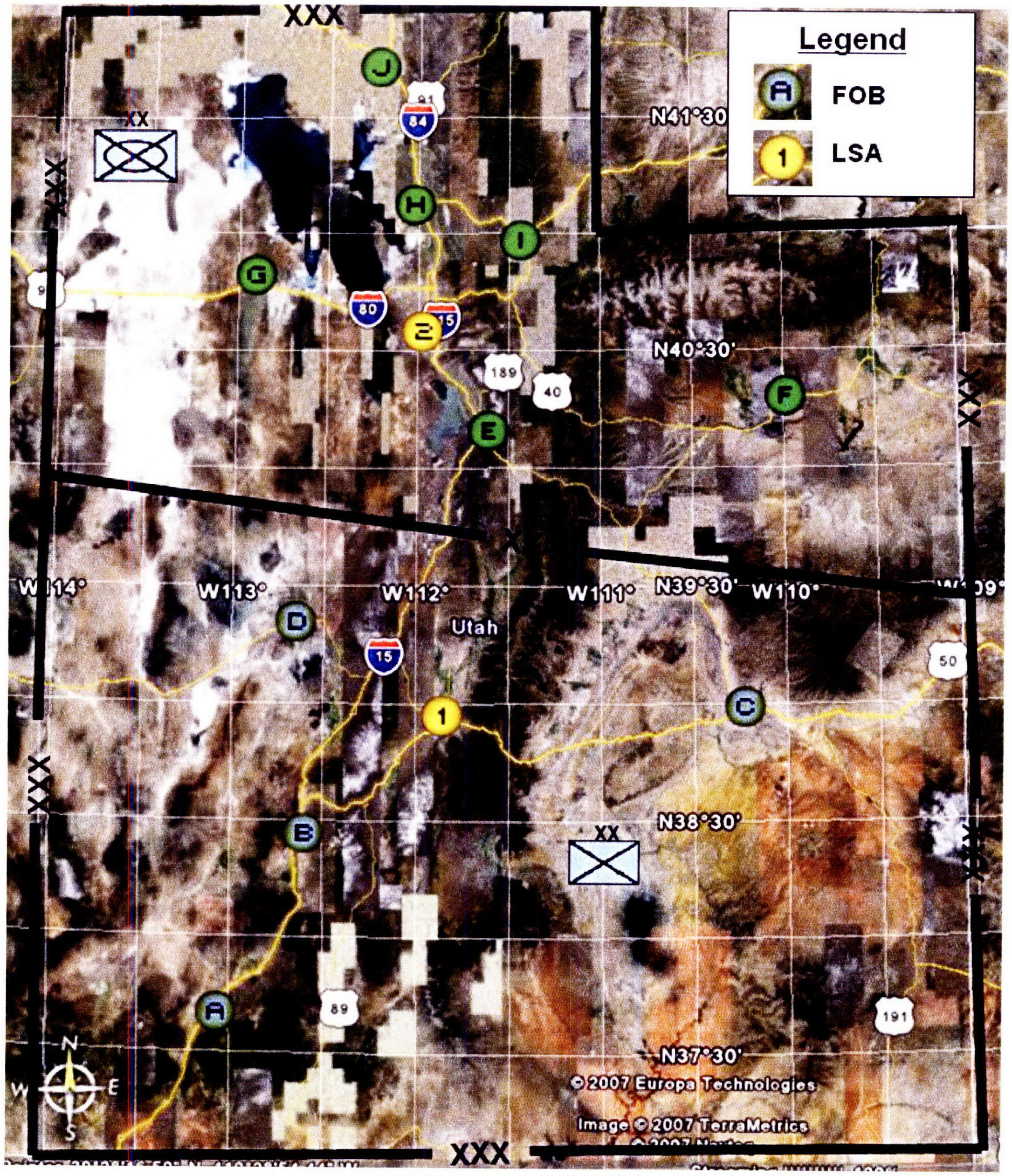


Figure 4-3: Operational graphics for scenario

The thick outer boundary labeled "**XXX**" outlines the corps' AO and the intersecting boundary across the middle of the AO labeled "**XX**" divides the corps' AO into two divisional sectors. The northern sector is controlled by a mechanized infantry division and a motorized infantry division controls the southern sector. Also included in the operational graphics are the various forward operating bases and logistics support areas from which Army forces operate. The lettered green and blue circles represent the FOBs for the respective subordinate brigades and battalions of the mechanized and motorized divisions, and the numbered yellow circles represent the LSAs. We now describe this notional environment and threat in the context of the data structure we use in the FPRAM.

Bases: < $b \in B$ >

The AO is comprised of a network of highways and subsidiary roads that connect the set of bases B in the scenario. We will generally denote individual bases by b where each base b is an element of the set B ($b \in B$). There are two types of bases of interest in the FPRAM model: LSAs and FOBs. The sustainment brigades operate out of the LSAs, which act as distribution hubs where all supplies enter the AO from external modes and are redirected via convoys to the various FOBs in the AO. The individual combat brigades and battalions are located at the FOBs.

Arcs: < $a \in A$ >

We divide each road in the physical network into smaller segments of bidirectional roadway, which we refer to as arcs. Each arc a is a continuous stretch of road where each end of the arc will either terminate at a base, form a waypoint (*wp*) by connecting to one other arc, or form a junction (*jct*) by intersecting with two or more other arcs. Figure 4-4 below illustrates the segmentation of a small network into four arcs *a1, a2, a3* and *a4*. We represent the set of all arcs in the scenario road network by *A*.

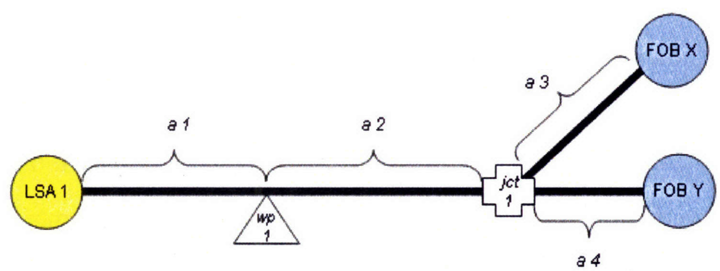


Figure 4-4: Example of roadway segmentation into arcs

The purpose of segmenting the road network into individual arcs is to facilitate the modeling of threat activity as it relates to the road network. This technique of modeling allows the assignment of a hazard to each individual arc. We describe later how we scale arc hazards and accumulate the scaled hazards as a convoy travels over contiguous arcs along a route.

Figure 4-5 [6] depicts a graphical representation of the arcs, waypoints, junctions, and bases found from the scenario AO pictured in Figure 4-3. The characteristic data for this road network was gathered from the Center for Transportation Analysis [4].

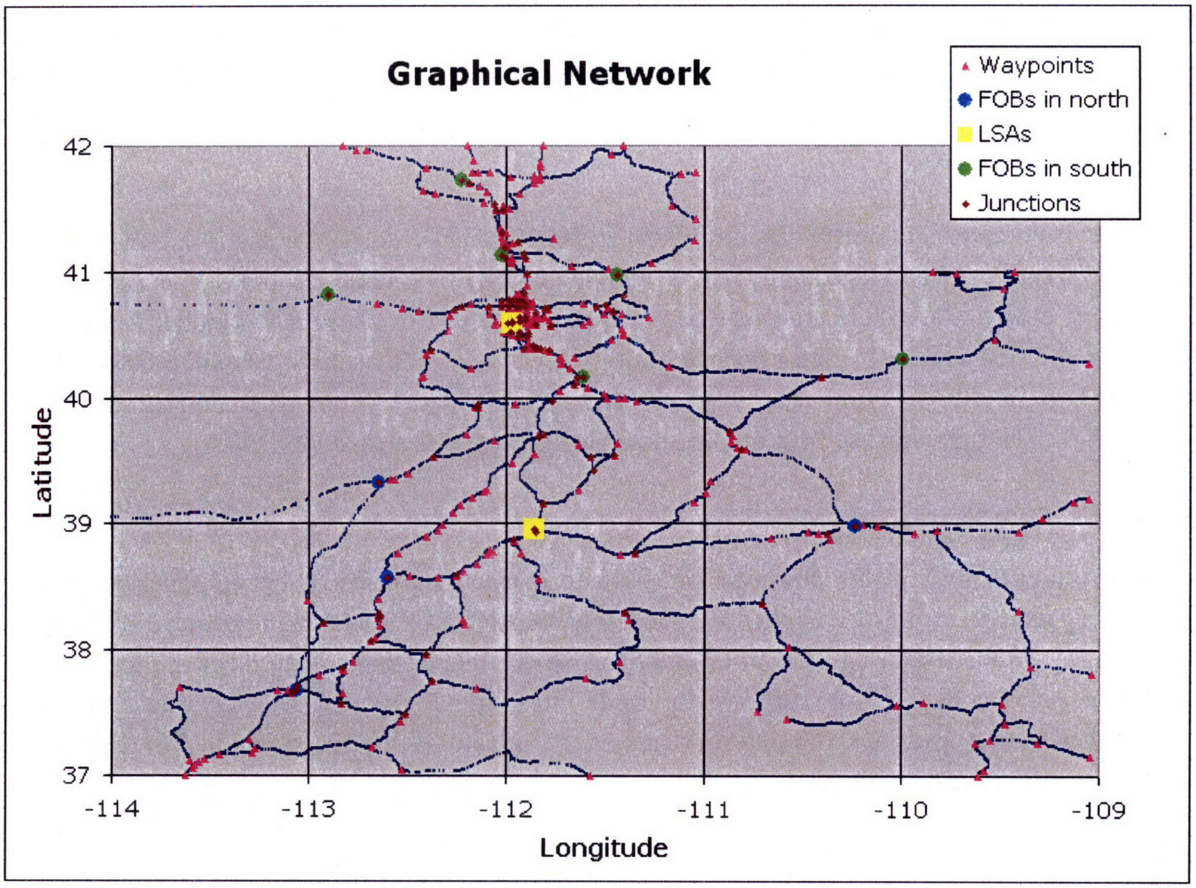


Figure 4-5: Graphical representation of the network

Each arc in this model has four identifying characteristics that we use for determining the scaled hazard of an arc. These characteristics include two static parameters: length of the arc and distance to nearest friendly base; and two dynamic parameters: a regional threat factor and a utilization level. Note that the dynamic parameters we will determine and fix prior to inputting into the FPRAM and the two static parameters we combined into one normalizing factor. There are many additional characteristics for the arcs that we do not model, e.g., number of lanes, posted speed limit, proximity to urban areas, and presence of a median divider. Each of these characteristics could conceivably impact the threat's decision to set up an ambush targeting a military convoy on a particular arc. For example, a median divider could facilitate the concealment of an IED or the proximity to an urban area could make for an easy hiding place or aid the escape of an IED triggerman. However, we limit our modeling to those arc characteristics we deem most important and easily measurable. We describe these characteristics in the context of the parameters utilized by the FPRAM starting with the normalizing factor.

The FPRAM uses two of these characteristics as components for the arc normalizing factor. We index the normalizing factor on arc *a* because according to our model of the network each arc has a unique normalizing factor. The first component of the normalizing factor depends on the arc length $length_a$ and is denoted $length\_comp_a$. One can argue that longer arcs pose greater risk to convoys due to the increased exposure time associated with traversing that arc. We also note that posted speed limits and effective traveling speed of a convoy also impacts the exposure time to risk along an arc; however, we only model arc length when accounting for the time of exposure in the FPRAM because this characteristic remains constant whereas the effective travel speed depends on multiple variables significantly complicating the model. In this thesis, we have chosen to model $length\_comp_a$ as a nonlinear function of the arc length in miles and two additional parameters β and δ.

$$length\_comp_a = \beta - 10^{-length_a / \delta}. \tag{4.1}$$

We chose this nonlinear model because the exposure to risk is expected to increase rapidly and level off as arc length approaches greater distances. For β = 1.5 and δ = 5 miles the length component takes on values between 0.5 and 1.5, meaning this component cannot reduce or increase the arc hazard by more than 50% of its original value. We discuss the concept of arc hazard later in this section. Figure 4-6 depicts the plot of the length component as a function of arc length. Note that arcs greater than 11 miles have little bearing on the value for the length component of the normalizing factor.

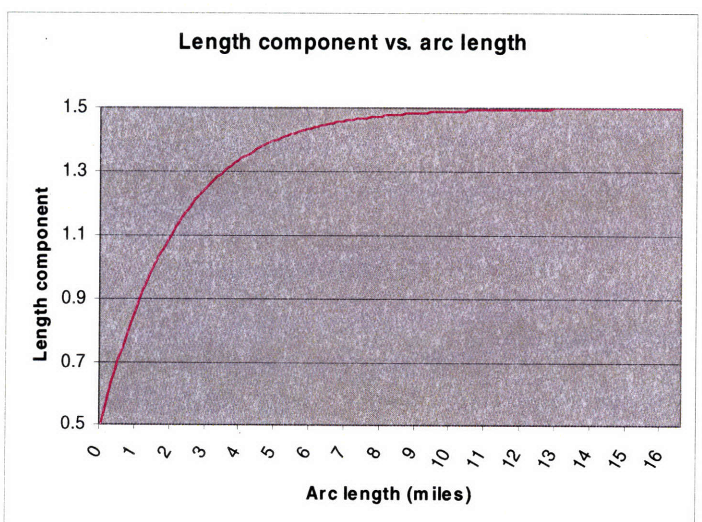


Figure 4-6: Length component versus arc length

The second component of the arc normalizing factor depends on the distance to the nearest base $dist2base_a$ and is denoted $dist2base\_comp_a$. The relative distance to a military base reflects the threat's propensity to set up an ambush on an arc. For example, base security forces frequently patrol the terrain directly outside the base perimeter, making it virtually impossible for the threat to set up an ambush within a certain distance of that base. Conversely, greater distances from a military base are less likely to have constant presence by military forces other than the occasional convoy passing through. This presents better conditions for the threat to emplace an ambush.

The further away the enemy decides to set up an ambush from a base, the more time and sense of security the enemy has for emplacement. Therefore, the size and complexity of such ambushes will increase as the distance between the ambush site and military bases becomes greater. However, planning an ambush too far out from a base may decrease the number of targeting opportunities, making it a less desirable site choice for the enemy.

To capture this trend, we measure the distance of each arc to the nearest base and group the arcs into one of five bins. Each bin represents a range of distances, such that if the distance to a base for an arc falls within a bin's range, we assign it to that bin. Each bin has an associated value for the distance-to-base component, which we subjectively set in this model based on the logic outlined in Table 4-1. The distance-to-base component serves as a scaling factor where a value of 1.0 represents the normal or expected threat activity.

Bin	*Range (miles)*	$dist2base\_comp_a$	*Logic*
1	0-1	0.2	Very high probability of detection
2	1-5	0.6	High probability of detection
3	5-10	1	Good conditions for ambush and greater targeting opportunities
4	10-25	1.2	Ideal distance and lower probability of detection
5	25+	0.8	Fewer targeting opportunities

Table 4-1: Distance-to-base factors

Arc normalizing factor: < $norm\_factor_a$ >

Finally, we use the above two components, $length\_comp_a$ and $dist2base\_comp_a$ in Equations (4.2) to calculate the arc normalizing factor $norm\_factor_a$:

$$
\begin{aligned}
norm\_factor_a &= length\_comp_a \cdot dist2base\_comp_a \\
&= (1.5 - 10^{-length_a/5}) \cdot dist2base\_comp_a .
\end{aligned}
\tag{4.2}
$$

The end result is a normalizing factor that has a scaling capability for each arc hazard between 0.10 and 1.80.

The first of the dynamic parameters for an arc is the arc utilization level which is based on one of five standard utilization levels. Utilization levels are determined by grouping together arcs that have similar measures of the frequency at which military vehicles travel that arc over a specified time period. Each truck that travels over an arc contributes to the cumulative usage count for that arc over the designated observation period. The observation period is a fixed time frame in which to observe and tally military traffic and threat activity. The counts over the observation period are moving counts; older data is either discarded or weighted using exponential smoothing.

In practice, the Army can collect utilization data through the use of pre-existing hardware installed on most military vehicles that tracks the path traveled by a vehicle via global positioning system technology. Although this capability currently exists, modifications to the software might be necessary to automatically upload and aggregate the track data of the entire truck fleet. The automation of this process would facilitate the collection of the cumulative usage counts for each arc in the network. Each arc in the network could then be automatically sorted by usage over the previous seven days and assigned a standard utilization level.

The utilization level is important to our model because we assume the threat bases its tactics on observation of military forces: the threat is more likely to target roads that are heavily trafficked by military trucks, resulting in greater hazards on arcs with higher utilizations. In its current form, the FPRAM models a static environment over one planning period and makes no attempt to apply game theory in capturing the dynamics of enemy tactics and friendly counter-tactics over time. We note the importance of game theory to this model, but leave this element of modeling to future research. For this reason, we use a fixed observation period without exponential smoothing that dumps data older than seven days to derive the utilization levels.

Standard utilization levels: $< u \in U >$

In this thesis we denote the five standard utilization levels by $u \in U$. We estimate the utilization levels for the arcs in our model by running and averaging the results from the SRMOD on seven sets of random demands. This estimation represents a seven day period in the absence of historical data. Arcs with zero usage are grouped into level 0. The next four levels are determined by evenly distributing the ranges for each level over the full range of arc usages. Our results yield a minimum arc usage (besides zero) of eight trucks per day and a maximum of 448 trucks per day. Using this spread, the standard utilization levels for levels 1-4 each cover a range of 110 trucks per day [26]. The results displayed in Table 4-2 are representative of a seven-day average over successive SRMOD plans.

Standard utilization level, *u*	**Usage range (trucks/day)**	**# Arcs in range**
0	0	253
1	8-118	147
2	119-228	27
3	229-338	13
4	339-448	2
	Total Arcs:	**442**

Table 4-2: Standard utilization levels

Arc utilization level: < $util_a$ >

Once all arcs are grouped by the standard utilization levels, we assign each arc within a certain level an individual arc utilization level $util_a$ equal to its associated standard utilization level. For example, the 147 arcs in the table with usage frequencies of 8-118 trucks per day are assigned an arc utilization level of 1 ($util_a = 1$). Note that there can only be one standard utilization level associated with each arc such that the total arcs contained in all the levels equals the total number of arcs in the network.

The arc utilization level is significant to predicting threat activity and will arise in the description of our threat model in the next section. We also cover the remaining dynamic arc parameter -- arc regional threat factor -- as it is also a component of the overall threat model.

4.2.2 Threat Model

We establish a method of modeling the threat along the roadways through the use of probabilistic models, trend analysis, and intelligence considerations. It is important to note that the threat model that follows allows us to quantitatively evaluate the threat such that we can solve the FPRAM model using the BIP discussed previously. All numerical data, while reasonable, is fabricated to demonstrate the utility of the model. If applied to real-world military applications, the Army's intelligence branch would provide the relevant threat models and methods for estimating the model parameters.

Arc regional threat factor: $< region\_factor_a >$

The arc regional threat factor $region\_factor_a$ is a dynamic arc parameter that takes into account the intensity of the threat in a given region. This factor is based on a number of variables, including sectarian violence and religious, social, and political considerations. Regional threats typically span a small area of the greater AO and are often temporary in nature, thus they change on a continual basis. The regional threat factor is essentially a scaling factor where a value of 1.0 is representative of normal or expected threat activity. The regional factor can take on values less than 1 for regions that are considered safer than normal, or values larger than 1 for regions that exhibit more dangerous conditions as a result of increased threat activity due to the considerations mentioned above.

The boundaries of the regions are subjectively determined by intelligence analysts based on trends and other relevant variables. The regions can adjust in size or disappear completely as analysts make updates to the threat assessment. Once a regional boundary is set, we scale all the arcs contained within the confines of that boundary by the regional factor. By default, the regional factor for all arcs not falling in a special regional threat boundary is 1. The regional threat areas in this model are arbitrarily set to simulate variations in threat activity throughout the AO. Figure 4-7 [23] illustrates the boundaries we use for the regional threats in our test scenario with the associated fixed value for the factor.

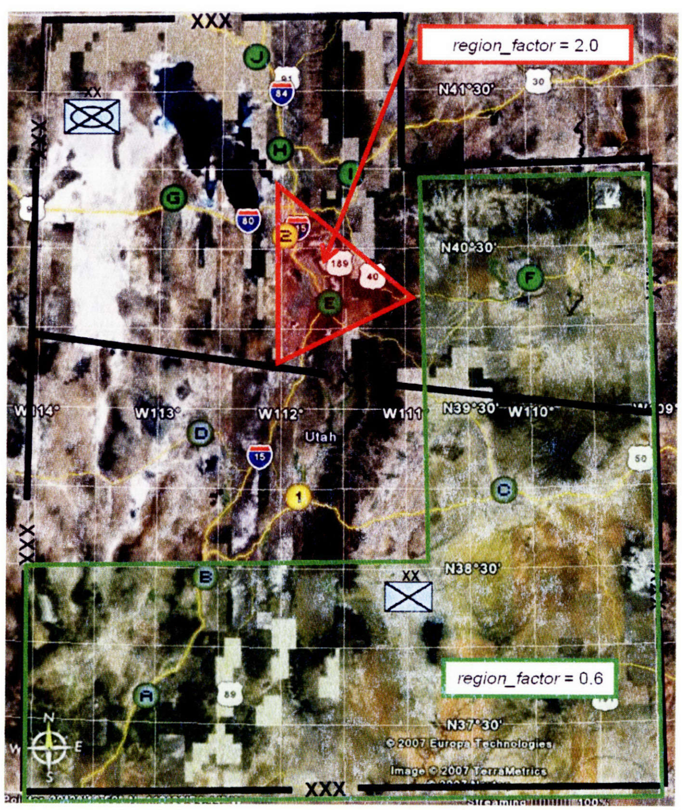


Figure 4-7: Regional threat areas and associated threat factors

Another element of our threat model is the inherent hazard associated with a particular utilization level. We mentioned earlier that the utilization level of an arc is a significant predictor of the threat, and therefore, critical in determining the inherent hazard for an arc.

The inherent hazard associated with a specified utilization level is the driving force behind the threat model and is dependent upon the probability a truck will sustain casualties while traversing an arc having that same utilization level. We derive this probability from the underlying threat model. The basic element of the threat model is the type of attack the threat chooses to use when targeting military convoys. We define a threat event E_j as an enemy ambush utilizing an attack of type $j \in J$ to target a military convoy traveling along an arc. In our scenario, we model 12 unique threat events $\{E_1,\ldots,E_{12}\}$ in addition to the null event E_0 representing no enemy ambush. The 12 threat events and null event are disjoint: they partition the set of possible outcomes for a convoy traversing a given arc. Figure 4-8 depicts a classification tree for the possible threat event types that can occur on an arc.

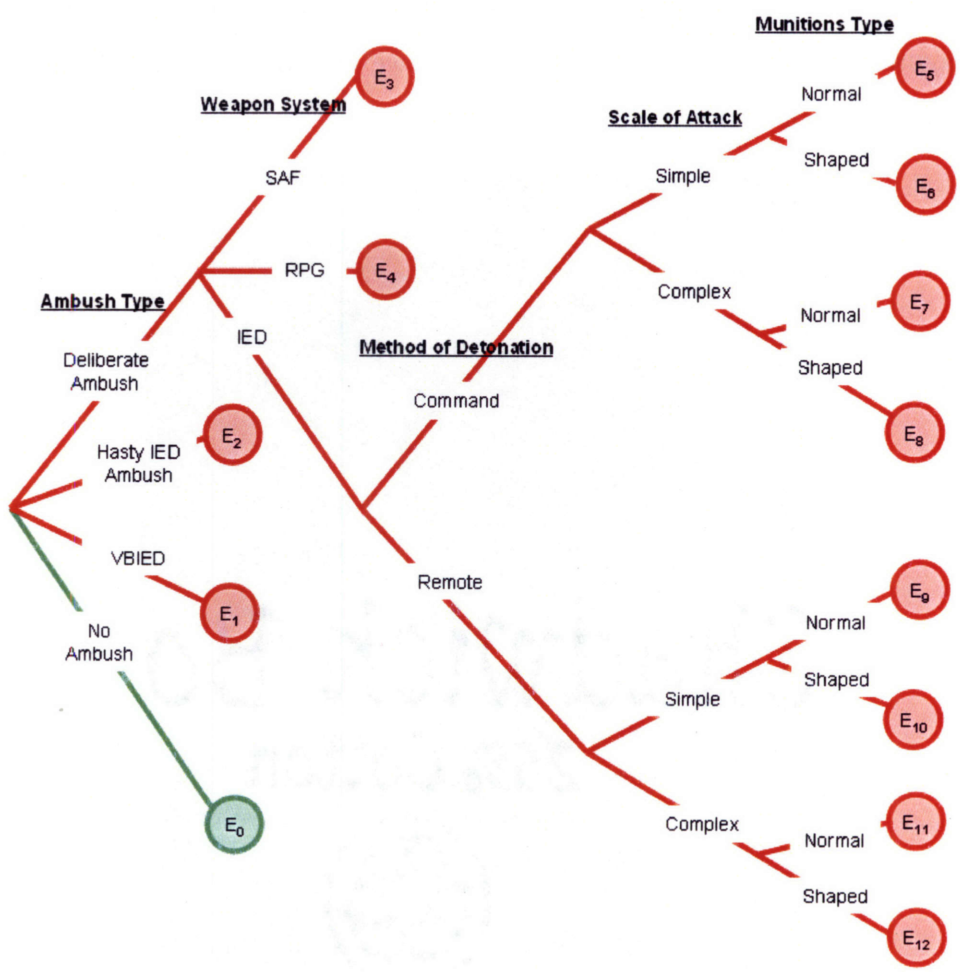


Figure 4-8: Threat event classification tree

Each branch of the tree represents a category of attack. For example, working left to right on the diagram, we have the major categories which include: no ambush, vehicle-born improvised explosive device (VBIED) attack, hasty IED ambush, and deliberate ambush. For this threat model, we assume the null event (no threat ambush) occurs the preponderance of the time, resulting in very small probabilities for occurrences for the remainder of threat types. The VBIED and hasty IED ambushes represent attacks by the threat on targets of opportunity or as a counter-action to a previously emplaced deliberate ambush thwarted by Army units.

A VBIED is either a stationary vehicle hastily parked on the side of the road or a moving vehicle rigged with explosives and driven by a suicide bomber. An example of a hasty IED ambush is a prefabricated IED that is dropped off on the side of a road by the threat as they drive onwards to a position where they can watch and then detonate the device at the appropriate time.

The second branch off the deliberate ambush category represents the choice of weapon the threat has at its disposal. These include deliberate small arms fire (SAF), rocket-propelled grenade (RPG), or IED ambushes. These types of ambushes are considered deliberate because the threat often puts extensive time and resources into the planning and emplacement phases. The SAF and RPG ambush are a quick, inexpensive, and easy method to disrupt Army convoys. However, these two methods are far riskier to the individuals executing the ambush as they are extremely vulnerable to military reactionary forces that respond to the event.

The deliberate IED ambush can take on many forms and levels of sophistication. In our model, we sub-categorize the deliberate IED ambush according to the next three branches of the diagram. First, the threat chooses its method of detonation: either remotely, using a radio controlled device, or command-detonated using a detonator hard-wired to a triggering device. Second, the scale of the attack is determined by the number of devices in place: one IED is characteristic of a simple attack, while multiple IEDs set up as part of the same ambush is characterized as a complex attack. Finally, the choice of munitions can impact the lethality of an ambush: construction of an IED using conventional munitions is characterized as "normal" while specially designed and shaped charges, which create an extremely lethal effect, we characterize as "shaped."

It is important to understand that the threat event classification tree we use for the SRMOD and FPRAM only captures a fraction of the possible threat variations. This tree can have many more branches and threat event types. For example, we can further subdivide the munitions type into all the possible conventional munitions available to the enemy. In practice, this model can be adapted to fit the appropriate threat for the AO.

Each threat event type in the classification tree has an associated probability of occurrence. As mentioned earlier, arc utilization is a significant predictor of threat activity, so we have chosen to model the inherent probability for a threat event of type j occurring on an arc, denoted $P^u(E_j)$, as a function of the standard utilization level of that arc. The threat event types $\{E_j\}_{j\in J}$ disjointly cover all possible outcomes of a convoy traversing an arc, so for all $u \in U$,

$$\sum_{j\in J} P^u(E_j) = 1 \quad \text{and} \quad P^u(E_j) \geq 0 \quad \forall j \in J. \tag{4.3}$$

Given appropriate historical data, we can estimate the inherent probability of a threat event $P^u(E_j)$ using the Dirichlet distribution $Dir(\alpha^u)$. The Dirichlet distribution utilizes Bayesian statistics to estimate a particular discrete probability distribution [27]. This technique is useful in threat modeling because the Army uses well-established reporting and archiving procedures in observing and recording threat activity over time, so the data needed to fit a Dirichlet distribution is already in the system. Furthermore, as the Army continues to observe and collect additional data, the resulting estimates of the inherent threat probabilities become increasingly accurate.

We define $\alpha^u = (\alpha_0^u, \alpha_1^u, ..., \alpha_{12}^u)$ as a parameter vector for the Dirichlet distribution where $\alpha_j^u \geq 0$ is a tally of the observed count (per arc mile) for each threat event type E_j along all the arcs having the specified utilization level u over the observation period. Note that we normalize the observed counts by the arc lengths because the arc lengths in the model are not all equal, and arc length is handled by the arc length component of the normalizing factor discussed in the previous section.

Operationally, the Army can capture the total count of all observations per mile through the use of the vehicle tracking hardware described earlier, combined with current reporting procedures. The observed count per mile of each threat event can then be determined by marrying the track data for each truck with geospatial situational reports containing detailed information on the types of threat events encountered along each arc traveled.

Using the parameter a^u, a Dirichlet model predicts the underlying threat probabilities as follows:

$$\hat{P}^u(E_j) = \frac{\alpha_j^u}{\alpha_{tot}^u} \qquad \forall j \in J, u \in U. \tag{4.4}$$

Obviously real-world historical data on threat activity is sensitive military intelligence; therefore, in order to develop a scenario that is sufficiently realistic to test the FPRAM, we have subjectively assigned values for the inherent threat probabilities according to the basic logic guidelines we outline in Table 4-3.

Utilization level	**Inherent threat probability trend**	**Logic guidelines**
0	negligible	- negligible threat - targets of opportunity / hasty ambush and SAF
1	slightly increases	- more targets of opportunity - increased deliberate IED ambushes - primarily simple command detonated devices
2	rapidly increase	- increase in deliberate planning / skilled triggermen - use of complex and remote devices on rise
3	peaks	- optimal conditions for enemy - looking for high payoff targets - greater use of remote, complex and shaped charges
4	slightly decrease	- some tapering off of threat attacks as increase traffic impairs emplacement - more use of hasty ambushes and VBIEDs

Table 4-3: Logic guidelines for inherent threat probabilities

In addition to the probability of a threat event type occurring, there is an associated probability of kill for each threat type. Traditionally, a probability of kill P_k is associated with conventional weapon systems, and military planners have access to planning charts that outline the P_k's for both friendly and enemy systems in order to facilitate war-gaming various COAs. However, the threat event types included in our model are based on unconventional uses of conventional ordnance, which brings us to uncharted territory in Army doctrine. In order to effectively model the threat to military convoys, we will need to measure the P_k's for these unconventional threat event types.

Whereas P_k's are normally associated with the probability of destroying or killing a target, in the FPRAM we are only concerned whether the threat has incapacitated the target, either personnel or equipment, to the point that it is removed from action. With respect to the FPRAM, we are minimizing the expected number of personnel casualties sustained while executing a logistical convoy in an asymmetric environment. Therefore, we have chosen to model the probability of kill for the various threat event types $(P_k)^j$ as the probability that an attempted attack either destroys a truck killing the personnel aboard, or it disables the truck and the personnel aboard sustain injuries that remove them from the mission.

To complicate matters, there are infinite variations on the setup of an IED ambush as well as numerous factors that would affect the values of the $(P_k)^j$'s. Thus, we make a few broad assumptions about the threat events and their effectiveness against the intended targets. The first assumption is that a threat event can only be grouped into one of the 12 previously defined events. Next, once grouped under a specific threat event, we assume that threat will behave according to the average historical behavior of all threats within that grouping. The historical behavior captures the likelihood the IED is not a dud, the expected number of fragments from the device, an expected blast radius, and other factors that may impact the effectiveness of a device. Finally, we assume that the target, the CSS soldier, is shielded by an expected level of protective armor around the cab of the truck.

Again, in absence of historical data we subjectively assign values for the $(P_k)^j$'s such that they are reasonable enough for the FPRAM. We use the simple logic guidelines we list in Table 4-4 to aid in our assignment of values.

Event	Logic guidelines	$(P_k)^j$
E_0	Negligible threat	0.00
E_1	Difficulty of steering VBIED into target balanced with high pay-load	0.12
E_2	Combination of hasty planning, positioning, and low pay-load	0.03
E_3	Difficulty of aiming at moving target and small-caliber bullets	0.08
E_4	Effectiveness of an RPG against logistical trucks	0.35
E_5	Smaller munitions reliant on accuracy of trigger puller	0.08
E_6	More lethal munitions than E_5	0.14
E_7	More devices leading to greater likelihood of hitting vehicles	0.22
E_8	More lethal munitions than E_7	0.46
E_9	More time and effort put into remote device over E_5	0.11
E_{10}	More time and effort put into remote device over E_6	0.18
E_{11}	More time and effort put into remote device over E_7	0.26
E_{12}	More time and effort put into remote device over E_8	0.55

Table 4-4: Logic guidelines for probabilities of kill

We can now define the probability a truck will sustain casualties while traversing an arc having a specified utilization level $P^u(casualty)$ which is necessary to compute the inherent hazard of an arc. We define this probability as the aggregate over all threat events of the inherent probability for a threat event type associated with a particular utilization level multiplied by the probability of kill for that type of threat event:

$$P^u(casualty) = \sum_{j \in J} P^u(E_j) \cdot (P_k)^j \qquad \forall u \in U. \tag{4.5}$$

It is important to realize that this inherent or baseline probability of sustaining casualties is not the end result for determining the probability of becoming a casualty. We have yet to scale the threat according to the normalizing and regional threat factors previously explained. However, according to the rules of probability, we cannot simply multiply a probability by a scaling factor as it violates the laws of probability. In addition, the probabilities along successive arcs in a convoy's route cannot simply be added up. Therefore, we convert the probability of a truck sustaining casualties while traversing an arc having a particular utilization level into an associated hazard value.

Inherent hazard associated with a specified *u*: < *inherent_hazard*^{u} >

We use the exponential hazard function found in Equations (4.6) to convert the probabilities of becoming a casualty associated with each utilization level into the inherent hazard associated with a specified utilization level $inherent\_hazard^u$.

$$inherent\_hazard^u = -\ln\left(1 - P^u(casualty)\right) \qquad \forall u \in U. \tag{4.6}$$

As we mentioned earlier, we are dealing with very small probabilities for the threat events, in which case

$$inherent\_hazard^u \approx P^u(casualty) \qquad \forall u \in U. \tag{4.7}$$

By converting $P^u(casualty)$ to a hazard, we can appropriately scale the hazard while maintaining a mathematically valid model, as well as accumulate the hazards, through summation, for the arcs that a convoy traverses over a convoy leg. Our data structure allows us to compute apriori the inherent probability of sustaining casualties, thus for our scenario we calculated the inherent hazards associated with the utilization levels using Equations (4.6) and list the values in Table 4-5 below.

u	$P^u(casualty)$	$inherent\_hazard^u$
0	4.90×10^{-6}	4.90×10^{-6}
1	1.08×10^{-4}	1.08×10^{-4}
2	8.93×10^{-4}	8.93×10^{-4}
3	2.72×10^{-3}	2.72×10^{-3}
4	5.88×10^{-4}	5.88×10^{-4}

Table 4-5: Inherent hazard values used in model

The final step in the threat model is to compute the unique scaled hazard (on a per truck basis) for each arc in the network.

Scaled truck hazard for an arc: < $scaled\_hazard_a$ >

The scaled truck hazard for an arc $scaled\_hazard_a$ is a function of the inherent hazard associated with that arc's utilization level, which we scale by the normalizing factor and the regional threat factor.

$$scaled\_hazard_a = inherent\_hazard^{u:u=util_a} \cdot norm\_factor_a \cdot region\_factor_a \quad \forall a \in A. \tag{4.8}$$

We can compute apriori the scaled hazards during a preprocessing stage prior to running the FPRAM. The FPRAM uses the scaled hazards to compute the reduced accumulated hazards for a convoy leg. We describe convoys and convoy legs in the next section, and we discuss accumulated hazards in Section 4.3.3 after addressing the force protection portion of our model.

4.2.3 Convoy Plans

The approved distribution matrix that results from the DM process is the set of planned convoys for a specified execution period. We will refer to the distribution matrix as the *convoy plan* from this point forward. The intent of the SRMOD is to automate the DM process we discussed in Chapter 3 through an algorithmic approach to deriving better convoy plans in a shorter planning time-frame. The automated SRMOD process is intentionally very similar to the current MDMP for planning DM, and the output of the SRMOD is a risk-optimized version of the distribution matrix. The FPRAM optimizes the allocation of FPRs with respect to the various convoys and associated convoy legs; note that the FPRAM does not depend on how the distribution matrix was created and can be used to improve force protection for either SRMOD or manually generated convoy plans. We describe the parameters associated with convoys below.

Convoys: $< c \in C >$

Each convoy c within the convoy plan includes information about that convoy. This information includes the origin base of the convoy $< origin_c >$, number of transport trucks $< num\_transport\_trucks_c >$, and the number of convoy legs $< num\_legs_c >$. We represent the set of all convoys for a given convoy plan by C.

There are additional details associated with each convoy used by the SRMOD such as the types of transport trucks, the cargo being transported, and the number of organic guntrucks assigned to the convoy, but we ignore this detail as it does not impact the calculations in the FPRAM.

Convoy legs: $< l \in L_c >$

A convoy leg l is the continuous movement from one base to the next base along the planned route of a given convoy. For example, if the convoy has only one planned delivery, then the first leg is from the convoy's origin to the destination base, and the second leg is the return trip from the destination base to the originating base. We denote the sequence of all legs for a specific convoy $c \in C$ as L_c where num_legs_c is the total number of legs for that convoy.

Set of arcs projected on convoy leg l: $< A \mid l >$

Similarly, we concern ourselves with the subset of arcs $a \in A$ covered by a convoy leg. We denote this subset as $A \mid l$, which is the set of arcs projected onto the convoy leg l.

The concept of a convoy leg is important in the FPRAM model because we assume the trucks in a convoy are only in danger when traveling along the arcs between bases, not while stopped at a base. Therefore, we characterize a truck that is part of a larger convoy as "surviving a leg" if it successfully travels from one base to its next planned base without sustaining casualties.

4.2.4 Force Protection Resources

The FPRAM uses a set of basic, heterogeneous force protection resources to reduce the expected number of casualties from the SRMOD solution. Each basic FPR has a specific purpose and exhibits varying reduction effects on the different threat types, which is why we consider them heterogeneous. We model five unique FPRs in the FPRAM, with the understanding that other resources do exist and could be similarly incorporated.

For modeling purposes, we divide the resources into two categories: global and local. A local resource is one that is local to a convoy and is assigned only to that convoy, such that it travels with or just in front of that convoy along the specified route. A local resource will only provide protection effects for its assigned convoy and only for the hazards along the arcs traversed by that convoy. We understand that residual protection effects may linger along the arcs that a local resource traverses and that these effects can be realized by a follow-on convoy, but we reserve this level of modeling to future research. Global resources are those resources that are not specifically tied to individual convoys but are employed in such a way that they cover a specific route or region within the overall AO. Global resources provide protection effects for any convoy that travels along arcs contained within the region covered by that resource.

Basic FPR types: $< x \in X >$

The five basic types of FPRs $x \in X$ in the FPRAM include: a fixed-wing aerial platform, armed helicopter platforms, and motorized infantry platoons capable of performing route security, route reconnaissance, or convoy escort. The fixed wing aerial platform and the motorized infantry platoons performing route security act as global resources. The remaining three types are local resources assigned to specific convoys.

DOCTRINALLY CORRECT TERMINOLOGY AND SYMBOLOGY							THESIS TERMINOLOGY AND DEPICTION	
#	Resource Type	Doctrinal Symbol	Mission	Task	Doctrinal Symbol	Assign-ment	Resource Short Name	Visual Representation
1	Fixed wing aerial platform		Air interdiction (AI)	Electronic protection (EP): jamming	EW	Restricted operating zone (ROZ)	*jam* {global}	
2	Armed helicopter platform		Escort	Secure		Convoy	*helo* {local}	
3	Motorized infantry platoon		Route security operations	Secure		Route	*patrol* {global}	P
4	Motorized infantry platoon		Route reconnaissance	Clear	c	Convoy	*clear* {local}	c
5	Armor protected ground vehicle with a light machine gun		Escort	Secure		Convoy	*augment* {local}	+

Note: A motorized infantry platoon is comprised of 6-9 armor protected ground vehicles, thus resource #5 results from dividing a motorized infantry platoon into smaller teams of two or more vehicles used in augmenting a convoy's organic guntrucks .

Table 4-6: Force protection resources

Each resource receives a tactical mission and task and is assigned to either a physical area or to a specific convoy. To enhance the readability of this thesis by someone unfamiliar with military doctrine, we refer to the basic FPR types by their respective "short names," *jam*, *helo*, *patrol*, *clear*, and *augment*, depicted in the column second from the right in Table 4-6. For a detailed description of the missions and tasks introduced in table below, refer to Appendix C: Force Protection Resource Doctrinal Missions and Tasks or Army Field Manual 1-02: Operational Terms and Graphics.

The later three resource types are special in that they access the same pool of physical resources: the motorized infantry platoons.

Motorized infantry platoons: $< s \in S >$

In the FPRAM, a set number of motorized infantry platoons $s \in S$, otherwise called security platoons, are set aside and dedicated for supporting CSS operations. A security platoon must operate as a whole unit to perform clearing or patrolling missions, but when assigned to augmentation missions, can subdivide into smaller teams with a minimum of two guntrucks to a team in order to augment the security for multiple convoys. If the FPRAM assigns platoon *s* to clear for convoy *c,* then platoon *s* cannot patrol one of the designated patrol routes. If any number of guntrucks from a platoon is assigned to augment a convoy, then that platoon is unavailable for to clear for another convoy or patrol a specified route.

Each security platoon is comprised of six to nine guntrucks. We represent the number of available guntrucks for a platoon by $num\_guntrucks^s$. Additionally, each security platoon has a home base $< home^s >$, usually an LSA, from which it operates.

We assume in our model that the *jam* resource is the scarcest of the resources as there is usually a small quantity available in theater, and combat units receive priority support from this resource. However, we propose dedicating one of these resources to CSS operations such that its utilization is directly planned by CSS planners with the convoy plan in mind. The *jam* resource operates in a predefined area called a restricted operating zone (ROZ); refer to Appendix C for a more complete definition. The purpose of the ROZ is to facilitate and add efficiency to the planning process. Rather than analyzing the infinite variations in flight routes and patterns over the AO, planners can pre-designate a finite number of ROZs for use in future plans. Therefore, time vested up front in the proper selection for the ROZs will return large dividends in the time saved from developing new force protection plans on a continual basis.

Restricted operating zones: $< f \in F >$

We denote each ROZ by *f* and the set of all ROZs by *F*. For our scenario, we pre-selected the four individual ROZs depicted by the boxes in Figure 4-9 [23].

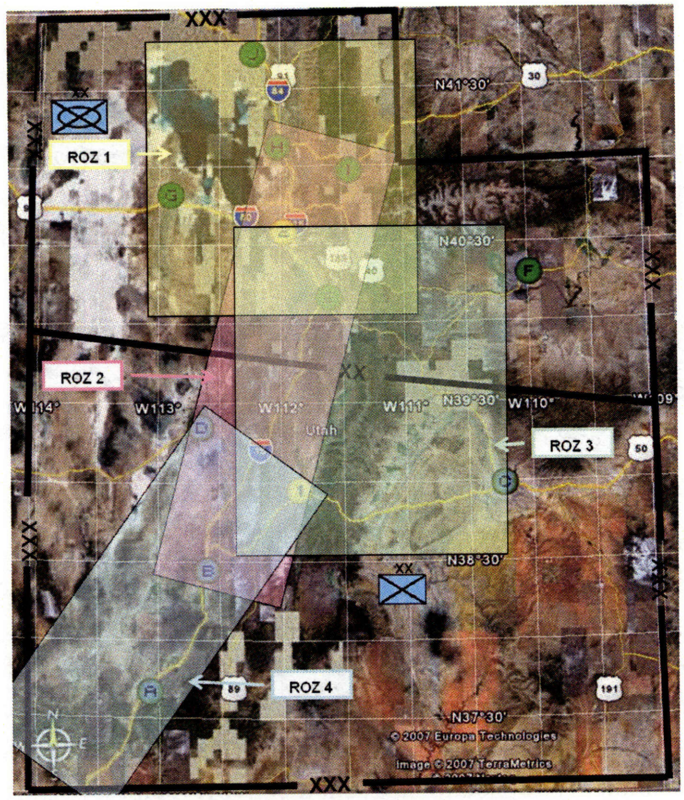


Figure 4-9: Restricted operating zones

Set of arcs projected on ROZ f: $< A \mid f >$

> Once a ROZ is initially set, planners determine the set of arcs on the ground contained directly under the confines of the ROZ. We denote this subset of A as the arcs projected onto ROZ f or $A \mid f$. Thus, when a decision is made to jam a particular ROZ, planners will know apriori which arcs the jamming will affect.

Operationally, the aerial platform flies some pattern, e.g., a figure eight or box pattern, within the ROZ, and its electronic warfare (EW) equipment emits jamming in a cone-shaped signal targeted along the roadways as depicted in Figure 4-10 [23]. However, for modeling purposes, we assume a uniform reduction effect from the jamming resource over all the arcs under the ROZ. The jamming resource is highly specialized in that it only counters the effects of remotely detonated IEDs and only when jamming over the bandwidth that includes the frequency used by that specific device. In this respect, the selection of the range of frequencies, and the intensity of the jamming signal that the resource emits, essentially represents an infinite spectrum of employment COAs for this resource. Breaking the electromagnetic spectrum into a finite number of predetermined ranges, similar to preplanning ROZs, makes mission planning easier for the planners. Our model assumes only one range of frequencies over which to jam.

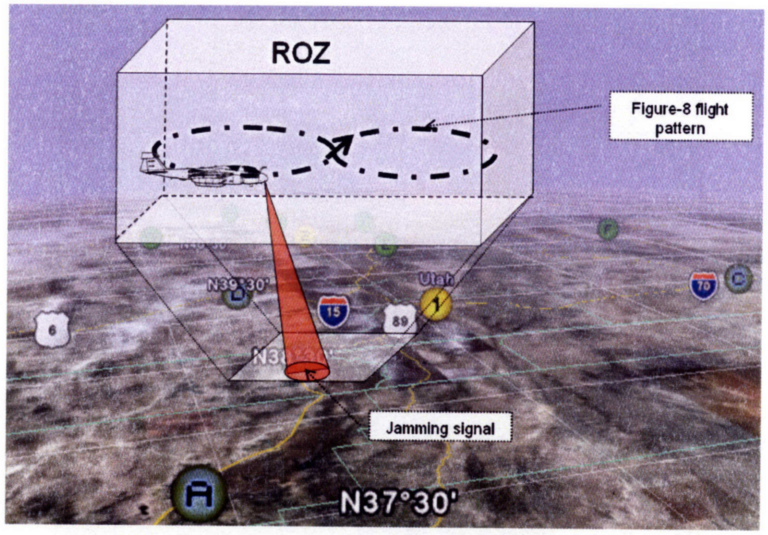


Figure 4-10: Area on ground effected by jammer

The use of preplanned ROZs and frequency ranges results in shorter solve times for the FPRAM by significantly limiting the solution space of possible flight plans and jamming options for the jamming resource over which the algorithm searches. This is a technique for maintaining a reasonable problem size, which is crucial for BIP as a problem can easily become too large to solve.

The second of the global resources, *patrol*, is similar to *jam* in that it is linked to a pre-planned subset of arcs contained in a fixed patrol route. A security platoon patrolling a specified route serves as a deterrent to the threat in their continuous presence along the route. Additionally, the platoon provides early warning detection by calling in explosive ordnance disposal (EOD) teams to remove any IEDs they locate along the route. Their effectiveness is dependent on the length of the route they are patrolling as well as the period of time they conduct the patrol. We further recognize that the use of this FPR does not fully protect against all threat types. For example, the threat can place a hasty IED on an arc just after the patrolling security platoon passes by that arc, so any follow-on convoys will encounter the hasty IED even though the route was being patrolled. For the FPRAM, we assume a constant reduction effect on the threat along the patrol route rather than one dependent upon the length of the patrol route.

Patrol routes: $< r \in R >$

Planners predetermine and fix a finite set of patrol routes $r \in R$ in the same manner as they determine the ROZs, such that careful selection of these routes upfront will pay dividends in efficiency of the solution algorithm used by the FPRAM. Figure 4-11 [23] illustrates the six patrol routes we use in our scenario.

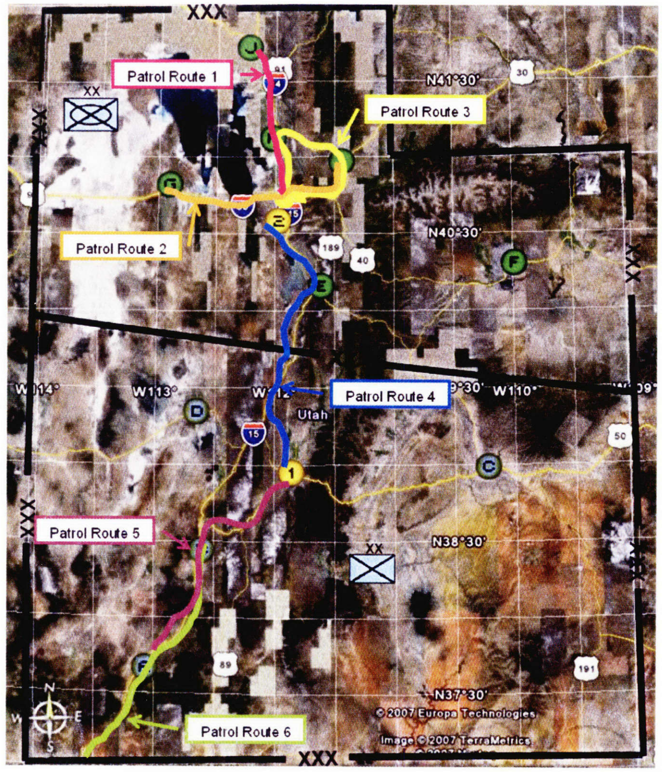


Figure 4-11: Patrol routes

Set of arcs projected on patrol route *r*: $< A \mid r >$

Each patrol route also consists of a subset of *A* representing the projection of arcs on patrol route *r* or $A \mid r$.

Set of origin bases projected on patrol route *r*: $< B \mid r >$

Additionally, each patrol route *r* is associated with a subset of bases from which the security platoon that patrols the route can originate. We denote this as $B \mid r$: the subset of origin bases projected on patrol route *r*. The purpose of the set of originating bases is to limit the platoons available to patrol a given route to those with a home base within proximity to the patrol route.

4.2.4.1 Resource Decision Variables

The intent of the FPRAM is to assist planners and enhance military decisions during the planning phase. Thus, one of the primary outputs from the FPRAM is the recommended employment decisions for the allocation of available FPRs with respect to the convoy plan. Therefore, the FPRAM uses binary decision variables for all the basic FPR types that are indexed on the various parameters. A value of 1 for one of these decision variables represents the decision to employ that resource and a value of 0 represents a decision not to use the resource.

Fixed-wing aerial platform (global): < jam_f >

The global decision variable associated with the fixed-wing aerial platform is jam_f. The decision is to which ROZ $f \in F$ to assign the *jam* resource, if at all. A value of 1 for jam_f represents the *jam* resource jamming in ROZ *f*, whereas a value of 0 represents the absence of the *jam* resource in ROZ *f*.

Armed helicopter platform (local): < $helo_c$ >

The decision to assign a pair of armed helicopter platforms to escort convoy $c \in C$ is represented by $helo_c$. Escort helicopters always operate in pairs for mutual protection. A value of 1 for the decision variable $helo_c$ represents a pair of helicopters assigned to escort convoy *c*. The commander must decide on the quantity of helicopter, an integer parameter we label *num_helos*, and from which aviation units they come. These helicopters can come from multiple units, in which case the model requires an additional index to represent the unit; however, to keep the experiment simpler, we assume the helicopters come from a single pool of helicopters. Like the aerial jammer, the helicopter platform is also a scarce resource. The decision to use this resource puts the aircraft at risk, and if one of the helicopters is shot down, it is not be available for future escort missions.

The next three FPR decisions -- *patrol*, *clear*, and *augment* -- all originate from the same pool of physical resources: available motorized infantry platoons $s \in S$.

Motorized infantry platoon conducting route security operations (global): < $patrol_r^s$ >

The decision variable $patrol_r^s$ is indexed on both the security platoon *s* and patrol route *r*. This is a global decision in which a security platoon *s* is assigned to a patrol route *r* such that all convoys traveling over the arcs contained along the patrol route receive benefit effects from the *patrol* resource.

Motorized infantry platoon clearing the route for a convoy (local): < $clear_c^s$ >

The decision variable $clear_c^s$ is indexed on security platoon $s \in S$ and convoy $c \in C$. The decision to assign a security platoon to a particular convoy means that that platoon is dedicated only to that convoy and travels some specified distance or time period just ahead of the convoy to clear the planned route of any threats. We recognize that clearing a route could have residual effects, e.g., exponential decay of resource effects for follow-on convoys traveling over some of the same arcs, but we assume no such effect in our model. We assume a constant reduction effect for the FPRAM, except that the effect is only realized by the convoy to which it is assigned.

Armor protected ground vehicle escorting a convoy (local): < $augment_c^s$ >

This resource is indexed on the same indices as the preceding resource. The purpose of the augmentation is to increase the guntruck to transport truck ratio for a convoy. As mentioned earlier, transport units have organic guntrucks at their disposal that they use to meet the minimum FP requirements set by command. If the convoy is set to travel through a particularly dangerous region and all other FPRs are committed, then the FPRAM can use guntruck teams from one of the security platoons to increase this ratio. The main differences with this resource and the clearing resource are that the augmentation guntrucks integrate and travel with one specific convoy and one security platoon can augment multiple convoys. However, the reduction effect is assumed to be less than that for the clearing resource. This type of tradeoff is relatively easy to model in the FPRAM, but can be challenging for staff planners working under time constraints.

These five resource types are heterogeneous in that each of them have unique tactical considerations and are employed in different manners. In Figure 4-12, we take the threat classification tree we introduced in Section 4.2.2 and overlay the basic FPR types at the branches where we assume they will have a positive effect against all the threat types along the branches to the right of the insertion point. For each FPR, we assume a reduction effect against each type of threat, which we describe at the end of this section.

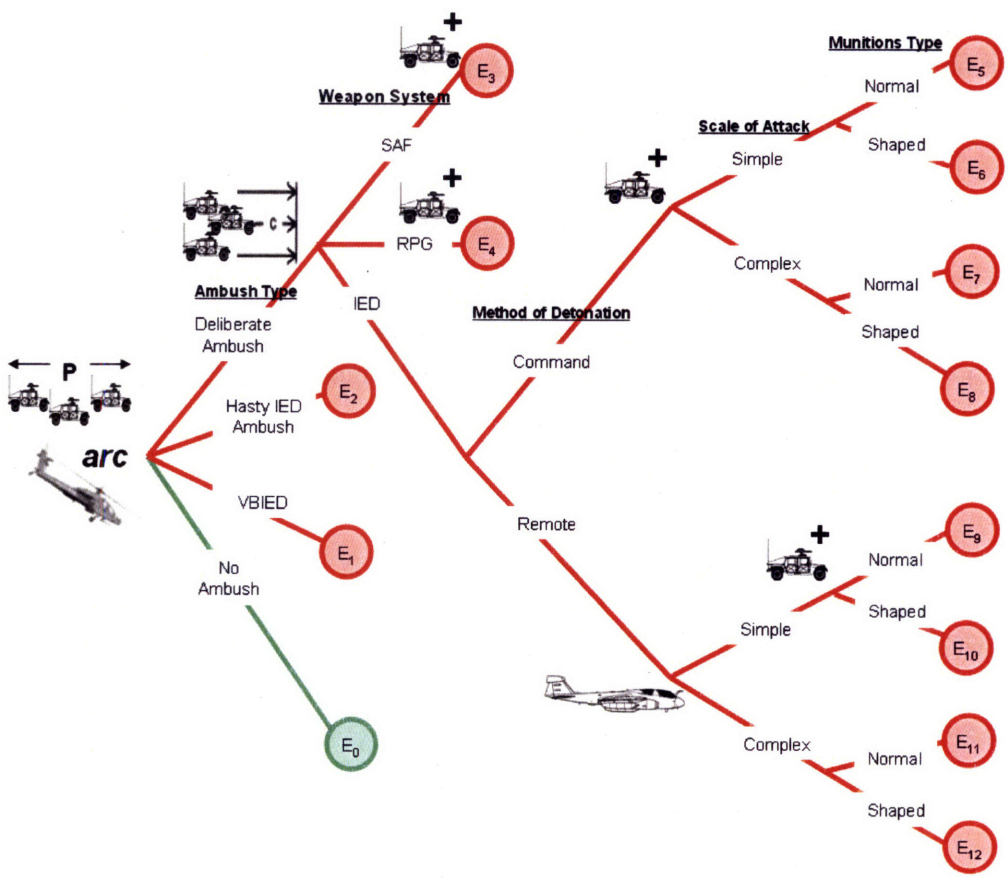


Figure 4-12: Insertion points for effective use of FPRs

Each of the basic resources has different effects against the various threat types. We assume none of the resources increase the hazard(s) that the threat poses, rather the resources reduce the threat effect or at worst, have no impact. Then through additional modeling or analysis of historical data, we can estimate the effectiveness of each resource against a specific threat type $reduce\_effect_x^j$. Thus, we construct Table 4-7 with threat event types for each column and each row representing a different FPR. In essence, this table is the P_k chart for the friendly weapons systems, or in our case, the available FPRs. We subjectively assign values for the reduction effects chart based on the justification logic in the last column.

FP Resource Reduction Effects Table	No Threat	VBIED	Hasty Ambush	Deliberate Ambush											Legend
				SAF	RPG	IED									Strong Affect
						Command				Remote					Moderate Affect
						Simple		Complex		Simple		Complex			Weak Affect
						Normal	*Shaped*	*Normal*	*Shaped*	*Normal*	*Shaped*	*Normal*	*Shaped*		No Affect
Threat Event ID	E_0	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	E_9	E_{10}	E_{11}	E_{12}		**Justification Logic**
jam (global)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.25	0.30	0.35	0.40		- only affective against remotely detonated devices
helo (local)	1.00	0.90	0.40	0.20	0.30	0.20	0.20	0.30	0.30	0.45	0.50	0.55	0.60		- serves as an intimadating deterrent to triggermen - greater impacts on threat events requiring insurgents to be closer to point of ambush
patrol (global)	1.00	0.40	0.30	0.40	0.40	0.35	0.30	0.25	0.20	0.40	0.45	0.50	0.55		- prevents emplacement and setup of deliberate ambushes, especially complex - acts as deterrant for VBIED and hasty ambush
clear (local)	1.00	1.00	1.00	0.90	0.80	0.50	0.40	0.30	0.35	0.55	0.50	0.45	0.40		- will identify and clear threats ahead of convoy position - greater impact on larger scale ambushes with a larger physical signature
augment (local)	1.00	0.85	0.95	0.75	0.80	0.75	0.75	0.85	0.85	0.90	0.90	0.95	0.95		- has slight deterrant affect on insurgents closest to point of ambush - adds small ability to neutralize VBIED and hasty ambush

Table 4-7: Force protection resource reduction effects chart

We do not use these reduction effects directly in the FPRAM, but rather we use them indirectly through the use of composite strategy variables which we explain next.

4.2.4.2 Composite Strategy Variables

In this scenario, we impose rules that limit, at most, one local resource to a convoy and, at most, one global resource to a ROZ or patrol route. This results in instances when local and global resources overlap. An example of this is a convoy, protected by a helicopter escort, traveling over some arcs contained in a route patrolled by a security platoon. Such interactions result in nonlinearities in the model if we simply multiply the hazards by the effects from multiple FPRs. Therefore, we introduce the use of composite strategy variables (CSVs) to capture the interaction effects when multiple basic FPRs are in effect on the same arc. This section describes the CSVs we use in the FPRAM as well as the new decisions that the algorithm must make as a result of introducing these CSVs.

Composite strategy variable: < $\gamma \in \Gamma$ >

The composite strategy variable γ in this model represents the protection effects from the interaction of multiple FPRs. We represent the set of all CSVs by Γ, which we generate by forming all possible combinations of one local resource with the subsets of the various global resources. We rule out combinations that include multiple local resources because one of the constraints we impose on our model limits to no more than one, the assignment of local resources to a convoy. Table 4-8 lists the set of all 15 CSVs in our model plus the null CSV and what they represent.

CSV	FPRs in force
0	{}
1	*{jam}*
2	*{helo}*
3	*{patrol}*
4	*{clear}*
5	*{augment}*
6	*{helo, jam}*
7	*{helo, patrol}*
8	*{clear, jam}*
9	*{clear, patrol}*
10	*{augment, jam}*
11	*{augment, patrol}*
12	*{jam, patrol}*
13	*{helo, jam, patrol}*
14	*{clear, jam, patrol}*
15	*{augment, jam, patrol}*

Table 4-8: Composite strategy variables

Subset of CSVs associated with a basic FPR *x*: < $\Gamma \mid x$ >

We can further reduce the number of CSVs to those associated with the basic FPR in effect, which will improve efficiency of the solution algorithm. We do this by creating subsets of Γ indexed on *x* such that the new subset, $\Gamma \mid x$, only contains those CSVs that include *x* as one of its basic FPRs. We use this limiting technique in the formulation presented in the last section of this chapter. Table 4-9shows all the subsets the model generates.

CSV Subset	CSVs in Subset
$\Gamma \mid jam$	{1, 6, 8, 10, 12, 13, 14, 15}
$\Gamma \mid helo$	{2, 6, 7, 13}
$\Gamma \mid patrol$	{3, 7, 9, 11, 12, 13, 14, 15}
$\Gamma \mid clear$	{4, 8, 9, 14}
$\Gamma \mid augment$	{5, 10, 11, 15}

Table 4-9: Composite strategy variable subsets

Effects of CSVs for a specified utilization level: < $composite\_effect_{\gamma}^{u}$ >

The CSV reduction effect $composite\_effect_{\gamma}^{u}$ is indexed on the utilization level and CSV. Thus, for an arc having a particular utilization level, the scaled hazard for that arc is reduced according to the reduction effect associated with the CSV in effect on that arc.

The overall reduction effect for a particular utilization level and CSV is described by a proportion of two quantities, as in Equations (4.9). The quantity in the denominator is the aggregate probability, over all threat types, of sustaining casualties for a specified utilization level from Equations (4.5). The numerator is essentially the same aggregated probability; however, before aggregating over the threat types, we use the best reduction effect from basic FPRs in play to scale the probability. The CSV effects are all computed apriori.

$$composite\_effect_{\gamma}^{u} = \frac{\sum_{j \in J} \min_{x: x \in \Gamma | x} (reduce\_effect_{x}^{j}) \cdot P^{u}(E_{j}) \cdot (P_{k})^{j}}{P^{u}(casualty)} \qquad \forall u \in U, \gamma \in \Gamma. \tag{4.9}$$

Composite strategy decision variable for an arc projected on a convoy leg: < $composite_{a,\gamma}^{l_c}$ >

The decision variable $composite_{a,\gamma}^{l_c}$ is a binary variable in the FPRAM that determines which CSV to use on a particular arc projected onto a convoy leg. The formulation constrains this decision variable such that only one CSV can be active for an arc associated with a convoy leg.

4.3 Binary Integer Program Formulation

This section merges the relevant data and decision variables required by the model that we described in Section 4.2. We present the binary integer program formulation of the FPRAM by outlining the objective function and the associated constraints of the model. See Appendix B for a complete stand alone FPRAM formulation.

4.3.1 Data

This section consolidates the relevant data which is input into the FPRAM. Note that the SRMOD uses the same data except for the data associated with the FPRs and reduction effects. The SRMOD derives its risk-optimal plan of convoy routes and schedules by minimizing the expected number of casualties in absence of any FPRs. The FPRAM uses the same data and parameters, but unlike the SRMOD, the FPRAM algorithm utilizes the available FPRs to reduce hazards optimally.

U	Set of standard utilization levels u used to characterize inherent hazards of and reduction effects on arcs;
C	Set of all convoys c output from the SRMOD;
L_c	Sequence of legs l for a given convoy $c \in C$;
F	Set of all ROZs f for aerial jamming resource;
R	Set of all predefined patrol routes r for a security platoon;
B	Set of all bases b including LSAs and FOBs;
$B \mid r$	Subset of B corresponding to possible originating bases b for security platoon potentially assigned to patrol route $r \in R$;
A	Set of all arcs a in the AO;
$A \mid l$	Subset of A corresponding to arcs projected on leg $l \in L_c$ such that $c \in C$;
$A \mid f$	Subset of A corresponding to arcs projected on ROZ $f \in F$;
$A \mid r$	Subset of A corresponding to arcs projected on patrol route $r \in R$;
X	Set of all basic FPRs x;
Γ	Set of CSVs γ representing all possible combinations of FPRs in effect;
$\Gamma \mid x$	Subset of Γ corresponding to those CSVs containing FPR $x \in X$;
S	Set of all security platoons s.

Figure 4-13: FPRAM data

Figure 4-14 consolidates the list of all other parameters used in the FPRAM. We only include parameters that have a bearing on the FPRAM algorithm. Any parameters previously discussed that are used apriori in preprocessing calculations are not included below.

num_helos	Number of available helicopters;
$\overline{w}$	Average number of casualties per truck hit;
$origin_c$	Originating base $b \in B$ of convoy $c \in C$;
$num\_transport\_trucks_c$	Number of transport trucks in convoy $c \in C$;
num_legs_c	Number of trip legs for convoy $c \in C$;
$home^s$	Home base $b \in B$ for security platoon $s \in S$;
$num\_guntrucks^s$	Number of available guntrucks for security platoon $s \in S$;
$scaled\_hazard_a$	Scaling factor calculated apriori using inherent hazards, normalizing and regional threat factors for arc $a \in A$;
$composite\_effect_\gamma^u$	Hazard reduction multiplier when CSV $\gamma \in \Gamma$ is used on an arc having a utilization level $u \in U$.

Figure 4-14: FPRAM parameters

4.3.2 Decision Variables

There are three types of decision variables: those associated with global resources, local resources, and the CSVs. Each of these decisions is binary. Figure 4-15 describes the decisions associated with the possible values for the variables. Note that there are three decision variables included below -- max_jam_a, max_patrol_a, and $max\_augment^s$ -- which we have not yet introduced. The first two are place holder variables used in the FPRAM in order to remove nonlinearities arising from the decisions to activate CSVs associated with the *jam* and *patrol* resources along arcs covered by overlapping ROZs or patrols routes, respectively. We create this place holder variable because we can only have one CSV in effect at a time along an arc associated with a particular convoy leg. The third, $max\_augment^s$, is a place holder variable that facilitates using one security platoon to *augment* multiple convoys while maintaining conservation of security platoon resources.

Composite Strategy Variables

$$composite^{l}_{a,\gamma} = \begin{cases} 1, & \text{if CSV } \gamma \in \Gamma \text{ is in effect on arc } a \in A \mid l \text{ given that } l \in L_c \text{ and given that } c \in C \\ 0, & \text{otherwise.} \end{cases}$$

Global Resources

$$jam_f = \begin{cases} 1, & \text{if a } \textit{jam} \text{ resource is assigned to ROZ } f \in F \\ 0, & \text{otherwise;} \end{cases}$$

$$max\_jam_a = \begin{cases} 1, & \text{if arc } a \in A \mid f \text{ is being jammed by a } \textit{jam} \text{ resource operating in ROZ } f \in F \\ 0, & \text{otherwise;} \end{cases}$$

$$patrol^{s}_{r} = \begin{cases} 1, & \text{if security platoon } s \in S \text{ is assigned } \textit{patrol} \text{ mission of predefined route } r \in R \\ 0, & \text{otherwise;} \end{cases}$$

$$max\_patrol_a = \begin{cases} 1, & \text{if arc } a \in A \mid r \text{ is under } \textit{patrol} \text{ by a security platoon patrolling route } r \in R \\ 0, & \text{otherwise.} \end{cases}$$

Local Resources

$$helo_c = \begin{cases} 1, & \text{if an } \textit{helo} \text{ resource is assigned to convoy } c \in C \\ 0, & \text{otherwise;} \end{cases}$$

$$clear^{s}_{c} = \begin{cases} 1, & \text{if security platoon } s \in S \text{ is assigned } \textit{clear} \text{ mission to convoy } c \in C \\ 0, & \text{otherwise;} \end{cases}$$

$$augment^{s}_{c} = \begin{cases} 1, & \text{if guntrucks from security platoon } s \in S \text{ are assigned } \textit{augment} \text{ mission for convoy } c \in C \\ 0, & \text{otherwise;} \end{cases}$$

$$max\_augment^{s} = \begin{cases} 1, & \text{if security platoon } s \in S \text{ is assigned an } \textit{augment} \text{ mission} \\ 0, & \text{otherwise.} \end{cases}$$

Figure 4-15: FPRAM decision variables

4.3.3 Objective Function

The objective function for the FPRAM is to minimize the expected number of casualties for a given convoy plan. We achieve this by optimally allocating the available FPRs such that their combined effects are maximized by employing the individual resources where they will have the greatest impact on reducing the arc hazards; a task which can be difficult for staff planners to conceptualize. In this section, we describe the intermediate steps leading to the calculation of the objective function, the first of which is to accumulate the hazards along a convoy leg.

Accumulated truck hazard: $< acc\_hazard_l >$

To calculate the probability of a truck not surviving a convoy leg, we must first calculate the accumulated hazard for that leg. We accomplish this by taking the scaled arc hazard from Equations (4.10) and multiplying it by the CSV in effect as well as its associated reduction effect. Summing these values over all the arcs contained in the convoy leg gives us the accumulated hazard for a convoy leg acc_hazard_l:

$$acc\_hazard_l = \sum_{a \in A|l} \sum_{\gamma \in \Gamma} composite^{l}_{a,\gamma} \cdot composite\_effect^{u:u=u_a}_{\gamma} \cdot scaled\_hazard_a \qquad \forall c \in C : \forall l \in L_c. \tag{4.10}$$

Probability of a truck not surviving a convoy leg: $< prob\_not\_surviving_l) >$

To compute the probability of a truck not surviving a convoy leg, we convert the accumulated hazard back to an appropriate probability using Equations (4.11). The result is the probability of a truck not surviving a convoy leg, $P_l(not\_surviving)$

$$P_l(not\_surviving) = 1 - e^{acc\_hazard_l} \qquad \forall c \in C : \forall l \in L_c. \tag{4.11}$$

The FPRAM utilizes binary integer programming (BIP), a subset of linear programming, that cannot handle exponential functions. Because Equations (4.11) is not a linear function, we derive a linear approximation such that we can use this probability in our BIP. Note that for the very small values of accumulated truck hazard we cover, the function is approximately linear. Therefore, the linear approximation function we use is that of Equations (4.12).

$$prob\_not\_surviving_l = 0.9999997 - 0.999 \cdot acc\_hazard_l \qquad \forall c \in C : \forall l \in L_c. \tag{4.12}$$

Expected number of trucks sustaining casualties for a convoy leg: $< E_l[CAS\_TRUCKS] >$

We can derive the expected number of trucks sustaining soldier casualties by treating the event of one truck sustaining casualties as a Bernoulli event with parameter $p = prob\_not\_surviving_l$. Furthermore, we assume that the probability of a truck sustaining casualties is identical for each truck in the convoy and independent of other trucks. Therefore, we model the expected number of trucks sustaining casualties for a convoy leg using a Binomial distribution with parameters $p = prob\_not\_surviving_l$ and $n = num\_transport\_trucks_c$:

$$E_l[CAS\_TRUCKS] = n \cdot p = num\_transport\_trucks_c \cdot prob\_not\_surviving_l \qquad \forall c \in C : \forall l \in L_c. \tag{4.13}$$

Average number of casualties per truck sustaining casualties: $< \overline{w} >$

In our model, we assume two soldiers per truck: the driver and the passenger. However, given that a truck is hit and sustains casualties, both soldiers might not suffer injuries. Therefore, we introduce a new parameter $\overline{w}$ which is the historical average for the number of casualties resulting from a truck that is hit and receives casualties. We calculate this average apriori from historical data using Equation (4.14).

$$\overline{w} = \frac{cumulative\_casualties}{cumulative\_hit\_trucks}. \tag{4.14}$$

The parameter takes on values between zero and the maximum number of soldiers in the truck, which we set at 2. Because we do not use actual historical data, we subjectively set $\overline{w}$ = 1.0 casualties per truck hit and casualties sustained.

Expected number of casualties along a convoy leg: $< E_l[CSS\_CASUALTIES] >$

We compute the expected number of CSS soldiers sustaining casualties, $E_l[CSS\_CASUALTIES]$, by multiplying $\overline{w}$ and the expected number of trucks sustaining casualties for a convoy leg as in Equations (4.15).

$$E_l[CSS\_CASUALTIES] = \overline{w} \cdot E_l[CAS\_TRUCKS] \qquad \forall c \in C : \forall l \in L_c. \tag{4.15}$$

Finally, our objective is to minimize CSS soldier casualties for the entire convoy plan. Thus, we sum the expected number of casualties along a convoy leg over all the legs for all the convoys, giving the BIP objective function (4.16) below.

Objective Function

$$\min \quad \sum_{c \in C} \sum_{l \in L_c} E_l[CSS\_CASUALTIES]. \qquad (4.16)$$

Figure 4-16: Objective function

The below three sets of equations consolidate the intermediate calculations we use to compute the expected number of casualties for a convoy leg, which is necessary for solving the objective function.

subject to:

$$acc\_hazard_l = \sum_{a \in A|l} \sum_{\gamma \in \Gamma} scaled\_hazard_a \cdot composite^l_{a,\gamma} \cdot composite\_effect_\gamma^{u:u=u_a}$$

$$\forall c \in C : \forall l \in L_c, \qquad (4.17)$$

$$prob\_not\_surviving_l = 0.9999997 - 0.999 \cdot acc\_hazard_l \quad \forall c \in C : \forall l \in L_c, \qquad (4.18)$$

$$E_l[CSS\_CASUALTIES] = \overline{w} \cdot num\_transport\_trucks_c \cdot prob\_not\_surviving_l$$

$$\forall c \in C : \forall l \in L_c. \qquad (4.19)$$

Figure 4-17: Intermediate objective function calculations

The accumulated hazard calculations, Equations (4.17), calculate the accumulated hazard on a per truck basis by first multiplying the scaled hazard for an arc by the binary CSVs and their reduction effects associated with the utilization level of the arc. Summing these reduced scaled arc hazards over all the arcs contained in a convoy leg gives the accumulated hazard for a truck traveling along one leg of a convoy.

The probabilities of a truck not surviving a convoy leg, Equations (4.18), involve a linear transformation of the accumulated hazards. We define "not surviving" as the event that truck sustains some number of casualties resulting from a threat event along the leg.

Equations (4.19) compute the expected number of casualties for a convoy leg is simply the metric we use in the objective function.

4.3.4 Constraints

In this section we list and describe the various sets of constraints within the FPRAM. To facilitate ease of understanding the model, we have grouped similar sets of constraints into one of three groups: those that handle the artificial rules that govern CSVs, those associated with policies set by unit commanders, and those which ensure conservation of FPRs.

Composite Strategy Variable Constraints

The sets of CSV constraints listed below place restrictions on the decision variables $composite^{l}_{a,\gamma}$. The first set of constraints (4.20) restrict every arc in the subset of arcs contained in a convoy leg to have exactly one CSV in effect.

$$\sum_{\gamma\in\Gamma} composite^{l}_{a,\gamma} = 1 \qquad \forall c\in C:\forall l\in L_c:\forall a\in A\,|\,l, \tag{4.20}$$

$$max\_jam_a - jam_f \geq 0 \qquad \forall f\in F:\forall a\in A\,|\,f, \tag{4.21}$$

$$\sum_{\gamma\in\Gamma|jam} composite^{l}_{a,\gamma} - max\_jam_a = 0 \qquad \forall c\in C:\forall l\in L_c,\forall a\in \bigcup_{f\in F} A\,|\,f, \tag{4.22}$$

$$\sum_{\gamma\in\Gamma|jam} composite^{l}_{a,\gamma} = 0 \qquad \forall c\in C:\forall l\in L_c,\forall a\in A-\bigcup_{f\in F} A\,|\,f, \tag{4.23}$$

$$\sum_{\gamma\in\Gamma|helo} composite^{l}_{a,\gamma} - helo_c = 0 \qquad \forall c\in C:\forall l\in L_c:\forall a\in A\,|\,l, \tag{4.24}$$

$$max\_patrol_a - \sum_{s\in S} patrol^{s}_{r} \geq 0 \qquad \forall r\in R:\forall a\in A\,|\,r, \tag{4.25}$$

$$\sum_{\gamma\in\Gamma|patrol} composite^{l}_{a,\gamma} - max\_patrol_a = 0 \qquad \forall c\in C:\forall l\in L_c,\forall a\in \bigcup_{r\in R} A\,|\,r, \tag{4.26}$$

$$\sum_{\gamma\in\Gamma|patrol} composite^{l}_{a,\gamma} = 0 \qquad \forall c\in C:\forall l\in L_c,\forall a\in A-\bigcup_{r\in R} A\,|\,r, \tag{4.27}$$

$$\sum_{\gamma\in\Gamma|clear} composite^{l}_{a,\gamma} - \sum_{s\in S} clear^{s}_{c} = 0 \qquad \forall c\in C:\forall l\in L_c:\forall a\in A\,|\,l, \tag{4.28}$$

$$\sum_{\gamma\in\Gamma|augment} composite^{l}_{a,\gamma} - \sum_{s\in S} augment^{s}_{c} = 0 \qquad \forall c\in C:\forall l\in L_c:\forall a\in A\,|\,l. \tag{4.29}$$

Figure 4-18: Composite strategy variable constraints

The next nine sets of constraints restrict the possible CSVs considered for each arc associated with a convoy leg, based on the combination of resources in effect on that arc.

Specifically, constraints (4.21) set the place holder variables max_jam_a to no less than the maximum value of the decision variables jam_f for all arcs covered by the respective ROZ f. These constraints ensure that the binary variables max_jam_a are set to 1 for arcs covered by two or more overlapping ROZs, one with an aerial jamming resource and the others without.

Constraints (4.22) only affect arcs covered by the union of all ROZs ($a \in \bigcup_{f \in F} A \mid f$). These constraints ensure that the possible CSVs for those arcs having a value of 1 for max_jam_a are restricted to those in the CSV subset associated with the *jam* resource. Otherwise, the possible CSVs for arcs having a value of 0 for max_jam_a are forced to come from the CSV subsets other than that associated with the *jam* resource.

Constraints (4.23) restrict the possible CSVs for arcs not covered under any of the pre-designated ROZs ($a \in A - \bigcup_{f \in F} A \mid f$). The CSVs contained in the CSV subset associated with the *jam* resource are forced to 0 for all arcs in this subset; thereby, ensuring these arcs only receive reduction effects from CSVs contained in CSV subsets other than that associated with the *jam* resource.

Constraints (4.24) restrict the possible CSVs for arcs along a leg of a convoy -- with an assigned *helo* resource -- to the subset of CSVs associated with the *helo* resource.

Constraints (4.25) are similar to those of Constraints (4.21) in that they set the place holder variables max_patrol_a to no less than the maximum value of the sum over all security platoons s of the decision variables $patrol_r^s$ for all arcs covered by the respective patrol route r. Likewise, because these place holder variables are binary, these constraints ensure max_patrol_a is set to 1 for all arcs covered by two overlapping patrol routes where at least one of the routes is being patrolled by a security platoon.

Constraints (4.26) only affect arcs covered by the union of all patrol routes ($a \in \bigcup_{r \in R} A \mid r$). These constraints restrict the selection of possible CSVs for all arcs having a value of 1 for max_patrol_a to the subset of CSVs associated with the *patrol* resource. Otherwise, arcs having a value of 0 for max_patrol_a forces the possible CSVs to a CSV subset other than that associated with the *patrol* resource.

Constraints (4.27) restrict the possible CSVs for arcs not covered under any of the pre-designated patrol routes ($a \in A - \bigcup_{r \in R} A \mid r$). The CSVs contained in the CSV subset associated with the *patrol* resource are forced to 0 for all arcs in this subset; thereby, ensuring these arcs only receive reduction effects from CSVs contained in CSV subsets other than that associated with the *patrol* resource.

Constraints (4.28) restrict the possible CSVs for arcs along a leg of a convoy -- with an assigned security platoon clearing for the convoy -- to the subset of CSVs associated with the *clear* resource.

Constraints (4.29) restrict the possible CSVs for arcs along a leg of a convoy -- augmented with additional guntrucks from one of the security platoons -- to the subset of CSVs associated with the *augment* resource.

Policy Constraints

The sets of policy constraints listed below impose specific policies set by the commander with respect to the FPRs.

$$\sum_{s \in B|r} patrol_r^s \leq 1 \qquad \forall r \in R, \qquad (4.30)$$

$$\sum_{s \notin B|r} patrol_r^s = 0 \qquad \forall r \in R, \qquad (4.31)$$

$$helo_c + \sum_{s \in S: home^s = origin_c} \left(clear_c^s + augment_c^s\right) \leq 1 \qquad \forall c \in C, \qquad (4.32)$$

$$\sum_{s \in S: home^s \neq origin_c} \left(clear_c^s + augment_c^s\right) = 0 \qquad \forall c \in C, \qquad (4.33)$$

$$max\_augment^s - augment_c^s \geq 0 \qquad \forall s \in S, c \in C, \qquad (4.34)$$

$$\sum_{c \in C} augment_c^s - \left(\frac{num\_guntrucks^s}{2}\right) \cdot max\_augment^s \leq 0 \qquad \forall s \in S. \qquad (4.35)$$

Figure 4-19: Policy constraints

Constraints (4.30) force the assignment of no more than one security platoon to patrol a pre-designated patrol route. Additionally, the security platoon's home base must be contained in the subset of bases associated with the specified patrol route.

Constraints (4.31) ensure that security platoons with a home base other than those associated with a particular patrol route are not assigned to that patrol route.

Constraints (4.32) force the assignment of no more than one local FPR (*helo*, *clear,* or *augment*) to a convoy. These constraints further insure that security platoons only *clear* or *augment* for a convoy if that platoon's home base is the same as the originating base of the convoy.

Constraints (4.33) ensure that convoys originating from bases other than that of a particular security platoon cannot be assigned that security platoon.

Constraints (4.34) set the place holder variables $max\_augment^s$ to no less than the value of the decision variables $augment_c^s$ for all security platoons s and all convoys c. This ensures that a security platoon that uses any of its guntrucks to *augment* any convoy is assigned a value of 1 for $max\_augment^s$, thereby restricting that security platoon to an *augment* mission, yet still allowing that security platoon to *augment* for more than one convoy.

The last set of policy constraints (4.35) limit the number of convoys that a security platoon can *augment.* The policy rule in effect in our model is that an augmenting force must contain at least two guntrucks from the security platoon, thus the number of convoys a security platoon can *augment* is no more than the total number of guntrucks in that platoon divided by 2.

Resource Conservation Constraints

The set of resource conservation constraints below ensure that the utilization of FPRs does not exceed the available FPRs or the physical limitations of those FPRs.

$$\sum_{f \in F} jam_f \leq 1, \qquad (4.36)$$

$$\sum_{c \in C} helo_c \leq \frac{num\_helos}{2}, \qquad (4.37)$$

$$\sum_{r \in R} patrol_r^s + \sum_{c \in C} clear_c^s + max\_augment^s \leq 1 \qquad \forall s \in S. \qquad (4.38)$$

Figure 4-20 Resource conservation constraints

The aerial jammer conservation constraint (4.36) represents only one *jam* resource available to support CSS operations, thereby limiting the number of ROZs the model can jam to 1.

The helicopter conservation constraint (4.37) limits the number of *helo* resources available to escort convoys to no more than the total number of helicopters divided by two. This is because all helicopters must operate in pairs for mutual protection and support

Finally, the security platoon conservation constraints (4.38) state that a security platoon can only be assigned to one type of mission: patrolling a route or clearing or augmenting for a convoy. This constraint also enforces the conservation of available security platoons.

This concludes the description of the model data and formulation. See Appendix B for the consolidated formulation of the model. In the next chapter we use our model in the conduct of two experiments designed to test the performance of the model and compare it to the performance of human generated plans using an appropriately sized scenario.

5 Experimentation: Design, Results, & Analysis

In this chapter we describe the design and implementation of two experiments aimed at demonstrating the potential benefits of the Force Protection Resource Allocation Model. Experiment I addresses some of the human factors that limit planners' abilities in producing optimal plans. Experiment II utilizes Monte Carlo simulation to generate a large number of samples so we can statistically analyze the performance of the FPRAM. For both experiments we run the FPRAM formulation using ©ILOG OPL Development Studio IDE, Version 5.0.

5.1 Experiment I Design

The goal of Experiment I is to evaluate human-only generated plans for convoy force protection. In addition, we demonstrate the utility of the FPRAM algorithm for enhancing the military decision making process by saving valuable time, and most importantly, its potential to save soldiers' lives. To achieve this goal, we assembled a group of ten active and prior-service military officers ranging in rank from lieutenant to major, each with different levels of operational experience. Our intent was to simulate Army staff planners at division and corps echelons via these military officers. In the experiment the simulated staffs used their operational experience to plan the allocation of force protection resources in support of multiple convoy plans generated from the Scheduling and Routing Module in the scenario we described in the previous chapter.

For this experiment, we set up three trials, each designed to simulate the planning process but with slight variations from one another. The variations of the planning process in the three trials include: 1) decentralized planning, 2) centralized planning, and 3) centralized planning with collaboration. Trial 1 models a situation where planners at the lower division echelon control a portion of the FPRs and are responsible for allocating them within their division's AO. Trial 2 consolidates all the FPRs for the entire corps and places control of their allocation under corps staff planners. Finally, Trial 3 is similar to that of Trial 2 in that the corps staff controls the FPRs, but we allow collaboration between planners in the development of the FPR allocation plan.

Figure 5-1: Scenario map with operational overlays

Prior to the first trial, we provided all the participants an operational and threat overview, much like one they would receive during actual operations. We also provided each planner with the scenario map and a series of operational overlays to assist them in developing their plans. The map and overlays were taken directly from the model building blocks outlined in Section 4.2 and when placed one on top of the other, the planners were looking at the illustration in Figure 5-1 [23].

Additionally, we provided them with the charts depicted in Table 5-1 and Figure 4-12: Insertion points for effective use of FPRs. As part of the overview brief, we generalized the threat and various FPR effects against the threat by providing a modified version of Table 4-7*:* Force protection resource reduction effects chart, where we concealed the specific reduction values in the chart. We focused on relative comparisons of the various threats and FPRs rather than providing the planners with specific probabilities and reduction effect values. Our reasoning for this was two fold: first, in a real-world situation, staff planners are unlikely to receive intelligence and information in a precise form; and second, if we had provided the larger set of quantitative data for the entire scenario, it would have likely overwhelmed the planners given the limited time available to plan.

Next, we provided the first convoy plan (Table 5-1) and described the relevant information contained in the plan. We outlined specific experiment rules to follow such as the policy constraints (4.32) from Section 4.3.4: no more than one local resource can be assigned to a convoy. Lastly, we provided a FPR worksheet for them to complete for each trial, in which they provided the details of their FPR allocation to support the given convoy plan.

#	Convoy ID	Distance Traveled	# Transport Trucks	Organic Gun Trucks	LSA	Stop1	Stop2	Stop3	Stop4
1	P0192	508	18	6	1	B	A	1	
2	P0063	520	26	8	1	A	1		
3	P0255	325	17	7	1	B	1		
4	P0016	550	13	2	2	F	C	2	
5	P0006	181	12	1	2	I	H	2	
6	P0002	439	11	0	2	I	E	2	
7	P1023	131	29	6	2	G	2		
8	P0126	323	7	1	2	I	J	2	
9	P0014	401	11	0	2	F	I	2	
10	P0015	321	22	4	2	F	2		
11	P0001	180	28	6	2	I	2		
12	P0003	270	27	6	2	E	2		
13	P0009	489	26	5	2	F	H	I	2
14	P0031	495	28	6	2	C	2		
15	P0511	297	19	3	2	D	2		

Table 5-1: Convoy plan for Trial 1

The control case we used for comparison of these trials is the convoy plan generated from the SRMOD without any allocated FPRs other than the convoy's organic guntrucks. Additionally, we compared the results of these trials to the optimal allocation of FPRs generated by the FPRAM using the respective convoy plan as an input. The three convoy plans generated for use in Experiment I were for 14 to 17 convoys; the convoys themselves were comprised of 3 to 29 transport trucks, with the majority of convoys having more than 20 trucks; the total distances traveled for the convoys ranged from approximately 100 to 500 miles; and the convoys made deliveries to 1 to 4 forward operating bases prior to returning to their originating logistics support area.

Experiment I Design		Staff 1		Staff 2		Staff 3		Staff 4		Staff 5	
		Participant 1	Participant 2	Participant 3	Participant 4	Participant 5	Participant 6	Participant 7	Participant 8	Participant 9	Participant 10
Trial 1	Part A	N	S	N	S	N	S	N	S	N	S
	Part B	N	S	N	S	N	S	N	S	N	S
Trial 2	Part A	C	C	C	C	C	C	C	C	C	C
	Part B	C		C		C		C		C	
Trial 3		C		C		C		C		C	

N: Division staff planner for northern AO S: Division staff planner for southern AO C: Corps staff planner(s) for entire AO

Table 5-2: Design of Experiment I

Table 5-2 lays out the basic structure for the various trials in Experiment I. In Trial 1, the participants play the role of a division planner for one of the respective division AOs. In Trials 2 and 3, the participants play the role of individual staff planners for the corps, operating either individually or in pairs within their respective staff grouping. Trials 1 and 2 both consist of two parts, A and B, in which the force protection plans developed by the participants in Part A are used during Part B of the respective trial. Part B of each of these trials represents an additional variation on the planning process. We explain the specifics of the two parts for Trial 1 and 2 in Sections 5.1.2 and 5.1.3, respectively. After analyzing each of the trials individually, we aggregate and summarize results across the three trials and state our final observations and conclusions from Experiment I.

5.1.1 Units of Measure

We use the following five metrics identified in Table 5-3 to compare the results from the trials of Experiment I. We chose these metrics because they capture aspects of mission planning that are important to military planners.

Metric	Unit of Measure
Expected number of casualties (E[cas.])	soldiers
E[cas.] as a percent of total soldiers	percentage
Percent improvement over base case	percentage
Plan generation time	minutes
Utilization of guntrucks	percentage

Table 5-3: Metrics for Experiment I

The first and third metric, which are directly related to one another, are the most important. These metrics measure the number of casualties from a given plan and the improvement over the base case. Obviously, this is not a prediction of the actual casualties that a plan would yield, but rather it is the expected number of casualties based on the underlying probabilistic threat model that the algorithm considers when solving for the optimal allocation of FPRs. Our choice in using soldier casualties as a metric is a sensitive one as a soldier's life is irreplaceable. An individual soldier is by far the greatest and most precious resource for a country and thus no monetary value or other quantification should be set for a soldier's life. In contrast, other physical resources that an army uses in war, while possibly scarce, are merely objects that can always be replaced. Therefore, we justify the decision to use casualties as a metric because our model serves to protect soldiers and decrease their exposure to risk, which is of significant value to military commanders.

The next two metrics measure benefits secondary to preserving soldiers' lives. The MDMP and the 1/3:2/3 planning guideline places planners under a constrained timetable when developing executable plans for the commander to approve. The FPRAM saves planners time by automating mundane tasks, thereby freeing more time to analyze the merits and/or drawbacks of a COA. The last metric measures the utilization of guntrucks. Because guntrucks are not immune from the threat, they can be destroyed just like any of the transport trucks. Over continuous operations, it is essential to conserve resources so they are available for future plans. One way to accomplish this is not to overuse the guntrucks and always maintain some percentage in reserve.

We recognize that the artificial nature of our experiment will not produce results that lead to definitive conclusions on the amount of improvement or benefit from using the FPRAM. Rather, one intent of the experimentation is to demonstrate the FPRAM's ability to process large quantities of data, use probabilistic models, and quickly arrive at better solutions than its human counterparts. Also, it is important to note that the scope of this experiment is significantly smaller than what an actual division or corps planning staff might have to process.

5.1.2 Trial 1: Decentralized Planning

Trial 1 is designed to model decentralized planning. In decentralized planning, control of resources and decision making authority is maintained at lower levels of command.

5.1.2.1 Design

In this trial we divided the officers into five groups of two. Within each group we assigned one officer to simulate a staff planner for the mechanized infantry division in the northern AO and the other officer in the group to simulate a staff planner for the motorized infantry division in the southern AO. In Part A of Trial 1, each officer was asked to plan for the force protection of the convoys moving in his respective division's AO independently of the planner in the adjacent AO for his group. We divided the set of convoys (output from the SRMOD) to those originating from LSA 1 and delivering supplies to FOBs in the south and those originating from LSA 2 and delivering to FOBs in the north. Additionally, we divided the set of available FPRs between the two sectors. Because there is only one aerial jamming platform in the scenario, we gave planning authority for this resource to the planning staff in the north as they control the larger of the two forces. In total, there were 294 transportation trucks moving as part of the convoy plan presented in this trial. At an assumed 2 soldiers per truck, this equates to 588 CSS soldiers on the roads who are exposed to the threat in support of this convoy plan.

We instructed the officers to plan the allocation of FPRs for their sector without collaborating with anyone else or coordinating with the planning staff in the opposite AO. The restrictions we placed on the planners simulate decentralized planning in which lower-echelon planners have control over their own resources and devise plans aimed foremost at supporting the missions of their own command level, in this case, the division. Additionally, we restricted the planners from coordinating with adjacent units, which is meant to simulate a high-stress, fast-paced planning environment in which planners might not have time to or possibly neglect to coordinate efforts across division boundaries.

In Part B of Trial 1, we allow the planners from both sectors to coordinate their respective plans with one another. This part builds off Part A in that we use both FPR allocation plans developed by the two planners for each group in Part A. We restricted the planners from making changes to their individual plans with one exception: we permitted them to cross-level FPRs across division boundaries. For example, if either of the planners had unused resources, they could offer them up to the other, or if one planner requested resources from the other and had a compelling argument for the need, then the other could remove that resource from its current assignment and provide it to the other planner for use in the other AO. This part of trial

1 maintained decentralized planning at lower echelons but allowed a degree of coordination and synchronization that is representative of staff coordination throughout the MDMP.

5.1.2.2 Results & Analysis

Figure 5-2 displays the results of the five groups for both parts of Trial 1. The solid red line is the expected number of casualties (1.59 out of 588 soldiers or 0.27% of total CSS soldiers comprising the first convoy plan) when the convoy plan is executed in absence of any FPRs. However, one of our assumptions was that commanders dedicate a fixed set of FPRs specifically to support CSS operations. Thus, we consider the red line as the upper bound for the expected number of casualties when no FPRs are utilized. We note, that in practice, even though FPRs may not have been dedicated to support CSS operations, transportation units may still request and receive FPRs and integrate them into their convoy plans resulting in better performance than the upper bound. The solid green line is the expected number of casualties (0.67 soldiers or 0.11% of total soldiers) for the convoy plan when we optimally allocate resources using the FPRAM. This line represents the lower bound for this trial and was a goal for the planning staffs to achieve.

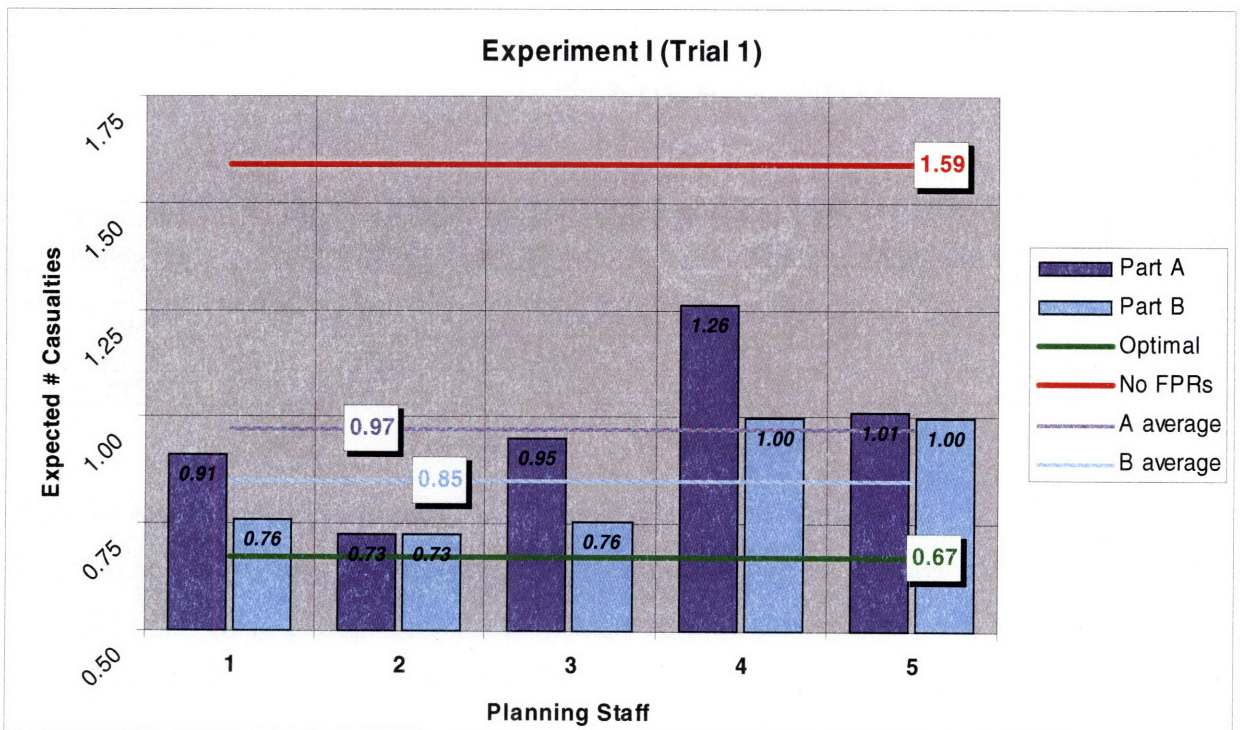


Figure 5-2: Graphical results for Trial 1

The dark blue bars represent the expected number of casualties using the plan generated by each of the five staff groups in part A of Trial 1. The average for the five plans in Part A is depicted by the dark blue line at 0.97 casualties (0.16% of total). Likewise, the light blue bars and line are for Part B of Trial 1. The average of the five plans in part B is 0.85 casualties (0.14% of total). Four of the five staff groups were able to achieve improvement over Part A once they were allowed to coordinate and cross-level resources with the planner from the other sector in their AO. Staff 2 was the only staff group that chose not to make any adjustments in Part B; however, this group still had the lowest expected number of casualties out of both of the trials.

As expected, decentralized planning, which takes advantage of coordination and cross-leveling resources, decreased the expected number of casualties. However, increased planning time was required to allow the necessary coordination across different staffs. The coordination in our experiment occurred between individuals in the same room working together with the same spreadsheets. During actual operations, this coordination is likely to occur over radio broadcast, phone lines, or the internet because planners are physically separated by significant distances. This physical separation adds a layer of complexity which results in more time needed to conduct necessary coordination. Table 5-4 tabulates the values for the four metrics associated with the solutions to the base case, the FPRAM, and the averages of both parts of this trial.

Trial 1	E[cas.] (soldiers)	E[cas.]/Total soldiers	Improvement over base case	Planning time (minutes)	Guntruck utilization
No FPRs	1.59	0.27%	n/a	n/a	0%
Part A average	0.97	0.16%	38.9%	15.0	90.5%
Part B average	0.85	0.14%	46.7%	20.8	96.4%
FPRAM	0.67	0.11%	57.6%	2.3	100%

Table 5-4: Tabulated results for Trial 1

In the table above, we note that the optimized plan from the FPRAM results in 18.7% improvement over the average for Part A, and a 10.9% improvement over the average of Part B. The FPRAM not only achieved these improvements, but it did so more quickly and efficiently. The FPRAM saved an average of 12.6 minutes (84.6%) in Part A and 18.4 minutes (88.9%) in Part B. The reason for the FPRAM's greater time savings in Part B is because it generated the optimal plan across the corps AO from the onset (Part A) and required no further planning.

This significant time savings is an important factor. The size of this experiment is relatively small, allowing for human planners to understand the inputs and arrive at good, feasible plans. However, as the problem size increases, it becomes increasingly more difficult for the human planner to process input data. Similarly, binary integer programs can take longer to solve larger-scale problems, or the problems may become intractable if too large for the BIP to handle. Thus, pruning the model during preprocessing stages and using more efficient solve techniques for the model become even more important. Further testing on larger convoy plans and/or larger AOs is necessary to observe the relative changes in both human and model planning times.

We note that the FPRAM allocates all of the FPRs in both parts of this trial. On average, the simulated planning staffs reserved 9.5% and 3.6% of the guntrucks in Parts A and B, respectively. This may account for part of the difference in the expected number of casualties between the staff generated plans and the FPRAM. The behavior of the military planners can be explained by their indoctrination into the principles of war fighting: Army planners have been taught to always maintain a reserve and conserve resources for future battles or plans. We note that the model, as it stands, assigns no benefit to guntruck or other FPR preservation, hence the 100% utilization rate. However, it might be useful to explore variations of the FPRAM that do not exhaust all available FPRs. This plays a significant role during closed-loop simulation where successive plans build off the state inputs from past plans.

5.1.3 Trial 2: Centralized Planning

Trial 2 models centralized planning in which the higher echelon retains planning responsibility for the FPRs.

5.1.3.1 Design

In practice, the corps commander accomplishes this by providing instructions to his staff through guidance provided during the MDMP, as depicted in Figure 2-7: Role of the command and staff in the MDMP. This guidance informs the staff of the commander's desire to maintain emplacement authority over the FPRs. This provides him with the flexibility to task and re-task these resources across division boundaries to support the corps' overall mission. The staff uses this guidance to create a fragmentary order that makes a change to the task organization of the force, moving control of the resource in question from divisional to corps control.

For Part A of Trial 2, we provided the planners with a "fresh" convoy plan and the same set of available FPRs. The fresh convoy plan represented a new planning cycle in which a new set of demands at the FOBs resulted in a unique set of convoys for that day. The convoy plan in this trial consisted of 14 individual convoys containing 276 transportation trucks (552 CSS soldiers). In the first part of this trial, all ten officers worked as individuals in assigning the FPRs for the entire convoy plan for the corps' AO. Military planning staffs are often short-staffed and work under constrained timelines, so specific elements of the plan, such as the allocation of FPRs, might be tasked to individuals on the staff for more detailed planning. When this occurs, it is plausible that these individuals might not have the opportunity or time to discuss the rationale for their decisions with other individuals prior to presenting the plan to the commander for approval.

Part B of Trial 2 is a variation of Part A in which multiple COAs are presented to the commander for his final decision. In this trial, the officers again formed groups of two. We instructed the officers to discuss the pros and cons of the force protection plans they developed in Part A, and within each staff group, come to a consensus on the best plan to select. Furthermore, no changes to the original plans were allowed. This trial represents a situation where a planning staff devises multiple COAs during the course of the MDMP. Typically, when presenting multiple COAs to a commander, the staff always recommends one over the other based on results from the war-gaming step of the process. A commander normally goes along with his staff's recommendation unless he has sufficient grounds to do otherwise. Therefore, the group's selection of one of the plans from Trial 3 represents the recommended COA they would present to the commander.

5.1.3.2 Results & Analysis

The results from Trial 2, depicted in Figure 5-3 and Table 5-5, are consistent with those from Trial 1. Note that for each planning staff in the chart, there are two dark blue bars for Part A and only one light blue bar for Part B. This is because Part A consisted of every participant planning individually, and Part B consisted of the participants pairing up in staff groups and selecting one of their plans to recommend. The improvement in reduction of expected number of casualties for the average of Parts A and B are 46.4% and 47.6%, respectively, while the improvement for the FPRAM solution exhibits a 57.7% reduction over the base case of no FPRs.

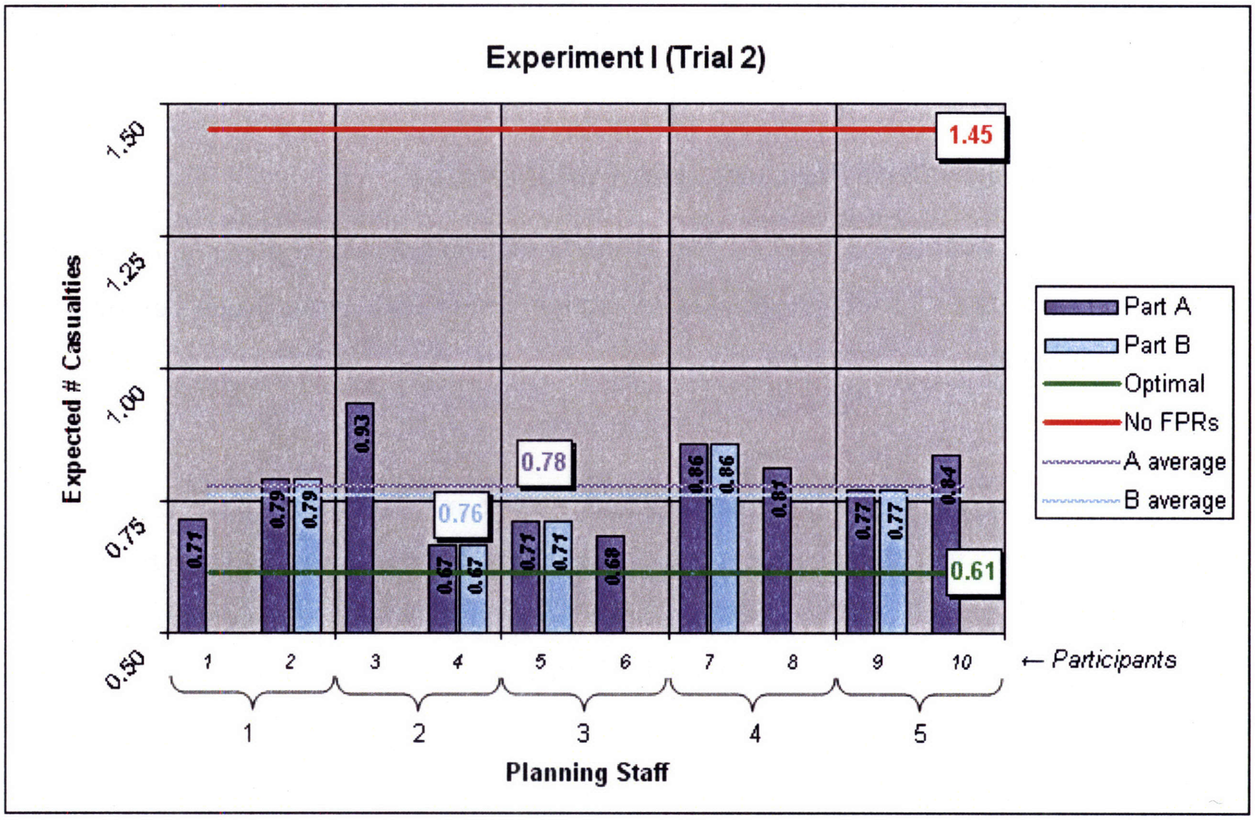


Figure 5-3: Graphical results for Trial 2

One interesting result of this trial is that only two of the five planning staffs in Part B selected the better of their two plans from Part A; this suggests that the underlying differences between two human-generated plans are not intuitively obvious or distinguishable to military planners. Another explanation is that one member of the group is dominant and possesses the ability to easily persuade or convince the other group member to go along with his plan. Further testing on a larger sample with variations on the testing parameters is needed to investigate these hypotheses.

Trial 2	E[cas.] (soldiers)	E[cas.]/Total soldiers	Improvement over base case	Planning time (minutes)	Guntruck utilization
No FPRs	1.45	0.26%	NA	NA	0%
Part A average	0.78	0.14%	46.4%	12.1	94.9%
Part B average	0.76	0.14%	47.6%	17.2	96.4%
FPRAM	0.61	0.11%	57.7%	2.87	100%

Table 5-5: Tabulated results for Trial 2

We observe the same phenomenon with respect to the utilization rates in Trial 2 that we did in Trial 1. The FPRAM uses 100% of the FPRs while the planners retain a small percentage of FPRs in reserve. Additionally, we observe improvements in planning time using the FPRAM over Parts A and B of 76.2% and 83.3%, respectively.

5.1.4 Trial 3: Centralized Planning with Collaboration

Trial 3 is similar to the previous trial in that it models centralized planning at the Corps echelon; however, in this trial we allow collaboration within each group when devising their respective group plan.

5.1.4.1 Design

This trial represents another "fresh" planning cycle in which we provide the simulated planning staffs with a new set of convoys and the same number of available FPRs to be allocated to the corps' convoy plan. The officers remain in groups of two and continue with centralized planning. However, the difference from Trial 2 is that each group can now collaborate within their group from the start of the planning cycle in order to best allocate the FPRs. This final trial represents collaborative planning often found at higher echelons in which staff sections are larger, allowing for the assignment of multiple planners to the same task. The third convoy plan, consisting of 17 individual convoys, was the largest of the three convoy plans, thus we used it for Trial 3 because the members of the groups could work together in handling this bigger scenario.

5.1.4.2 Results & Analysis

We plotted the expected number of casualties for Trial 3 in Figure 5-4 and included the results of the other metrics in Table 5-6. We observe in the plot that the upper bound associated with the base case for this trial is 2.02 casualties (0.29% of total soldiers). On average, the five groups developed force protection plans that achieved 1.11 casualties (0.16% of total soldiers). The optimal solution produced by the FPRAM is 0.86 casualties (0.12% of total soldiers). This is an improvement of 45.3% and 57.4%, respectively, over the group average and the base case for this trial.

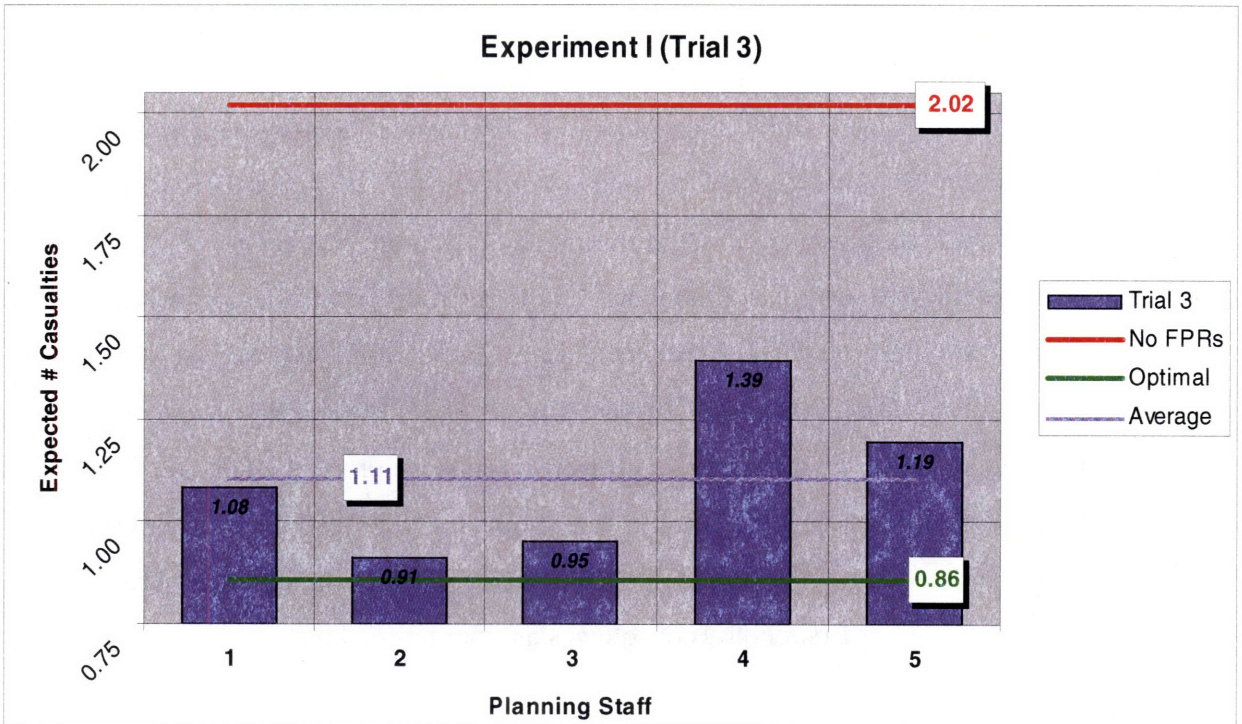


Figure 5-4: Graphical results for Trial 3

We expected better performance on the part of the planning staff for the percent improvement over the base case because of the collaboration element. Aside from Part A of Trial 1, which is designed to perform poorly, we observed the improvement over the base case for Trial 3 drop 1 to 3 percent from Part A of Trial 1 and both parts of Trial 2. It is likely that the increase in the number of convoys, even though it was small, was sufficient enough to make it significantly more difficult for the human planner to process and manipulate the input data than in previous trials. Conversely, the FPRAM has no problems handling this slightly larger scenario and actually improved performance by one percentage point over the FPRAM improvement for Trials 1 and 2.

Trial 3	E[cas.] (soldiers)	E[cas.]/Total soldiers	Improvement over base case	Planning time (minutes)	Guntruck utilization
No FPRs	2.02	0.29%	NA	NA	0%
Average	1.11	0.16%	45.3%	10.2	95.6%
FPRAM	0.86	0.12%	57.4%	3.6	100.0%

Table 5-6: Tabulated results for Trial 3

We observe that the planning time decreased for the simulated staffs from the other two trials and that the FPRAM solution time increased. This reduced the percentage of time improvement to 64.7%, which is more than 11.5% worse than the best improvement observed in each of the other two trials. Obviously, for the FPRAM, a larger scenario with more inputs, will take longer for the model to process, resulting in the increased solve time. As for the decrease in planning time for the simulated staffs, there may have been other factors involved which skew any conclusions made on time required to plan. For example, this experiment possessed a learning curve in which the participants spent more time during the earlier trials in familiarizing themselves with the operational environment and learning the artificial rules of the experiment. Once the participants understood the experiment rules and familiarized themselves with the operating environment (which remained constant for all three trials), they began to develop simple heuristics to facilitate their thinking and decision making process. This led to less time required for plan development. Interestingly, this might not diminish the meaningfulness of these results as this "learning-curve" phenomenon is observed on a much larger scale when a new unit or individual soldier first deploys or relieves another unit/soldier.

5.1.5 Summary of Experiment I

By aggregating the individual results of the three trials, we are able to conduct limited statistical analysis. We use Analyse-it, Version 1.73, a third-party add-in for © Microsoft Excel developed by ©Analyse-it Software, Ltd., for the statistical analysis on all of our results for this experiment as well as Experiment II. The first statistic we analyze is the mean of the expected number of casualties from the 15 individual results from Trial 3 and Part B of Trials 1 and 2. The blue line series on the left of Figure 5-5 depicts the parametric statistics for the mean of this sample and the box-and-whisker plot on the right illustrates the non-parametric statistics for the sample. The blue diamond shows the mean (0.905 casualties) and the 95% confidence interval for the mean (0.793 to 1.1017). The notches at the end of the vertical blue line depict the range for which 95% of the values in the sample fall. The horizontal mid-line of the box and whisker plot represents the median; the top and bottom of the box depict the upper and lower quartile, respectively; the dotted-line connects the nearest observations within 1.5 IQRs (inter-quartile ranges) of the upper and lower quartiles; and the red cross represents a near outlier. From this plot we observe that the distribution is slightly skewed towards lower values because of the condensed lower quartile. Therefore, we will presume that the sample size does not follow a normal distribution.

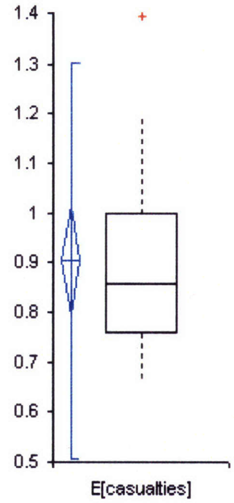


Figure 5-5: Box-and-whisker plot of sample mean for Experiment I

Assuming we do not know the actual sample distribution, we will use a *t*-test to test for a distance between our sample mean and a hypothesized mean. For our hypothesized mean, we will use the average expected number of casualties (0.72) generated from the FPRAM solutions of the three convoy plans used in the trials. Our alternate hypothesis is that the mean expected number of casualties for human-generated plans is greater than that of the FPRAM. Table 5-7 provides a *t*-statistic of 3.53 which strongly supports our alternate hypothesis. Therefore, we conclude for this experiment that the FPRAM generates plans with lower expected number of casualties and with 95% confidence the difference is at least 0.093 casualties.

Test	One sample t-test			
Alternative hypothesis	E[casualties] ≥ 0.72			
n	15			
	n	Mean	SD	SE
E[casualties]	15	0.905	0.203	0.0524
Hypothesised		0.720		
Difference between means	0.185			
95% CI	0.093 to +∞			
t statistic	3.53			
1-tailed p	0.0017			

Table 5-7: One sample t-test for Experiment I

An improvement of this magnitude would be significant for CSS operations by saving many lives and preventing many debilitating injuries over continuous military operations. However, we recognize the absolute values we arrive at in this experiment are based off subjective input data; therefore, further testing on actual threat models and more realistic data is required in order to determine the real benefit from the model.

In addition to the life saving benefits from the FPRAM solution, there is the additional benefit associated with generating plans more quickly. As demonstrated in these three trials, the FPRAM performed significantly better than the human planners with respect to plan generation time. We attribute this to the automation of time-consuming tasks and the software capability to process and search over vast quantities of data. However, due to nature of BIP, it is possible that larger-scale problems could quickly become intractable using the FPRAM. Therefore, in Chapter 6 we propose future studies of preprocessing/pruning techniques for scaling the solution space, as well as improving solve-efficiency of the model by exploring formulation variations.

5.2 Design of Experiment II

In Experiment II, we conduct Monte Carlo Simulation by randomizing one of the input parameters. Monte Carlo simulation is a technique used to produce large sample sizes quickly for an experiment in order to perform statistical analysis [27]. This form of simulation is useful in preliminary testing as it is cheap, fast, and easy to perform. We structured our Monte Carlo simulation to change the demand randomly at the FOBs and rerun the SRMOD and FPRAM for each change of demands. The impact of varying demand at the FOBs is a slightly different SRMOD generated convoy plan. Effectively this allows us to generate a large sample size of different convoy plans in which to test the performance of the FPRAM. Note that the underlying threat model does not vary in this experiment because we do not manipulate the utilization rates. Effectively randomizing the demands simulates the staff planning allocation of FPRs over and over again for varying convoy plans on the same state inputs associated with the threat and environment. We will call this Run A, the first of three runs in Experiment II.

In the next two runs of Experiment II, we explore FPRAM results stemming from two variants of the SRMOD, which significantly affects the generated convoy plans. The first variant completely changes the objective function from minimizing the expected number of casualties to minimizing the distance traveled by the convoy. This change in model focus is more aligned with private-sector objectives where transportation networks are free of threats. We again use Monte Carlo results from this variant to compare distance-oriented plans to our risk-oriented plans. This is Run B of the experiment.

Finally, Run C captures another variant of the SRMOD, in which the objective function includes a trade-off between risk and distance. We form a convex combination of risk and distance $\left((1-0.5^{16})\cdot risk + 0.5^{16}\cdot distance\right)$ so that reducing a path option (convoy) by 100 miles is worth increasing the per-truck accumulated hazard by approximately 0.0015. The multi-commodity flow function of the SRMOD uses this convex combination as the cost of sending a transport truck along a given path-option. This trade-off only occurs in the SRMOD; the FPRAM still optimizes with respect to risk only [4]. We collect results from Monte Carlo simulation on this run and compare it with Runs A and B. As part of our analysis for Experiment II, we conduct pair wise comparisons of the three runs. Also of interest is how the plans generated from these variants of the SRMOD affect the performance of the FPRAM in reducing expected number of casualties.

For each of the Monte Carlo runs we use a sample size of 500. Using this sample size allows us to conduct the simulation of each run in less than 6 hours and still provides us with sufficient results to perform statistical analysis on the metrics of interest. We consider the portion of the run without FPRs as the base case within each run to which we compare the results of the portion of the run which includes FPRs.

5.2.1 Units of Measure

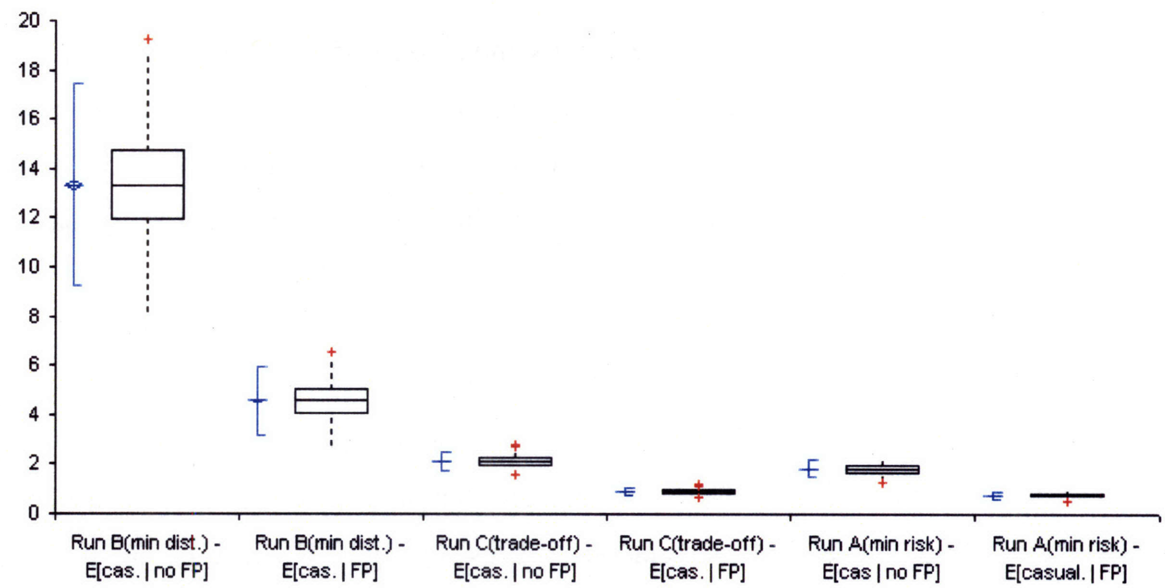
We use metrics similar to those we used in Experiment I (Table 5-8). The main difference is now we are capturing the underlying distribution parameters associated with the 500 samples from the Monte Carlo simulations. Thus, the first two metrics are the mean expected number of casualties and the standard deviation about the mean. In this experiment we are not interested in utilization of guntrucks, as we have pointed out that the FPRAM currently has no incentive for not using all the guntrucks. However, we note that modifying the FPRAM formulation to consider this could be valuable during closed-loop simulation in which we consider previous plans and state inputs when generating new plans.

Metric	Unit of Measure
Mean E[cas.]	soldiers
Standard deviation of E[cas.]	soldiers
Percent improvement over base case	percentage
Plan generation time	minutes

Table 5-8: Metrics for Experiment II

5.2.2 Results & Analysis

The first chart depicted in Figure 5-6 displays the Monte Carlo results for the mean and standard deviation for expected number of casualties for the three runs with and without FPRs. At the top of the figure we provide the parametric statistics (depicted in blue) and the non-parametric box-and-whisker charts for each of the runs. At the bottom we provide the tabulated results along with respective 95% confidence intervals. The run without FPRs is representative of the upper bound we discussed in Experiment I where we compute the expected number of casualties from the convoy plan generated by the SRMOD prior to inputting into the FPRAM. It follows then that the run with FPRs computes the expected number of casualties for the convoy plan/FPR plan output from the FPRAM.

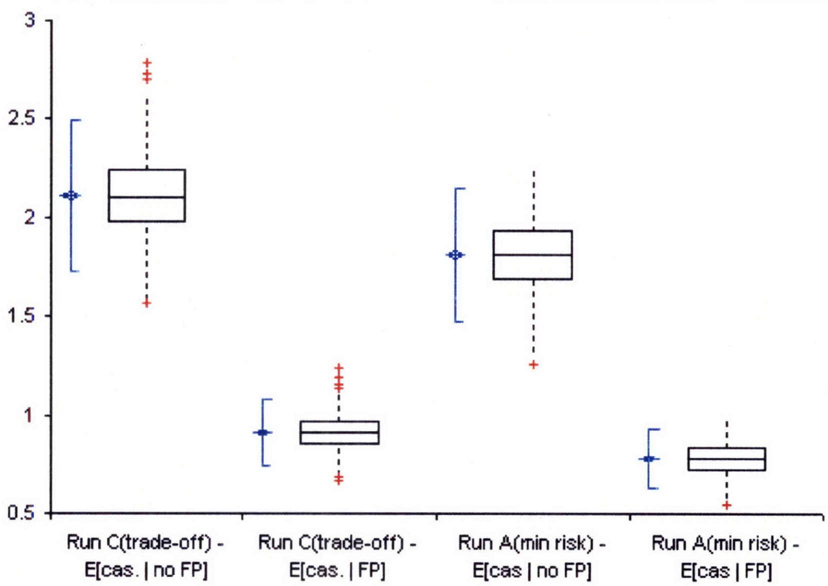


	n	Mean	SD	SE	95% CI of Mean	Median	IQR	95% CI of Median
Run B(min dist.) - E[cas. | no FP]	500	13.323	2.0834	0.0932	13.140 to 13.506	13.328	2.789	13.099 to 13.533
Run B(min dist.) - E[cas. | FP]	500	4.551	0.7143	0.0319	4.489 to 4.614	4.552	0.971	4.475 to 4.626
Run C(trade-off) - E[cas. | no FP]	500	2.112	0.1956	0.0087	2.094 to 2.129	2.098	0.265	2.083 to 2.120
Run C(trade-off) - E[cas. | FP]	500	0.912	0.0841	0.0038	0.904 to 0.919	0.909	0.109	0.902 to 0.917
Run A(min risk) - E[cas | no FP]	500	1.811	0.1714	0.0077	1.796 to 1.826	1.807	0.251	1.789 to 1.829
Run A(min risk) - E[casual. | FP]	500	0.781	0.0754	0.0034	0.774 to 0.788	0.777	0.108	0.771 to 0.789

Figure 5-6: Comparative statistics for mean expected casualties from Runs A, B, and C

We observe that Run B -- based on SRMOD minimizing distance -- without FPRs (the plot on the far left of the chart) yields the highest mean at 13.323 casualties. This is at least 11 casualties over the means for Runs C or A. While this number appears high, we reiterate that we do not place emphasis on the absolute values for the metrics, as our scenario contains subjective data; rather, we demonstrate the relative improvements between the various runs with and without FPRs. Run B achieves a 65.8% improvement over the mean expected number of casualties just by adding FPRs to the convoy plan generated by the SRMOD. Alternately, if we compare the results with no FPRs for Run B against Run A, we observe that just shifting the routing objective from distance-oriented to risk-oriented we achieve an astounding 86.4% improvement.

From inspection alone, we see that both Runs A and C perform considerably better than Run B. Thus, we will remove Run B from the comparison and take a closer look at the box-and-whisker plots for the other two runs which we include in Figure 5-7.

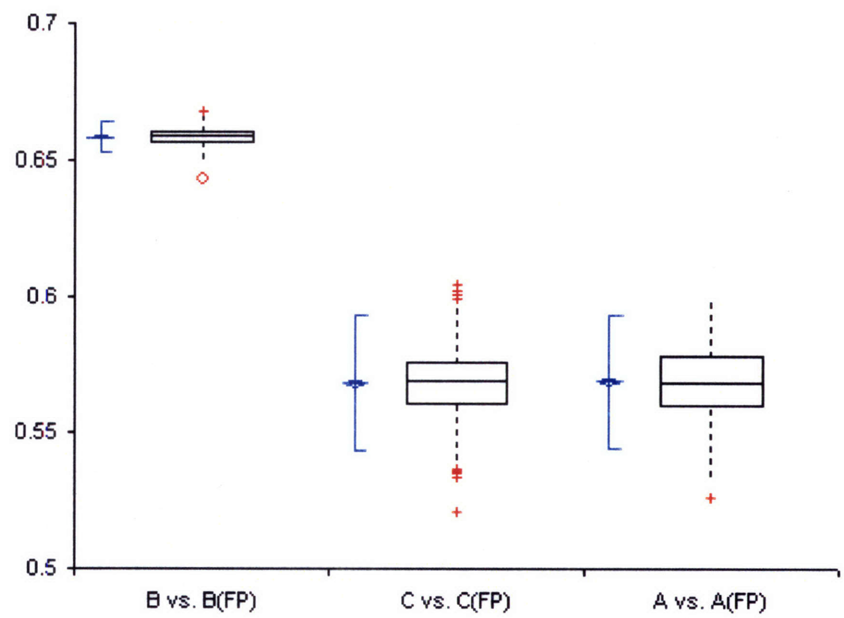


	n	Mean	SD	SE	95% CI of Mean	Median	IQR	95% CI of Median
Run C(trade-off) - E[cas. | no FP]	500	2.112	0.1956	0.0087	2.094 to 2.129	2.098	0.265	2.083 to 2.120
Run C(trade-off) - E[cas. | FP]	500	0.912	0.0841	0.0038	0.904 to 0.919	0.909	0.109	0.902 to 0.917
Run A(min risk) - E[cas | no FP]	500	1.811	0.1714	0.0077	1.796 to 1.826	1.807	0.251	1.789 to 1.829
Run A(min risk) - E[cas | FP]	500	0.781	0.0754	0.0034	0.774 to 0.788	0.777	0.108	0.771 to 0.789

Figure 5-7: Comparative statistics for mean expected casualties from Runs A and C

First, we note that the confidence intervals for the mean expected number of casualties are very tight (a range less than 0.015 soldiers) for both runs with FPRs and only include a small number of outliers. Next, we note that the trade-off run (C) results in a 16.8% increase in the mean expected number of casualties over the minimum risk run (A). However, a commander might consider this an acceptable increase in risk if he considers other factors, e.g., time to complete a mission. If the commander has to deliver certain high priority supplies under a constrained timeline, then a trade-off between risk and distance might be an acceptable alternative. The addition of the trade-off option provides the commander with more flexibility if planners use the SRMOD/FPRAM to generate multiple COAs to present to the commander. Future testing should consider trade-offs between risk and other parameters deemed important by decision makers.

The next chart (Figure 5-8) depicts the mean percentage improvement over the base case for each run. The base case for each run is the portion without FPRs.

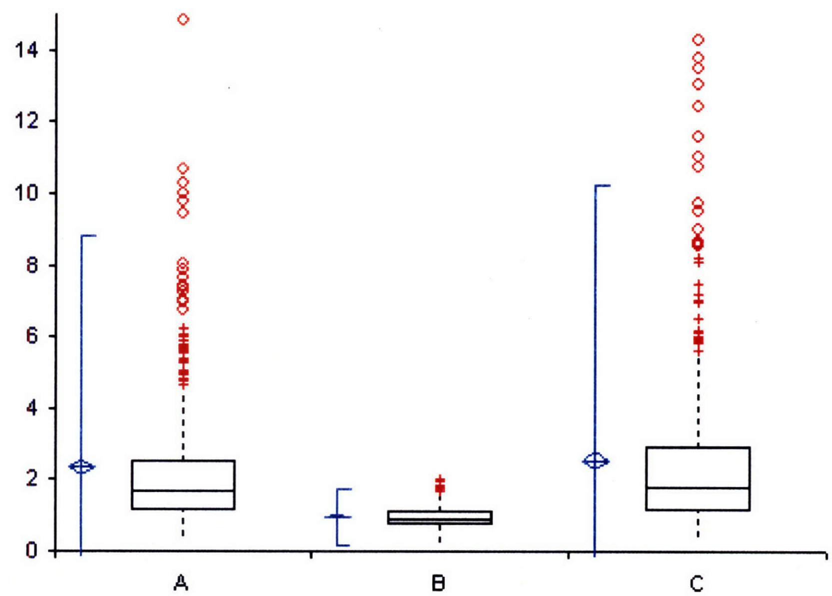


Percent Improvement	n	Mean	SD	SE	95% CI of Mean	Median	IQR	95% CI of Median
B vs. B(FP)	500	0.658	0.0030	0.0001	0.658 to 0.659	0.659	0.004	0.658 to 0.659
C vs. C(FP)	500	0.568	0.0125	0.0006	0.567 to 0.569	0.569	0.015	0.567 to 0.570
A vs. A(FP)	500	0.569	0.0123	0.0006	0.567 to 0.570	0.568	0.018	0.567 to 0.570

Figure 5-8: Comparative statistics for percent improvement over base case for Runs A, B and C

From the table at the bottom of Figure 5-8, we see that Run B performs the best with respect to the percent improvement over the base case with a value of 65.8%. We speculate that this is because in the minimum distance run, there is the greatest room for improvement in reducing casualties. The mean expected number of casualties was 13.323, indicating that the convoys accumulated many hazards over the course of the plan. This implies that there are many opportunities to realize reduction effects by the smart placement of FPRs. The improvements of Run A and Run C are approximately equal at 0.569 and 0.568, respectively.

Figure 5-9 displays the plots of the mean plan generation times for the three runs of the SRMOD/FPRAM. Note that the FPRAM accounts for the majority of the total plan generation time, taking, on average, 97.2% of the total time across the three runs. We attribute this to the type of linear programming approach we modeled each after. The SRMOD is a mixed binary integer program which typically solves faster than a binary integer program that is representative of the FPRAM.



Plan Generation Time	n	Mean	SD	SE	95% CI of Mean	Median	IQR	95% CI of Median
A	500	2.334	2.5215	0.1128	2.112 to 2.555	1.687	1.365	1.582 to 1.812
B	500	0.963	0.3013	0.0135	0.936 to 0.989	0.918	0.358	0.885 to 0.951
C	500	2.556	2.9853	0.1335	2.293 to 2.818	1.825	1.759	1.690 to 2.004

Figure 5-9: Comparative statistics for plan generation time for Runs A, B and C

We highlight the fact that if the trade-off option was generated in addition to the minimum risk option, so that the staff could provide multiple COAs to the commander, then depending on the number of runs the system could handle at a time, the plan generation time is either the maximum of the two times (two simultaneous runs) or the aggregate of the two times (one run at a time). Regardless, the mean planning times for any one of these runs is significantly lower than what we'd expect from human-generated planning. For obvious reasons, we cannot conduct Monte Carlo simulation of human-generated plans. But we venture to say that in the average time it takes to generate a plan using the SRMOD/FPRAM, the typical staff planner will have only gathered the necessary tools and reports required to make the plan. Furthermore, it would take at least 15 minutes just to study and visualize the available data and possibly hours to arrive at a feasible solution for appropriate loads, convoy configurations, routings, and the FPR allocations. We observe some outliers that take considerably longer times to plan than the mean times, but while the models are running, the staff planner can use that time to accomplish other tasks or analyze previously generated COAs.

5.2.3 Summary of Experiment II

Experiment II demonstrates that the SRMOD and the FPRAM, whether utilized individually or in concert, have the potential to generate lower-risk convoy and force protection plans. Furthermore, the models generate these plans in a small fraction of the time it takes human planners to arrive at lower quality plans. The Monte Carlo simulation demonstrates the consistent high-performance by these models by way of the tight confidence intervals on most of the parameters. However, like Experiment I, we recognize that the models, in their current states, do not account for all variables of the real world. Additionally, we have made some broad assumptions in order to simplify the models to a scale commensurate with a thesis-sized problem.

Further expansion and additional experimentation are needed to more fully explore the benefits of the model. Monte Carlo simulation should be applied to other model parameters to identify aspects of the modeling that affect performance. For example, we could randomize the utilizations such that the threat probabilities shift with each iteration of the simulation, which would represent a staff planning the same convoy on different days with different threats. These tests would help to identify the areas in the model where we need to build in robustness. By making the model more robust, the algorithm can create slack, which allows the plans to hold up longer during execution. This additional modeling and testing can demonstrate the true benefits of the approach we use to reduce CSS soldier casualties in an asymmetric environment.

6 Future Research & Application as a Decision Support Tool

In the first half of this chapter we discuss aspects of our solution approach, model formulation, and the experimentation that requires further exploration before implementing this technology into current systems and processes in the Army. The second half of the chapter we dedicate to describing how the proposed technology can integrate with existing Army systems and processes used by the combat service support community.

6.1 Future Research

The research presented in this thesis is an important step towards realizing a refined technology that can be used to save soldiers' lives in the Global War on Terrorism. The results and analysis of the experiments from Chapter 5 demonstrate the capability of the Scheduling and Routing Module and Force Protection Resource Allocation Model to generate lower-risk plans and achieve results unattainable by planning staffs in a constrained planning environment. However, we recognize the need for further research into the modeling approach for the problem of high casualties to CSS soldiers in the asymmetric threat environment. We have identified five areas on which to focus future research: 1) expanding the FPRAM, 2) incorporating a feedback loop between the SRMOD and FPRAM, 3) devising alternate threat models to test model performance against, 4) exploring robust modeling techniques that account for the uncertainty in the input data, and 5) developing a simulation environment to conduct closed-loop testing of the SRMOD/FPRAM solutions.

6.1.1 Model Expansion

We recognize that the two models, in their current form, do not take into consideration all the variables necessary for deriving real-world plans. They may also incorrectly emphasize certain real-world aspects while de-emphasizing others; additional feedback and "tuning" from domain experts can address this issue.

One variable we have not fully taken into consideration is time. We currently use time in a limited capacity within the SRMOD to track estimated times of departures and arrivals for the convoys at planned stops along their route. The SRMOD also uses time to constrain a convoy to a maximum amount of time that a convoy can spend away from its origin base when delivering supplies. This is the extent for the use of time in the SRMOD and FPRAM models.

Future research is needed to explore other impacts that the time component has on the two models. The time of day and/or day of the week might cause the threat to behave differently, e.g., the threat will use the cover of darkness at night to emplace ambushes, more so than during hours of light when there is heavy civilian or military traffic on the roads.

Time also factors into the FPRAM by placing limitations on the various FPRs. In the thesis, we assume a static execution period (24-hours) for all FPR decisions. If the FPRAM assigns a security platoon to a patrol route, then the model assumes the platoon patrols that route for the entire execution period. Obviously, limitations associated with soldier rest and vehicle maintenance render this infeasible. Therefore, FPRs require an additional index in the FPRAM associated with blocks of time, such that FPRs are utilized within their physical limitations.

One approach to adding time into the FPRAM is to model it over a time-space network. In such a network, time is segmented into blocks and each block of time has an associated carbon-copy of the entire FPRAM model as currently portrayed. Implications of this modeling approach are that the model scales in size with the number of time segments, and the solve times are anticipated to grow rapidly, or even exponentially, with the size of the model.

6.1.2 Feedback Loop

Currently, the SRMOD and FPRAM occur in sequence where the convoy plan output from the SRMOD becomes one of the inputs for the FPRAM. The end result of the entire process is the convoy plan and associated force protection plan that supports that convoy plan. We propose that greater improvement could be possible by modifying this process to include a feedback loop that revisits the SRMOD after completion of the FPRAM. The purpose of the feedback loop would be to reduce the expected number casualties even further.

For example, if we input the locations (and associated reduction effects on the threat) of the global FPRs decided upon by the FPRAM into the SRMOD, we believe that the SRMOD could improve upon its original convoy plan by making adjustments to the existing convoys to reroute those convoys over arcs covered by the global FPRs. This should result in a lower risk convoy plan than originally output by the SRMOD. This modified convoy plan is then fed back into the FPRAM a second time, allowing the FPRAM algorithm to make refinements that may further reduce the risk. The original plan remains feasible, so in no case can this feedback loop increase the overall risk to a convoy plan.

6.1.3 Alternate Threat Models and FPR Modeling

Our current model works off an artificial threat model derived to demonstrate the SRMOD and FPRAM capabilities. In practice, the various intelligence agencies in the U.S. have existing threat models that capture trends and attempt to predict threat activity. The Army's intelligence branch is connected to these agencies through its All Sources Analysis System, allowing them access to the type of data necessary to derive appropriate threat models and predictive tools. The technology we propose needs to tie into these threat models and use actual threat data in order to capture the environment effectively. The goal is that the SRMOD and FPRAM produce convoy plans that minimize exposure to the threat, thereby resulting in fewer casualties. This level of integration takes this research into a classified domain, which at some point is inevitable if the Army is to implement the proposed technology in its current systems.

Game theory can also play a significant role in threat model development and SRMOD/FPRAM formulation. The value of our model to commanders would increase dramatically if our model could produce plans that predict changes to threat activity based off results from execution of past plans. Another element that would greatly enhance the system is if the SRMOD randomized elements of our tactics and polices to make it difficult for the threat to ascertain any patterns in our operations.

Future research is needed to further explore the current FPRs in our model as well as other potential FPRs not considered in this thesis. We suggest the exploration of methods to model possible residual effects left in the wake of local FPRs supporting a specific convoy: is it reasonable to assume that follow-on or crossing convoys can realize some of these residual effects? We also need to investigate the assumption we attached to the aerial jamming resource in Section 4.2.4. We assumed that they operate over the entire electromagnetic spectrum and thus we modeled a constant effect over any remotely detonated IED. However, in the real world, remotely controlled IEDs operate on varying frequencies; likewise, an aerial jamming resource is limited by the physics associated with electronic warfare. As the resource jams over larger bandwidths, the jamming signal becomes less intense and vice-versa. Furthermore, there is the potential negative effect of electronic warfare when it interferes with Army communication systems. This is an important aspect of command and control that could actually degrade operations and result in increased risk to convoys.

6.1.4 Closed-loop Simulation

The next step in testing the models will be to build a simulation environment in which we can execute the generated plans. Through this simulated environment, we can conduct closed-loop testing, which takes into consideration previous plans and updated state inputs based on the outcomes of previous plans. For example, destroyed trucks or FPRs are not be available when generating the next plan and road segments would become temporarily unusable if they required repair from an IED attack that damaged the road. This closed-loop testing allows us to test the potential benefits of some of our other proposals, such as reformulating the FPRAM to hold back some FPRs for use in future plans. Finally, we can use Monte Carlo simulation of closed-loop scenarios that span greater than one execution period to generate enough samples to statistically analyze the performance of the SRMOD/FPRAM over an extended period of time.

6.1.5 Robust Planning Under Uncertainty

Most importantly, the model must be robust. It must generate solutions that will hold up longer when executed under uncertainty in the model parameters. Many of the parameters in the model are only best guesses and the model's performance is only as good as its inputs and underlying models. One way to add robustness to the model is to build in slack around the variables affected by the uncertain parameters. The downside of adding slack to the model is that the plan becomes more costly. Although the plans generated from a robust model may be more costly, the realized performance of robust plans can far exceed their deterministic counterparts.

We use the aerial jamming variable to illustrate the concept of robustness and how it affects the optimality of a plan. In the FPRAM presented in our experiment scenarios, we assumed with certainty that there is always one aerial jammer available. However, let us instead suppose that with some probability the *jam* resource is unavailable, e.g., down for maintenance or diverted to support a combat mission. In the non-robust FPRAM, the model solved for the greatest effect from the *jam* resource by assigning it to a ROZ that: 1) covers arcs with higher probabilities of remotely detonated devices; and 2) has a large number of convoys running through it. Additionally, because the threat from remotely detonated devices is already reduced along the arcs covered by the *jam* resource in this ROZ, other FPRs that have a relatively high effect against remotely detonated devices are systematically diverted to other areas or convoys in the AO to generate optimal effects.

In contrast, when the FPRAM is reformulated to handle the uncertainty of the availability of the *jam* resource, the algorithm considers trade-offs in the event that the *jam* resource is unavailable. A possible trade-off is not diverting all those other FPRs with strong effects against remotely detonated devices from the high threat area where the jammer is planned for use. This new solution, when evaluated in the context of the original non-robust model, produces a larger expected number of casualties than the non-robust plan. In the context of the new robust model, however, it can perform better in a simulation or when executed for a real mission. Monte Carlo simulation can demonstrate that the realized casualties are less for the robust plan when the *jam* resource is not available versus the non-robust plan in this situation.

6.2 Application as a Decision Support Tool

In this section we discuss how to integrate the SRMOD and FPRAM into the Army's existing planning tools and the military decision making process in order to streamline planning. Secondly, we describe the concept of *trust-based design* of human-guided algorithms and how we can apply this concept to the SRMOD/FPRAM system.

6.2.1 Integration into Trans-Log Web

In the Section 2.3.3 we introduced BCS3, the C2 system for CSS. Within BCS3 there is a tool for use by planners called Trans-Log Web (TLW). Trans-Log Web assists the planner in the development and management of the transportation request and transportation movement release procedures discussed in Chapter 3. TLW has features that assist planners in managing truck capacities and calculating minimum-distance routes. However, TLW does not account for the threat, nor does it or plan for force protection of convoys. Our intent is to add these features to TLW. TLW is currently undergoing multi-phase implementation in which all of the planned improvements and features are systematically added over time until the desired end state of the software is reached. We propose that the threat modeling portion from ASAS be tied into TLW, with the added capability to optimize routes based on minimizing risk and to plan optimal allocation of force protection to convoys.

A major advantage of the SRMOD/FPRAM system is its time saving potential and ability to generate multiple COAs for comparison. Because the model can search through and process vast amounts of data, it does what was previously unattainable by human planners: it considers all the data and variables for an entire AO to derive the optimal solution with the lowest number of expected casualties. The planning software not only arrives at better solutions faster than human planners, but while it is processing, it frees up time for staff planners to perform other aspects of their job.

Figure 6-1, below, illustrates how the SRMOD/FPRAM system can be rerun successively throughout the planning phase of the MDMP, both to generate the initial plan and later to refine the plan, as the time of execution nears, to account for state updates from the completion of past plans. The refinement runs of the SRMOD/FPRAM allow for minor adjustments that do not require significant changes to truck loads, convoy configurations, or allocation of FPRs.

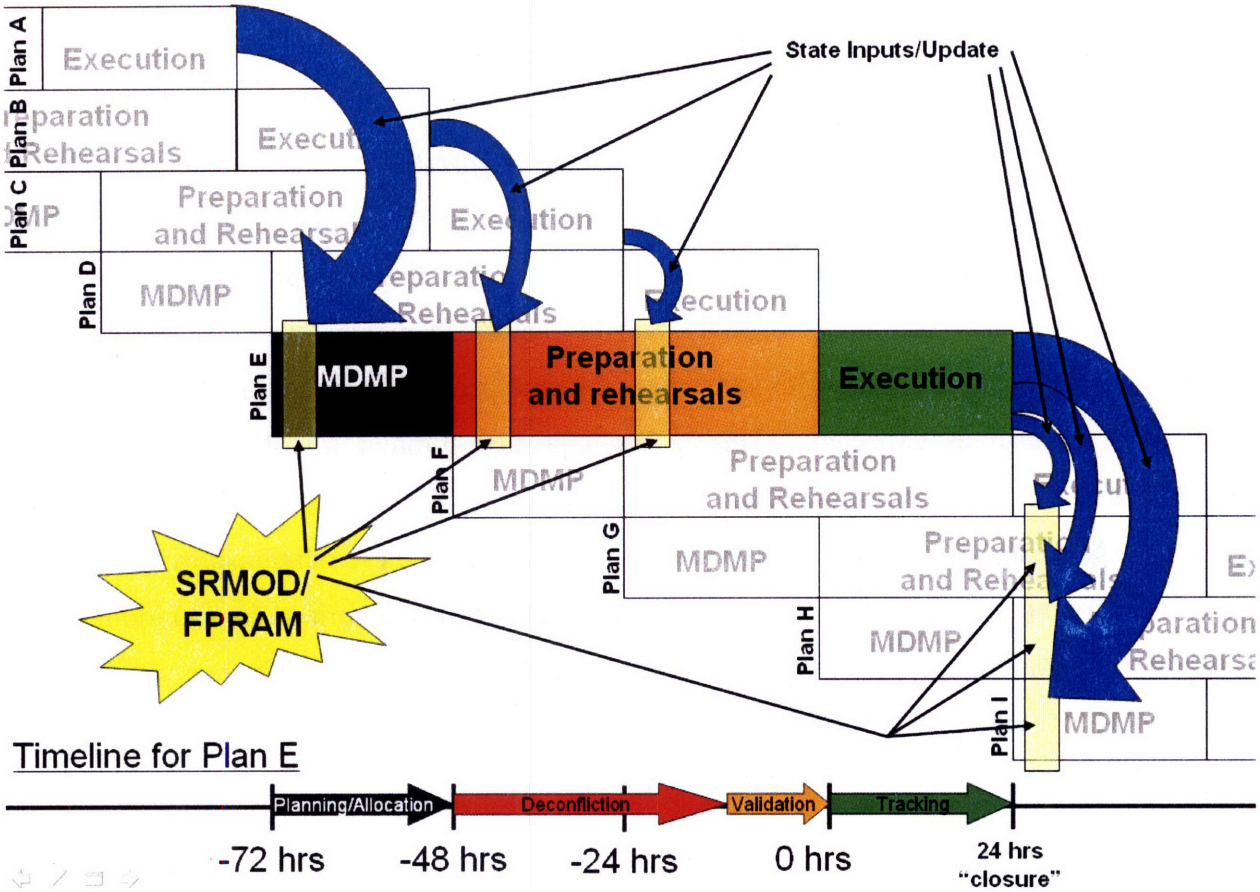


Figure 6-1: SRMOD/FPRAM integration into MDMP

Note that the blue arrows coming out of Plans A, B, and C are used as the state input for the initial running of the SRMOD/FPRAM system in Plan E and the updates for Plan E's refinement runs during the Deconfliction and Validation phase of the DM process. Likewise, the state at the end of the execution of Plan E becomes the state input and updates for the SRMOD/FPRAM runs during Plans G, H, and I, respectively. In essence, we rerun the SRMOD/FPRAM model at the completion of each execution period. In addition, we must add a weighted term to the objective function that penalizes significant changes to any elements of the plan.

Another major advantage of the SRMOD/FPRAM system is its ability to generate multiple COAs based on user preferences. We demonstrated an example of this in Experiment II when we changed the objective function from risk-oriented to distance-oriented to a trade-off between the two. One could optimize on additional factors as well, such as time on roads, priority of supplies, or priority to a unit or base. These other factors require further modifications to the model but are important additions, as we point out in our discussion of trust-based design and human-guided algorithms in the next section.

6.2.2 Trust-Based Design and Human-Guided Algorithm

Ultimately, the FPRAM could be most beneficial to Army planners if its underlying algorithm were human-guided. Human-guided algorithm's give more control to the user via his understanding of how the model operates and his ability to manipulate preference settings. Additionally, human-guided algorithms increase the confidence of the user in that the generated plans will perform as expected. This is accomplished through trust-based design where comprehensive training and intelligent user interfaces reveal to the user the relationships between input data, decision variables, and constraints and how these relationships lead into the objective solution. When a planner understands the mathematical algorithm in operational terms familiar to him and plays an active role guiding the algorithm through preference settings, then the result is better, more quickly devised plans that take into account data and variables previously unmanageable by human processing alone [24].

7 Summary & Conclusion

In this chapter, we review the original problem, the technical approach we devised to address the problem, and the two experiments we designed and ran to test our model's performance. We end the thesis by highlighting the main conclusions from the analysis of our experiments, as well as emphasizing the benefits of integrating this approach into current distribution management planning tools for the Army.

7.1 Summary

In Chapter 1, we discussed Operation Iraqi Freedom as the motivating factor for the research in this thesis. We identified that the nature of an asymmetric threat in the contemporary operating environment puts logistical convoys at risk, resulting in a high number of CSS soldier casualties. We also presented a list of possible contributing factors for this large number of casualties. In Chapter 2, we provided an operational overview in the context of combat service support operations. This covered elements of the organizational and staff structures of the Army as well as external considerations such as the environment and the threat. In Chapter 3, we discussed in detail the distribution management process that leads to the development of a convoy plan that satisfies the logistical requirements for the force. We modeled the distribution system as a simple input-output functional model, which became the basis for our technical approach.

In Chapter 4, we fully explain the decomposition of our approach into the Scheduling and Routing Module developed by Draper Laboratory and the Force Protection Resource Allocation Model, which is the focus of the thesis. We described the data structure, a detailed threat model tied to the road network, and the binary integer program we used to solve for the lowest expected number of casualties. In Chapter 5, we described the scenario and design for the two experiments we conducted. In the first experiment, we modeled human factors associated with traditional planning methods practiced by Army staff officers compared with performance by the FPRAM. In the second experiment, we utilized Monte Carlo simulation to generate large sample sizes on which to conduct statistical analysis. In Chapter 6, we identified areas for future research to improve the model and data structure. We also described how the model and our approach to reducing CSS casualties could integrate into current Army systems and processes.

7.2 Conclusion

In this section, we discuss the general conclusions and insights we gathered from our technical approach, model formulation, and results from our experiments.

7.2.1 Modeling the Asymmetric Threat

The threat model we presented in Section 4.2.2 is an important step towards a technology that can assist military planners in developing effective plans that can mitigate casualty risk to CSS soldiers. Currently, planners receive threat briefs throughout the MDMP, but often the intelligence is broad and generic in nature. CSS planners do not receive the specific threat intelligence as it pertains to the roads on which their convoys travel daily. We recognize that the nature of an asymmetric threat makes it very difficult to model and predict, but we suggest the need to explore techniques that mathematically model the threat and its relationship to the road network. This allows for our model to accumulate hazard data over the arcs traveled by a convoy, which is a significant concept in our thesis that allows planners to construct and run convoy plans with far less risk than current operations.

7.2.2 Deliberate Force Protection Planning

In this thesis, we emphasized the importance of developing plans with force protection considerations at the forefront. We pointed out that logistical convoys are more vulnerable to the threat than combat forces, thus force protection resources should be specifically dedicated to support CSS operations. This provides flexibility to CSS planners to plan for the force protection of their convoys without having to rely on external support. Additionally, through centralized planning at the higher echelon, planners can consider the overall picture and benefits for the area of operation when deciding when and where to task a FPR, as opposed to decentralized planning, which is less likely to place FPRs where they are needed most. By utilizing FPRs in this way, to achieve their greatest potential, planners are also able to maximize the opportunities they have of creating the lowest-risk convoy plan.

7.2.3 Benefits of Optimization-Based Planning

The optimized plans produced by both the SRMOD and FPRAM not only save valuable time during the planning process, but they also produce plans that yield lower threat risk convoys for soldiers. Of importance is that this decreased risk can even extend to the experienced soldier during the middle of their deployment. In Section 2.4, we discussed that soldiers and units deploying into a particular theater are susceptible to the threat according to the graph we presented in Figure 2-11: Deployment risk curve. Through the utilization of optimization-based decision support tools (SMROD and FPRAM) successfully integrated into existing Army systems, we expect that the ends of the deployment risk curve will flatten and the entire risk curve will lower as depicted in Figure 7-1. The goal of saving CSS soldiers' lives and decreasing casualty rates can be realized through this technology.

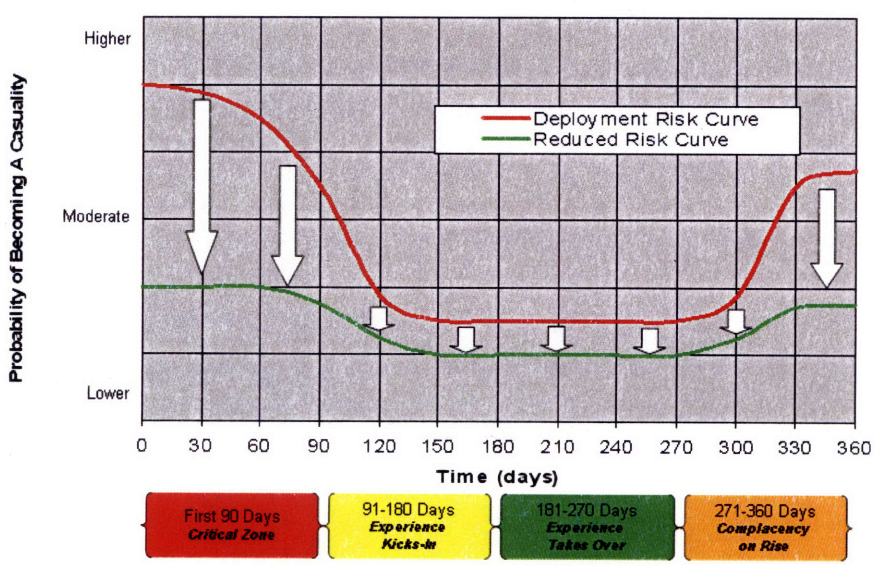


Figure 7-1: Reduced deployment risk curve

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Appendix A: Abbreviations and Acronyms

Abbreviation/ Acronym	Term
ABCS	Army Battlefield Command System
AFATDS	Advanced Field Artillery Tactical Data System
AO	area of operations
ASAS	All Source Analysis System
BCPT	battle captain
BCS3	Battlefield Command Sustainment Support System
BIP	binary integer program/programming
BSB	brigade support battalions
C2	command and control
CALL	Center for Army Lessons Learned
CBT	combat
CCIR	commander's critical information requirements
Cdr	commander
CLP	combat logistics patrols
COA	course of action
COE	contemporary operational environment
CONUS	continental United States
COP	common operating picture
CoS	chief of staff
COSCOM	corps support command
CSS	combat service support
CSSB	combat sustainment support battalion
CSV	composite strategy variable
CULT	common user land transportation
DISCOM	division support command
Div	division
DM	distribution management
DMB	distribution movement board
DMC	distribution management center
DoD	Department of Defense
EOD	explosive ordnance disposal
EP	electronic protection
EW	electronic warfare
FAADC3I	Forward Area Air Defense Command, Control, Computers, and Information
FBCB2	Force XXI Battle Command, Brigade and Below
FOB	forward operating base
FP	force protection
FPR	force protection resource
FPRAM	Force Protection Resource Allocation Model
FRAGO	fragmentary orders
FSC	field service companies
G1	personnel staff section (units commanded by general officer)
G2	intelligence staff section (units commanded by general officer)
G3	operations staff section (units commanded by general officer)
G4	logistics staff section (units commanded by general officer)

G5	civil military operations staff section (units commanded by general officer)
G6	communications staff section (units commanded by general officer)
GCCS	Global Command and Control System
GCCS-A	Global Command and Control System - Army
HEMMT	heavy equipment multipurpose mobile truck
HETT	heavy equipment and truck transport
IED	improvised explosive device
ISYSCON	Integrated System Control Program
ITV	in-transit visibility
jct	junction
JDB	joint distribution board
LCOP	logistics common operating picture
LNO	liaison officer
LP	Linear Program/Linear Programming
LSA	logistical Support Area
LTC	lieutenant colonel
MCO	movement control officer
MCS	maneuver control station
MCT	movement control team
MDMP	military decision making process
MTS	movement tracking system
OIF	Operation Iraqi Freedom
OPLAN	operations plan
OPORD	operations order
O.R.	operations research
PIC	positive inbound clearance
P_k	probability of kill
PLS	palletized loading system
QSC	quartermaster supply company
RFID	radio-frequency identification tag
ROZ	restricted operating zone
RPG	rocket-propelled grenade
S1	personnel staff section (brigade and below)
S2	intelligence staff section (brigade and below)
S3	operations staff section (brigade and below)
S4	logistics staff section (brigade and below)
S5	civil military operations staff section (brigade and below)
S6	communications staff section (brigade and below)
SAF	small arms fire
SC(E)	sustainment command (expeditionary)
SRMOD	Scheduling and Routing Module
STB	special troops battalion
SUS	sustainment brigade
TASKO	task organization
TC-AIMS II	Transportation Coordinator's Automated Information for Movement System, Version II
TLW	Trans-Log Web
TMR	transportation movement release
TSC	theater support command
TTP	tactics, techniques, and procedures
U.S.	United States

VBIED	vehicle borne improvised explosive device
WARNO	warning order
wp	waypoint
XO	executive officer
$\forall$	math: for all
$\in$ / $\notin$	math: an element of / not an element of
Σ	math: summation
I	math: intersection
U	math: union
$\vert$	math: projected on
:	math: such that

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Appendix B: Force Protection Resource Allocation Model Formulation

$$\min \quad \sum_{c \in C} \sum_{l \in L_c} E_l[CSS\_CASUALTIES]$$

Subject to:

$$acc\_hazard_l = \sum_{a \in A|l} \sum_{\gamma \in \Gamma} scaled\_hazard_a \cdot composite^l_{a,\gamma} \cdot composite\_effect_\gamma^{u:u=u_a} \quad \forall c \in C : \forall l \in L_c,$$

$$prob\_not\_surviving_l = 0.9999997 - 0.999 \cdot acc\_hazard_l \quad \forall c \in C : \forall l \in L_c,$$

$$E_l[CSS\_CASUALTIES] = \overline{w} \cdot num\_transport\_trucks_c \cdot prob\_not\_surviving_l \quad \forall c \in C : \forall l \in L_c,$$

$$\sum_{\gamma \in \Gamma} composite^l_{a,\gamma} = 1 \quad \forall c \in C : \forall l \in L_c : \forall a \in A|l,$$

$$max\_jam_a - jam_f \geq 0 \quad \forall f \in F : \forall a \in A|f,$$

$$\sum_{\gamma \in \Gamma|jam} composite^l_{a,\gamma} - max\_jam_a = 0 \quad \forall c \in C : \forall l \in L_c, \forall a \in \bigcup_{f \in F} A|f,$$

$$\sum_{\gamma \in \Gamma|jam} composite^l_{a,\gamma} = 0 \quad \forall c \in C : \forall l \in L_c, \forall a \in A - \bigcup_{f \in F} A|f,$$

$$\sum_{\gamma \in \Gamma|helo} composite^l_{a,\gamma} - helo_c = 0 \quad \forall c \in C : \forall l \in L_c : \forall a \in A|l,$$

$$max\_patrol_a - \sum_{s \in S} patrol^s_r \geq 0 \quad \forall r \in R : \forall a \in A|r,$$

$$\sum_{\gamma \in \Gamma|patrol} composite^l_{a,\gamma} - max\_patrol_a = 0 \quad \forall c \in C : \forall l \in L_c, \forall a \in \bigcup_{r \in R} A|r,$$

$$\sum_{\gamma \in \Gamma|patrol} composite^l_{a,\gamma} = 0 \quad \forall c \in C : \forall l \in L_c, \forall a \in A - \bigcup_{r \in R} A|r,$$

$$\sum_{\gamma \in \Gamma|clear} composite^l_{a,\gamma} - \sum_{s \in S} clear^s_c = 0 \quad \forall c \in C : \forall l \in L_c : \forall a \in A|l,$$

$$\sum_{\gamma \in \Gamma|augment} composite^l_{a,\gamma} - \sum_{s \in S} augment^s_c = 0 \quad \forall c \in C : \forall l \in L_c : \forall a \in A|l,$$

$$\sum_{s \in B|r} patrol^s_r \leq 1 \quad \forall r \in R,$$

$$\sum_{s \notin B|r} patrol^s_r = 0 \quad \forall r \in R,$$

$$helo_c + \sum_{s \in S:home^s = origin_c} \left(clear^s_c + augment^s_c\right) \leq 1 \quad \forall c \in C,$$

$$\sum_{s \in S:home^s \neq origin_c} \left(clear^s_c + augment^s_c\right) = 0 \quad \forall c \in C,$$

$$max\_augment^s - augment^s_c \geq 0 \quad \forall s \in S, c \in C,$$

$$\sum_{c \in C} augment^s_c - \left(\frac{num\_guntrucks^s}{2}\right) \cdot max\_augment^s \leq 0 \quad \forall s \in S,$$

$$\sum_{f \in F} jam_f \leq 1,$$

$$\sum_{c \in C} helo_c \leq \frac{num\_helos}{2},$$

$$\sum_{r \in R} patrol^s_r + \sum_{c \in C} clear^s_c + max\_augment^s \leq 1 \quad \forall s \in S.$$

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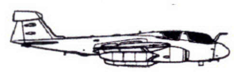
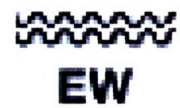
Appendix C: Force Protection Resource Doctrinal Missions and Tasks

jam		(global resource)

Resource type

Fixed-wing aerial platform, e.g., EA-6B Prowler or EC-130 Compass Call

Symbology



Sample tactical mission and task

Conduct air interdiction between 060900ZJUN2007 to 061800ZJUN2007 within restricted operations zone (ROZ) 123 by jamming remotely detonated IEDs emplaced on ground in order to protect friendly ground convoys from their effects.

Doctrinal Definitions

air interdiction – (DOD, NATO) Air operations conducted to destroy, neutralize, or delay the enemy's military potential before it can be brought to bear effectively against friendly forces at such distance from friendly forces that detailed integration of each air mission with the fire and movement of friendly forces is not required. Also called AI [12].

jamming – The deliberate radiation or reflection of electromagnetic energy to prevent or degrade the receipt of information by a receiver [12].

electronic warfare – (DOD) Any military action involving the use of electromagnetic and directed energy to control the electromagnetic spectrum or to attack the enemy. Also called EW [12].

electronic protection – That division of electronic warfare involving passive and active means taken to protect personnel, facilities, and equipment from any effects of friendly or enemy employment of electronic warfare that degrade, neutralize or destroy friendly combat capability. Also called EP [12].

restricted operating zone – (DOD, NATO) Airspace of defined dimensions, designated by the airspace control authority, in response to specific operational situations/requirements within which the operation of one or more airspace users is restricted. Also called ROZ [12].

helo

(local resource)

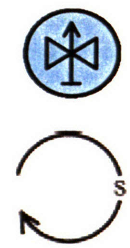
Resource Type

Armed helicopter platform, e.g., AH-64 Apache or OH-58 Kiowa Warrior

Sample tactical mission and task

At 061200ZJUN2007, secure convoy XYZ while escorting along specified route from LSA 123 to FOB ABC in order to protect convoy from threat ambushes along the route.

Symbology

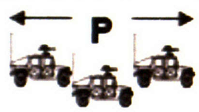


Doctrinal Definitions

escort – (DOD, NATO) A combatant unit(s) assigned to accompany and protect another force or convoy [12].

secure – (Army) A tactical mission task that involves preventing a unit, facility, or geographical location from being damaged or destroyed as a result of enemy action [12].

patrol



(global resource)

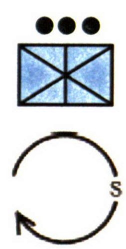
Resource Type

Motorized infantry platoon, e.g., military police or national guard infantry unit

Sample tactical mission and task

Between 061200ZJUN2007 and 062000ZJUN2007, conduct route security operations along MSR DENVER and BRONCOS to secure the routes for continuous logistical convoy operations.

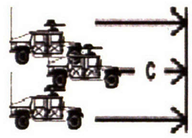
Symbology



Doctrinal Definitions

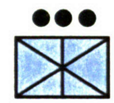
route security operations – A specialized kind of area security operations conducted to protect lines of communication and friendly forces moving along them [12].

secure– (Army) A tactical mission task that involves preventing a unit, facility, or geographical location from being damaged or destroyed as a result of enemy action [12].

clear		(local resource)

Resource Type

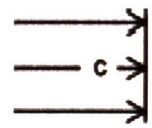
Symbology



Motorized infantry platoon, e.g., military police or national guard infantry unit

Sample tactical mission and task

At 061400ZJUN2007, clear the designated route from LSA 123 to FOB ABC for convoy XYZ in order to identify and remove any threat ambushes along the route.



Doctrinal Definitions

route reconnaissance – (Army) A directed effort to obtain detailed information of a specified route and all terrain from which the enemy could influence movement along that route [12].

clear – (Army) A tactical mission task that requires the commander to remove all enemy forces and eliminate organized resistance in an assigned area [12].

augment		(local resource)

Resource Type

Symbology

Armor protected ground vehicle with a light machine gun, e.g., up-armored highly mobile multi-purpose wheeled vehicle (HMMWV) or armored security vehicle (ASV). Note: these vehicles are taken from splitting up a motorized infantry platoon.

Sample tactical mission and task

At 060800ZJUN2007, secure convoy XYZ while escorting along specified route from LSA 123 to FOB ABC in order to protect convoy from threat ambushes along the route.

Doctrinal Definitions

escort – (DOD, NATO) A combatant unit(s) assigned to accompany and protect another force or convoy [12].

secure (Army) A tactical mission task that involves preventing a unit, facility, or geographical location from being damaged or destroyed as a result of enemy action [12].

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