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THESIS

AN EXPLORATORY ANALYSIS OF CONVOY PROTECTION USING AGENT-BASED SIMULATION

by

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June 2004

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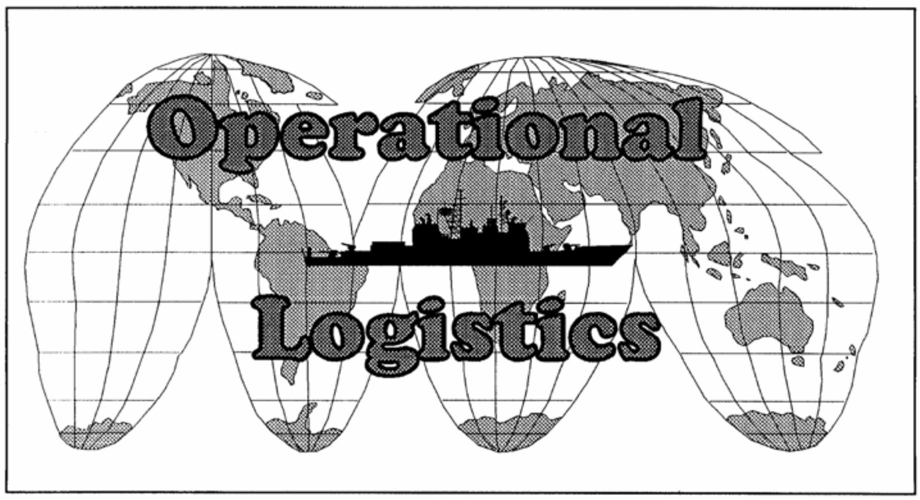
Amateurs discuss strategy, Professionals study logistics



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Recent insurgent tactics during Operation Iraqi Freedom (OIF) have demonstrated that coalition logistical convoys are vulnerable targets. This thesis examines the tactics, techniques and procedures (TTPs) used in convoy operations in an attempt to identify the critical factors that lead to mission success. A ground convoy operation scenario is created in the agent-based model (ABM) Map Aware Non-uniform Automata (MANA). The scenario models a generic logistical convoy consisting of security vehicles, logistical vehicles, an unmanned aerial vehicle (UAV) and an enemy ambushing force. The convoy travels along a main supply route (MSR) where it is ambushed by a small insurgent force.

We use military experience, judgment and exploratory simulation runs to identify 11 critical factors within the created scenario. The data farming process and Latin Hypercube (LHC) experimental design technique are used to thoroughly examine the 11 factors. Using the 11 factors 516 design points are created and data farmed over to produce 25,800 observations. Additive multiple linear regression is used to fit a model to the 25,800 observations. From the created scenario it is concluded that: convoy mission success may be determined by only a few factors; the actions of logistical vehicles are more critical than those of security vehicles; UAVs provide a statistically significant advantage; and ABMs coupled with LHCs and data farming are valuable tools for understanding complex problems.

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AN EXPLORATORY ANALYSIS OF CONVOY PROTECTION USING AGENT-BASED SIMULATION

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THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAV	Amphibious Assault Vehicle
ABD	Agent-Based Distillation
ABM	Agent-Based Model
ANOVA	Analysis of Variance
AOR	Area of Responsibility
APC	Armored Personnel Carrier
C^2	Command and Control
CAS	Complex Adaptive System
CSS	Combat Service Support
DTA	Defence Technology Agency (New Zealand)
EFCAT	Enduring Freedom Combat Assessment Team
FIST	Fire Support Team
GDL	Gunfire Detection and Location
GUI	Graphical User Interface
HMMWV	High Mobility Multipurpose Wheeled Vehicle
IED	Improvised Explosive Device
ISAAC	Irreducible Semi-Autonomous Adaptive Combat
LHC	Latin Hypercube
LOC	Lines of Communication
MANA	Map Aware Non-Uniform Automata
MCCDC	Marine Corps Combat Development Command
MCWL	Marine Corps Warfighting Lab
MEF	Marine Expeditionary Force
MOE	Measure of Effectiveness
MSR	Main Supply Route
NOLHC	Nearly Orthogonal Latin Hypercube
NPS	Naval Postgraduate School
NVA	North Vietnamese Army

OIF	Operation Iraqi Freedom
OMFTS	Operational Maneuver from the Sea
OR	Operations Research
PA	Project Albert
PK	Probability of Kill
R^2	Coefficient of Determination
RPG	Rocket Propelled Grenade
SA	Situational Awareness
SME	Subject Matter Expert
STOM	Ship to Objective Maneuver
TTP	Tactics Techniques and Procedures
UAV	Unmanned Aerial Vehicle
USMC	United States Marine Corps

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Finally and most importantly, I thank my family. Rebecca, Jacob and Lucas you have sacrificed our time together over the past two years so that I could accomplish this personal goal. I could never have completed this program without your support and understanding.

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EXECUTIVE SUMMARY

During Operation Iraqi Freedom (OIF) and the current nation building effort taking place, small guerilla type forces ambushed and continue to ambush coalition ground convoys. We can continue to expect small attack attempts on logistical convoys as long as coalition forces remain in Iraq. “Since the fall of Saddam Hussein, riding Iraq's roads has been risky business. U.S. military convoys have been targets for ambushes, and armed bandits have cruised the highways” [Riccardi and Sanders, 2004]. Furthermore, as the Iraqi’s are learning the lessons of past insurgent conflicts, we can assume that future enemies will also learn from the success of Iraqi insurgent tactics. For this reason, it is imperative we learn to better defend logistical convoys.

“Marine Corps training for convoy operations was commonly identified as a deficiency, to include training of primary staff members, convoy commanders, drivers and participants” [EFCAT, 2003]. Until recently, the protection of a convoy was given little thought when planning a logistical movement. Logisticians are now well aware that convoy protection lies at the forefront when planning a logistical movement. It is no longer a simple optimization problem of supply, demand and vehicle capacities.

This thesis develops a simulation utilizing an agent-based model (ABM) representing a ground convoy operation and identifies the vital parameters that contribute to mission success in our scenario. With the use of an agent-based distillation (ABD), which reflects the intention to model just the essence of a problem [Anderson, et al., 2003], this thesis provides insight into the characteristics of the parameters that can be varied to increase the probability of convoy mission success. In addition, this thesis provides another valuable scenario to support the simulation and data farming processes under development by Project Albert (PA). PA is a research and development effort of the US Marine Corps Warfighting Lab (MCWL).

The agent-based modeling environment, Map Aware Non-uniform Automata (MANA), was used to model convoy operations. The created scenario depicts a typical logistical convoy consisting of security vehicles, logistical vehicles and an unmanned aerial vehicle (UAV). The enemy agents consist of an observer, improvised explosive device (IED) and ambushers with individual rifles and rocket-propelled grenades (RPG). As the scenario runs, the convoy follows a pre-determined route where the enemy agents will eventually ambush them. Figure 1 displays the baseline scenario in MANA.

Figure 1. Baseline MANA Scenario (Best Viewed in Color).

There are hundreds of factors within a MANA scenario that can be varied to gain insights. Based on military experience, judgment and exploratory runs, 11 factors believed to be relevant during convoy operations were selected. Each of our 11 factors consists of multiple levels, which rules out the possibility of a full factorial experimental design. A Latin Hypercube Design (LHC) was used as the experimental design. The LHC design is a sampling technique where the goal is to sample the experimental area not only on the edges but also in the interior to maximize the space filling of the sampled area. [Cioppa, 2002] The LHC technique provides an efficient method to examine many factors each with multiple levels in an attempt to uncover any non-linearities within the response surface [Brown et. al., 2002]. Supercomputing assets were used to data farm the 11 factors, each consisting of 33 levels. Each design point is replicated 50 times, producing a final data set of 25,800 observations.

Linear regression is used to fit a model to the 25,800 observations. The final model consists of 14 relevant terms. Through common statistical analysis practices, we interpret each of the terms in the final model and relate them to the "real world." Though most of the results found from our research seem to be intuitive, we did find some interesting observations that could provide some insights to the tacticians in the field.

Based on our scenario, the following list summarizes our primary findings:

- The tactics and actions employed by logistics vehicles within our scenario are more of a success determinant than those of the security vehicles. In examining the critical term interactions within the model, it was discovered that if logistical vehicles remain on the route rather than seek concealment, the results are independent of the security vehicle actions.
- The use of a UAV can provide significant benefits to a convoy by providing more situational awareness to the vehicles.
- Combined situational awareness of surroundings can substantially increase the probability of mission success.
- The more that a convoy operates as a single unit, the greater the chance of mission success.
- The possibility exists that convoy mission success when an ambush is encountered can be determined by a few factors.
- Agent-based models offer us a tool that can help in understanding extremely complex problems.
- The data farming process is an exceptional technique for examining numerous variables with expanded levels.

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I. INTRODUCTION

A. MOTIVATION

Over the past year during Operation Iraqi Freedom (OIF) and with the current nation building effort taking place, the American people continually hear about the ambush of coalition ground convoys by small guerilla type forces. Now that coalition forces have transitioned the strategic goal from regime change to nation building and occupation, logistical movements have become routine and predictable. We can continue to expect small attacks on logistical convoys as long as coalition forces remain in Iraq. For the foreseeable future, ground logistical movements utilizing trucks for carrying supplies will remain the foundation of the transportation needs in an area of responsibility (AOR). While the simple solution to defend against enemy ambushes might seem to be heavily armored vehicles with massive amounts of firepower, this solution is by no means economically feasible for the time being. Although this thesis topic was motivated by recent events in Iraq, the author believes that as the United States (U.S.) Armed forces transition to a lighter, faster and more lethal force, the logisticians within the Armed forces will be forced to find ways to better defend logistical convoys. It can be assumed that future U.S. enemies will learn from the success of the Iraqi ambush techniques. For this reason, it is imperative we learn to better defend logistical convoys.

B. PURPOSE

The purpose of this thesis is to develop a simulation utilizing an agent-based model (ABM) representing a ground convoy operation in an attempt to identify the vital parameters contributing to mission success. History states that the enemy will attack logistical trains, yet it is still difficult to ensure their security. As seen since the beginning of OIF, and continually, as the conflict evolves into a nation building operation, convoys are the enemy's targets of choice. With the use of an agent-based distillation (ABD), which reflects the intention to model just the essence of a problem [Anderson, et al., 2003], this thesis will seek to provide insight into the characteristics of the parameters that can be varied to increase the probability of convoy mission success. In addition, this thesis will provide another valuable scenario to support the simulation and data farming processes under development by Project Albert (PA). PA is a research and development effort of the U.S. Marine Corps Warfighting Lab (MCWL) and will be discussed further in a later section.

C. BACKGROUND

In the current global atmosphere, no nation can match the combat power of the U.S. Armed forces in a head-to-head engagement. This past year has witnessed the Iraqis continuously attacking ground logistical convoys, indicating the adoption of a tactic of harassment in an attempt to prolong operations. Known as a "Fabian Strategy," a weaker force will avoid decisive battle with a more powerful or skillful enemy. While avoiding decisive battle, the side employing this strategy harasses its enemy to cause attrition and loss of morale. Employment of this strategy implies that the weaker side believes time is on its side, but it may also be adopted when no feasible alternative strategy can be devised [Hart, 1967]. This strategy derives its name from Quintus Fabius Maximus, who defended Rome against Hannibal in the Second Punic War (218-201 B.C.). The colonists during the American Revolution, the Confederacy during the American Civil War, the North Vietnamese Army (NVA) during the Vietnam War, utilized the strategy. Currently, it is evident that the Iraqis have adopted this strategy as a last resort to weaken the resolve of the American people and force the U.S. Government to withdraw from Iraq.

With future United States Marine Corps (USMC) doctrinal concepts such as "Sea-Basing," Operational Maneuver from the Sea (OMFTS) and Ship to Objective Maneuver (STOM) lurking on the horizon of the next decade, battlefield distribution planning becomes more crucial than ever before. Whether on the ground or at sea, the convoy operation is, and will continue to be, the primary means of transportation and a critical part of the overall logistical plan. Tactics used during OIF provide some insight into what the future holds for the U.S. war fighting playbook and identifies some of the problems we are likely to encounter. One such example, as the combat element moves quickly to reach ultimate objectives, we can probably expect the tactic of bypassing low threat enemy positions to continue to be utilized. This will no doubt cause great headaches for the logistical planners as they struggle to produce solutions for supplying the fast moving combat elements while simultaneously protecting logistical trains from those bypassed threats. With the use of an ABD, this thesis seeks to gain insight into how we can best defend logistical trains.

Recognizing that the current enemy, and most likely any foreseeable future enemy, will shy from decisive engagements, it is possible to use history as a guide to speculate that they will seek out the "soft targets." There are numerous "soft targets," but the obvious target is any type of logistical convoy supporting the forward combat troops. The simple nature and composition of a convoy makes it a vulnerable target. A convoy is typically slow and cumbersome with logistical vehicles that are lightly armored and armed, organic security and firepower tends to be disbursed, fire from any supporting arms may be limited, and it takes the enemy minimal resources to cause damage to the convoy. Support of large combat maneuvers requires enormous amounts of fuel, ammunition, rations, and so forth. Consequently, numerous convoys on the road offer the enemy multiple targets. After action reports, lessons learned reports and the history books from OIF, Vietnam and other past wars consistently reference the Tactics, Techniques and Procedures (TTPs) used during convoy operations as problem areas. During the United States Civil War both the Union and Confederate forces would destroy rail lines cutting the Lines of Communications (LOC) to the combat forces. During World War II (WWII), the Germans used U-boats to attack the weakly defended supply ships in the Atlantic. More recently and relevant to this thesis, the North Vietnamese Army (NVA) used ambushes to attack logistical convoys with great success. The Vietnam reference is particularly relevant. The NVA tactics were similar to the Iraqi tactics currently being employed. For example, the U.S. Army's 8th Transportation Group was frequently ambushed up until the winter of 1968 when they were forced to harden logistical convoys with the use of the somewhat homemade "Gun Trucks" to increase the amount of security within the convoys. This is interesting, as the U.S. Army is currently tinkering with this idea almost forty years later. The fact that there are numerous historical references regarding convoy security coupled with the reality of the continual struggle to defend the convoys provides the purpose for applying modern modeling techniques to this problem to gain insight into convoy protection. In order to minimize both human and equipment losses, it is necessary to harden the targets in the area of operations and deny the enemy the ability to project its will on the United States' strategic goals.

D. SCOPE

During the course of a ground convoy operation, it is possible to examine hundreds of parameters that might contribute to the success of the operation. Obvious items of interest may include equipment, tactics, communications, speeds and enemy actions. In an effort to confine this thesis to issues of reasonable examination, we refer the reader to the following analysis plan:

- Identify possible enemy courses of action, including known weapons utilized.
- Review practiced Tactics, Techniques and Procedures for convoy operations.
- Identify the appropriate measures of effectiveness.
- Explain the capabilities of the chosen modeling environment.
- Examine the construction of our ground convoy simulation model.
- Present the design of experiment for the simulation model.
- Explain data farming and its application to our ground convoy simulation model.
- Analyze and fit models to data output from the simulation runs.
- Examine the results of the data analysis and its usefulness in conducting ground convoy operations.

E. AGENT-BASED MODELS

Combat operations take place in an extremely dynamic environment where the human element plays a more prominent role than the technologies utilized. While technology and the weapon systems utilized are the means to an end, human interactions control these technologies and determine the ultimate outcome of a conflict. Unlike the traditional combat models that utilize physics and historical data to determine outcomes, ABMs attempt to model the human decision making element. Relatively new in the world of combat simulation, ABMs provide a tool that attempts to capture complex interactions between individual entities on the battlefield.

ABMs center on the individual entity, known as the agent and are not programmed to react in a prescribed manner. Rather, they are setup to have tendencies towards a certain reaction or behavior. The power of ABMs lies in the ability to quickly create scenarios, examine the outcomes of the adaptive properties of the agents and compile numerous scenario runs quickly. For this reason, ABMs appear to be ideally suited for modeling convoy operations in an unknown hostile environment.

F. PROJECT ALBERT

PA is a research and development effort of the United States Marine Corps Warfighting Lab, a branch of the Marine Corps Combat Development Command (MCCDC) in Quantico, Virginia. PA utilizes a vast array of experimental modeling tools to explore questions posed by military decision-makers. The goal of PA is to apply data farming techniques to an ABD in an attempt to explore the intangible factors of combat that influence a commander's decision-making process [Horne and Johnson, 2002]. Data farming is a method of investigating a large number of factors over a wide range of values. This technique allows the modeler to explore thousands of combinations of factors in an attempt to relate simulation outcomes to real life problems. For the record, PA does not proclaim to possess the ability to develop and run models for the purpose of prediction or to identify final answers to problems. Rather, PA seeks to gain insight into a problem through exploring a multitude of possible outcomes. For information on PA and past research done by PA, refer to their website at www.mcwl.quantico.usmc.mil.

G. GROUND CONVOY SIMULATION

The ground convoy simulation model created for this thesis will be fully described in a later chapter. To give the reader an idea of the composition of the simulation, a brief description is provided to ease in understanding the following problem description. The creation of the ground convoy simulation used Map Aware Non-uniform Automata (MANA), an ABM, as the modeling environment. The screenshot in Figure 2 displays the simulation in the midst of a simulation run. Blue trucks and armored personnel carrier (APC) icons represent the friendly convoy. Blue trucks are logistical vehicles while the APC icon represents the security element of a convoy. The red cross on the road represents an improvised explosive device (IED), the red artillery piece is an enemy rocket propelled grenade (RPG) type weapon and the red infantry icons are enemy agents with AK-47's. Detailed descriptions of the agents and information on how the scenario executes appear in a later chapter.

Figure 2. Ground Convoy Model (Best Viewed in Color).

H. THE PROBLEM

"Marine Corps training for convoy operations was commonly identified as a deficiency, to include training of primary staff members, convoy commanders, drivers and participants." [EFCAT, 2003] Until recently, the protection of a convoy was given little thought when planning a logistical movement. Over the past year, logisticians have been made aware that the protection of the convoy now lies at the forefront of movement planning and is no longer a simple optimization problem of supply, demand and vehicle capacities. While it might seem awkward for logisticians to be concerned with the tactics of combating an enemy ambush, it is pertinent because the logisticians are planning and conducting the majority of the convoy operations. During the course of a convoy operation, a convoy commander faces numerous decisions that can enhance the chance of success or lead to failure. While there are numerous decisions made during the operation, this thesis will focus only on those decisions made upon encountering an enemy ambush. Both the Army and the Marine Corps teach tactics for combating an enemy ambush at the Motor Transport schools. New technologies and an elusive enemy with less than traditional goals during the ambush engenders whether other ways might exist to employ these new technologies coupled with different tactics to defend these convoys better. This thesis will attempt to capture these loosely defined parameters in an ABD to try to gain insight into the critical parameters surrounding a convoy operation in a hostile environment. This thesis will apply data farming techniques to an ABD that models ground convoy operations during an ambush in an attempt to determine which parameters, such as security vehicle locations within a convoy, aggressiveness of security and the desire of a convoy to drive through an ambush or to stop, have the greatest effect on mission accomplishment in our scenario.

I. THESIS ORGANIZATION

Chapter II begins by detailing the basics of Marine Corps convoy doctrine, some of the currently practiced methods, and finally, some unclassified enemy tactical observations. Chapter III covers a detailed description of MANA and an in-depth description of how it works. Next, a complete description of the convoy simulation created for this thesis is discussed and how the parameters chosen relate to the "real world." This chapter also discusses the results from the base case convoy model runs. Chapter IV discusses the analysis methods used in interpreting the results of the model. Chapter V explains the simulation results and the models fitted. Chapter VI completes the thesis with a discussion of conclusions from the simulation and final model interpretations. This chapter also presents recommendations for future research.

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II. DOCTRINAL PRINCIPLES OF CONVOY OPERATIONS

"Determine what improvements to training and doctrine are needed to provide adequate convoy operations training and TTPs, to include security measures" [EFCAT, 2003]. The quote was listed as an area for further study in the reference. This chapter will begin by summarizing some of the historical insurgent tactics, identify relevant doctrinal convoy procedures, then move on to some of the observed enemy tactics being employed in the AOR. It should be noted that in an attempt to keep this thesis unclassified, current enemy tactics are covered vaguely from unclassified sources. For a more detailed exploration of some of the enemies TTPs, the reader is directed to relevant SIPRnet websites. In the interest of brevity, we will only cover doctrinal convoy practices that are pertinent to this thesis. For a complete listing of all doctrinal procedures, the reader is directed to the US Marine Corps Publication MCRP 4-11.3F, *Convoy Operations Handbook*.

A. INSURGENT TACTICS, TECHNIQUES AND PROCEDURES (TTP)

Though most of the reports detailing enemy ambushes in Iraq remain classified, we will attempt to identify some of the observed enemy tactics from unclassified sources. It has become evident that the enemy insurgents seem to be far more organized than previously suspected. It also appears that the insurgents may be applying some of the ambush techniques used by the Chechnyan's against the Russians and by Al-Qaida and the Taliban in Afghanistan against U.S. Forces, observed by a US Army 3^{rd} Corps Intelligence Officer [Krane, 2004]. If the Iraqi insurgents are utilizing historical guerilla tactics, then it is also safe to assume they are following the tactics of other past guerilla type forces. In this section, we will first cover some observed historical insurgent or guerilla tactics and some of the current observations from Iraq relating to convoy ambushes.

1. Historical Guerilla Tactical Observations

The Iraqi tactics currently being employed are characteristic of observed guerilla tactics of the recent past. Guerilla warfare can be defined as a set of tactics used by a minority group within a state to oppose a government or occupying force [Ipecki, 2002]. In most cases, it seems the goal of a guerilla force is to prolong a conflict, weakening the resolve of their opponent. The guerilla force uses terrorism and harassment to accomplish their goals. With extensive knowledge of their environment and terrain, they tend to be far more mobile than their enemy. They tend to be extremely self-reliant with little dependence on formidable lines of communication (LOC). Even in the face of ultimate defeat, they possess a strong will to carry-on the fight at all costs. In the provided reference, six 20th century guerilla conflicts were examined; some of the pertinent observations are listed below [Ipecki, 2002]:

- Guerillas tend to move and fight at night.
- They fight mostly offensively avoiding defensive strongholds.
- Guerilla attacks are typically conducted at close range.
- They rely on shock, surprise, speed and intelligence.
- They tend to attack from unpredictable positions, utilizing their vast knowledge of the terrain and environment to acquire speed and surprise.
- Guerillas typically gain intelligence through unconventional means having extensive communications and observation networks within the local populace.

The reference was written prior to OIF and did not examine the Iraqi tactics. However, one can look at the list and relate most of them to the current situation in Iraq.

2. Observed Iraqi Tactics Against Convoys

It is estimated that 1-5 percent of coalition convoys are attacked daily [181st Trans. Bn, 2003]. It is apparent that we are not dealing with a static insurgent group; the enemy is constantly evolving to counter our tactics and our use of modern technology. The insurgent's attacks are complex, well coordinated and are increasing in both number and sophistication. A presentation from the 181st Transportation Bn, lists some of the observed Iraqi tactics:

- The enemy insurgents are not easily identifiable; they seek to blend in with populace.
- They are often attacking the "soft" targets.
- They are using IEDs, small arms and RPGs in the attacks.
- They avoid decisive and sustained contacts.
- They attack the rear of convoys 70 percent of the time.
- They are practicing "hit-and-run" tactics.

- They are utilizing an extensive scout network to monitor convoy movements.
- The insurgent TTPs are constantly evolving; they select convoys which provide maximum damage to coalition.
- Their methods for IED employment is constantly changing.
- They seek to disrupt convoys with vehicles, civilians and natural hindering points of routes in attempt to slow the convoys down.
- The ambushes are typically command executed from observers.
- The small arms and RPG fire is usually directed at lead or trail vehicle.

The reader is advised that this is not an all encompassing list, specifically because the enemy continues to evolve. However, the insurgent's goals when an ambush is conducted seem to be remaining constant. They seek to stop movement, isolate desirable targets and kill coalition forces in an attempt to demoralize and weaken our resolve.

3. Coalition Convoy Defensive Tactics

It is assumed that current coalition tactics are probably somewhat different based on the unit, environment, terrain and organic assets. Since it is impossible to ascertain how every unit in the AOR is operating, we will briefly summarize some of the TTPs being practiced from the limited unclassified sources.

a. Convoy Layout

The 181st Transportation Battalion dictates having an experienced driver in the lead vehicle with some sort of gun truck or security vehicle directly behind the lead. Gun trucks were used extensively during the Vietnam conflict and have resurfaced in recent months to combat the growing threat to convoys. A gun truck in most cases is simply a logistical vehicle such as a 5-ton truck with automatic weapons mounted in the bed. Not only do they possess increased firepower but also act as a deterrent based on their intimidating posture. Figure 3 is a picture of one type of gun truck.

Figure 3. Vietnam Era Gun Truck (From: Army Transportation Association).

The convoy commander's vehicle should be placed centrally within the convoy to allow for enhanced command and control (C^2). The second security vehicle should be placed directly behind the commander's vehicle to guard flanks and act as a reserve if necessary. A third security vehicle should be the last vehicle in the convoy to enable over-watch of the entire column. All other combat logistic vehicles should be spread evenly throughout the serial. A serial is the name given for a single convoy. There should be 2-3 security vehicles per convoy and convoys with more than 10 vehicles should have 3 security vehicles. A few other current practices are listed below:

- No headlights on, only running lights.
- Take quickest lane or lane that allows for easiest travel. Reference claims that IEDs are statistically ineffective on vehicles moving faster than 40 mph with 50 meter dispersions between vehicles.
- Attempt to stay in middle of roads away from sides where IEDs could be placed.

- Gun trucks display tough and offensive posture.
- Gun trucks aggressively suppress small arms fire.
- Every member of a convoy is responsible for security.

Again, these tactics are strictly limited to the unit for which information was available. Research of other similar presentations by both the US Army and Marine Corps units report similar tactics and all seem to be somewhat typical and do not alter much from the provided doctrinal practices. During a visit to the I Marine Expeditionary Force (MEF) it was also stated that convoy sizes do not tend to exceed 20 vehicles in the current environment [Widdowson, 2004]. During the offensive phase of OIF, convoys were in excess of 20 vehicles as the combat units made their way from Kuwait to Baghdad. This thesis is examining the current operating environment.

B. MARINE CORPS DOCTRINE

In this section, we will cover prescribed movement formations, placement of vehicles, and actions upon altering types of ambushes.

1. Vehicle Movement

Logistical convoy movements are typically organized in some type of column with altering amounts of dispersion. Dispersion of vehicles is noted as of critical importance when trying to minimize the effects of an enemy attack. Some important considerations are that it is difficult for an enemy to bring large amounts of fire to bear on vehicles that are widely dispersed, mine damage is localized when dispersed and the efficiency of an enemy air attack is minimized. Convoy speeds are prescribed to be 5-10 miles per hour (mph) below the posted road speed limits depending on road conditions, weather conditions, vehicle capabilities and urgency of move. Listed below are the three doctrinal formations [MCRP 4-11.3F, 2001].

- Open Column – Used during daylight hours, vehicle dispersion is typically 50-100 meters, with a vehicle density of 10-15 vehicles per kilometer.
- Close Column – Used in darkness and when visibility is limited. Dispersion is typically 25 meters.
- Infiltration – Movement of dispersed, individual vehicles or units at irregular intervals. Prevents undue massing of vehicles and reduces traffic density. Used when security, deception and dispersion are the goal. This technique provides a passive defense against enemy observation.

2. **Immediate Action Drills**

a. Snipers

According to the *Convoy Operations Handbook,* snipers alone can do little damage to moving vehicles. However, a sniper can be used to try and stop a convoy and a larger ambush could follow. Actions to take when a sniper is encountered are as follows:

- Do not stop.
- Throw smoke to screen enemy observation.
- Provide suppressive fire.
- Be vigilant of potential future confrontations.

b. Air Attacks

Though enemy air attacks are not presently a concern the following is provided. Enemy aircraft will attempt to fire along the long axis of a convoy in an attempt to cause maximum damage on a single pass. Vehicles should drive off the road in a herring bone formation seeking concealment and attempt to return fire. The herring bone formation is displayed in Figure 4.

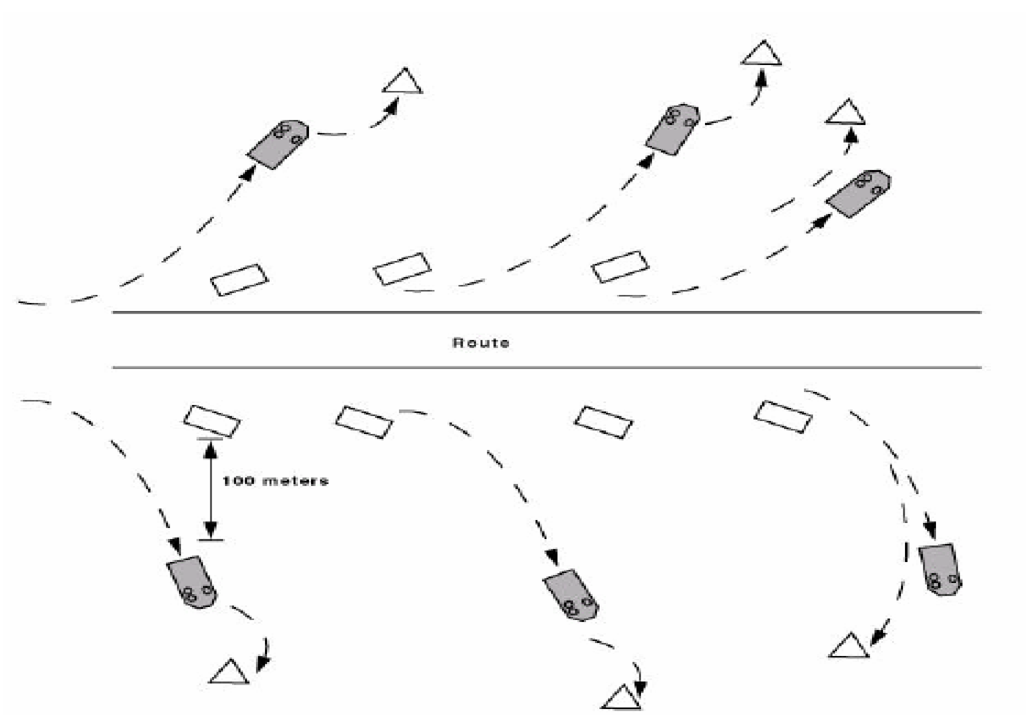

Figure 4. Herring Bone Formation (From: MCRP 4-11.3F, 2001).

c. Ambushes

Accordingly, the enemy ambush is described as the single greatest threat to a convoy's mission success and survival [MCRP 4-11.3F, 2001]. Enemy ambushes are categorized in two areas: unblocked and blocked.

During an unblocked ambush, vehicles caught in the kill zone should continue to move through. Vehicles that have yet to reach the kill zone should stop, seek cover and concealment and dismount. Armored security vehicles should find positions that enable providing suppressive fire and support the maneuver of the security forces. Security forces should then close with and assault the enemy based on rehearsals. Close air support and indirect fire assets should also be called in on the enemy.

In the case of a blocked ambush, vehicles not yet in the kill zone should stop, seek cover and concealment and dismount. Vehicles that are caught in the kill zone should conduct unloading drills and return fire and/or assault the enemy. Security vehicles seek positions to return fire and provide support for security forces maneuvering. Security forces should maneuver from outside the kill zone and assault enemy positions.

3. Convoy Security Forces

A convoy security element will typically consist of some type of armored vehicle with a mounted machinegun or MK-19 grenade launcher. Vehicles could be Amphibious Assault Vehicles (AAV), tanks or, more likely, armored High Mobility Multipurpose Wheeled Vehicles (HMMWV). MCRP 4-11.3F states that the mechanized vehicles, such as AAVs, are preferable as escort vehicles due to their firepower and protection from mines, indirect and direct fire. Though some type of mechanized vehicle would be ideal as an escort, the reality is that rarely will a Combat Service Support (CSS) unit have access to mechanized vehicles. It is conceded that every situation is different and there are probably incidences when this is not true, however, this thesis assumes that escort vehicles are armored HMMWVs.

a. Security Element Tactical Disposition

The number of escort vehicles per convoy in reality is probably based more on available assets than on doctrinal publications; however, MCRP 4-11.3F states that each escort vehicle should protect 5 to 10 convoy vehicles. Security during a convoy must be throughout the entire convoy and in all directions. For this reason security should be evenly dispersed amongst the convoy vehicles. A fire support team (FIST) should be located near the convoy commander and engineer assets near the front of a formation in order to deal with obstacles. A column formation as depicted in Figure 5 will normally be utilized due to its inherent speed and ease of movement.

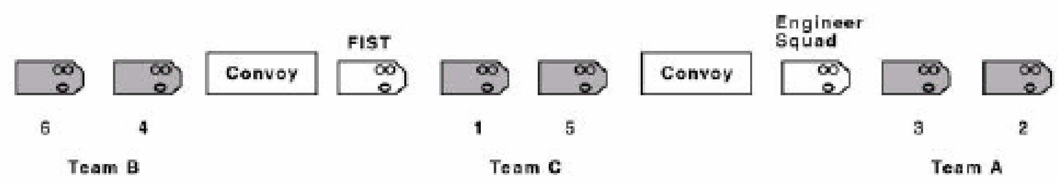

Figure 5. Column Formation. Teams A, B and C are an example of the security element dispersed throughout the column. Convoy blocks represent multiple logistics vehicles (From: MCRP 4-11.3F).

b. Security Element Actions Upon an Ambush

As mentioned before, the enemy ambush is the single greatest threat to the survival of a convoy, therefore the security element must be prepared to respond quickly, overwhelmingly and decisively. Security vehicles must be well rehearsed and clear on their responsibilities if an ambush is encountered. The following are escort vehicle actions when an ambush is encountered [MCRP 4-11.3F, 2001]:

- Upon enemy detection, escort vehicles seek covered positions between the convoy and enemy providing the maximum amount of fire possible (see Figure 6).
- The remainder of the convoy continues to move along the route at the highest possible rate of speed.
- Armed convoy vehicles return fire until escort or security vehicle is in position.
- Damaged or disabled vehicles should be abandoned and pushed off the route.
- If available, escort vehicle leader will call for fire support.
- Once the convoy is clear of kill zone, escort vehicles will either, based on escort composition and enemy strength, continue suppressive fire while waiting on additional forces, assault the enemy or break contact and move out of kill zone.

The *Convoy Operations Handbook* goes on to explain actions the security element takes during halts, obstacles and how to provide area security. These details will not be covered due the fact they are not relevant to the scenario created for this thesis.

We have briefly discussed some of the historical aspects of insurgent groups, some of their observed tactics, doctrinal principles of convoy operations and finally some of the observed Iraqi tactics as well as some coalition TTPs being practiced to combat the evolving threat. It is clear that our current enemy is extremely intelligent and adapts to the environment. It is also evident that they are learning from past conflicts, it is imperative that our forces take advantage of the mass amounts of lessons learned files compiled from previous conflicts.

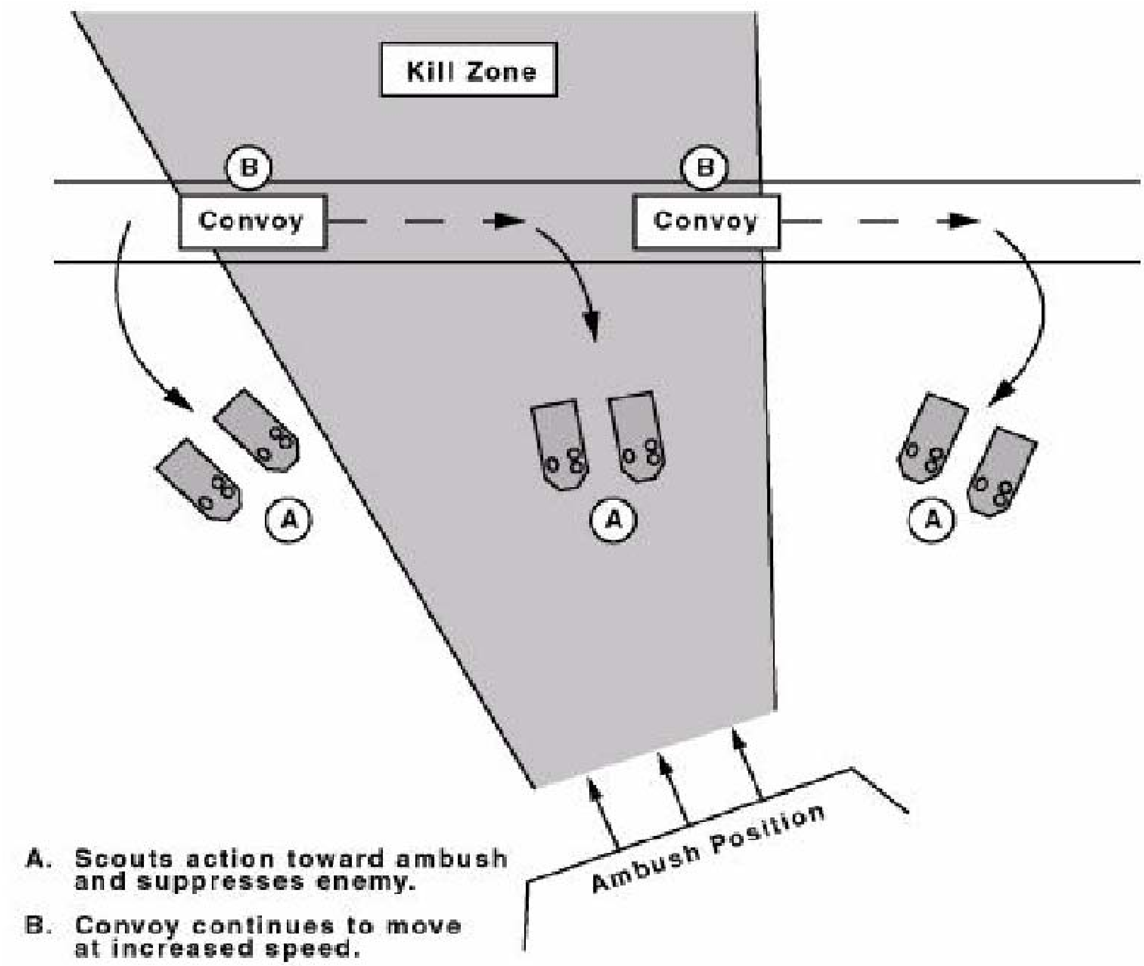

Figure 6. Security Actions Upon Ambush (From: MCRP 4-11.3F)

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III. MODEL DESCRIPTION

The agent-based modeling environment, MANA, was chosen for this thesis to model convoy operations. This chapter covers MANA in detail including; the history, the purpose, why it was chosen as the modeling environment and key features within MANA. In the interest of brevity, we will cover the key features of MANA are covered as they relate to our ground convoy scenario.

A. MANA

One of the many desirable aspects of MANA is the easily understandable user's manual that accompanies each new version of the program. Most of the information relating to MANA in this chapter is taken from the April 2004 version 3.0.35 user's manual.

1. MANA Overview

"It's the unconquerable soul of man, and not the nature of the weapon he uses, that ensures victory." [General George S. Patton] This quote simply summarizes why the MANA developers were frustrated with conventional physics-based combat models and began exploring ways to model the intangible aspects of combat. Many aspects of combat can be modeled using physics, such as; the impact point of a projectile, the explosion radius of an artillery round or the amount of fuel needed to get an aircraft into flight. Physics-based models cannot model the behavior of troops in combat which can be argued to be far more decisive in combat than the knowledge of where a round impacts. In the conventional models such as JANUS, the entities' decisions are programmed and completely deterministic in nature. These facts led the developers to the following observations,

> Behaviour of troops in any kind of scenario plays an important role, but it is often overlooked by analysts because human nature is a mathematical intangible, just as is the weather. As with many other intangibles in analytical combat models, it is often thrown away in favour of dwelling on infinitesimal details, often of little real importance to a given scenario. Generally speaking, there seems to be a school of analysts who believe that just because they have an equation to describe some aspect of a scenario, then that aspect must be more "real" than the aspects of the scenario that cannot be so easily described. We would argue that is precisely the aspects that are most difficult to describe which are of the

greatest importance. So much in war is intangible, and these intangibles are spoken about so often it is impossible to ignore them [Anderson et al., 2004].

MANA is based on two key ideas [Anderson et al., 2004]:

- That the behaviour of the entities within a combat model (both friend and foe) is a critical component of the analysis of the possible outcomes.
- That we are wasting our time with highly detailed models for determining force mixes and combat effectiveness [Anderson et al. 2004].

MANA was developed by New Zealand's Defence Technology Agency (DTA) with initial work beginning in February 1999 after the US Marine Corps chief scientist Dr. Alfred Brandstein and colleague Dr. Gary Horne made a visit to DTA. During the visit, DTA was introduced to the models ISAAC and EINSTein. Using these models DTA explored how automation models could be used for analysis. In 2000, DTA used a program in MATLAB in an attempt to increase the sophistication of the automation models using a concept of a "situational awareness map." Later in 2000 it was discovered that the MATLAB environment lacked the programming flexibility to meet the task at hand. DTA then turned to building a new model in the Delphi Object Pascal Language. The result is the MANA model. Many of the original concepts in MANA were derived from the ISAAC model [Anderson et al., 2004].

2. Why MANA

MANA was developed with the ability to quickly set-up scenarios and observe global behaviors that emerge from many local non-linear interactions between entities. "MANA is not intended to be able to describe every aspect of a military operation. Furthermore, there is no built-in "intelligence" that determines the plan that MANA entities are working towards. Consequently, careful thought must be given when setting up a scenario" [Anderson et al., 2004]. The MANA user must have a particular aspect of combat in which the designed scenario is modeling and what the agents are trying to accomplish. Although this might seem to add an element of scripting "the non-linear nature of the model ensures that, regardless of the modeller's preconception, a startlingly large number of outcomes are possible" [Anderson et al., 2004].

MANA is not the answer for all combat modeling and does have some limitations. One such limitation is in the exploration of strict combat formations. Formations are difficult to model in MANA, and will typically appear in a scenario by accident rather than by design. Though this might seem to be a problem at first, these occurrences add to the randomness of human behavior and can be expected in "real life" [Anderson et al, 2004]. MANA offers the ability to quickly examine many different ways of doing things rather than one perfect or supposed perfect way. For this reason MANA lends itself well to modeling convoy operations and examining the outcomes of many different combinations of factors. Logistical convoy formations are few in practice, typically a single file line of vehicles, but the actions of the vehicles when enemy contact is encountered are infinite. MANA enables us to vary numerous factors controlling the convoy in an attempt to identify what combinations of factors seem to produce the best results in the MANA scenario.

Ultimately, MANA was chosen for this thesis for several reasons. First, there are an infinite number of factors which contribute to the success or failure of a convoy, MANA provides an environment in which many of these factors can be varied. Second, the actions that a convoy might take when enemy contact is encountered, is described in the simulation community as a "change in state." MANA provides an extensive ability to alter agent desires when a state change is encountered. Third, MANA is extremely user friendly and easily learned from the user manual and by trial and error. Finally, the purpose for why MANA was created grasps the essence of what this thesis hopes to identify. There are many physical aspects of a convoy that could probably be modeled with physics-based simulation environments, such as, armor and weaponry, but a conventional model would have difficulty combining these two factors with numerous others to identify global effects of many local relationships.

B. FEATURES OF MANA RELATED TO OUR SCENARIO

Here we will go into detail describing the inner workings of MANA and how they are used to construct our ground convoy model. The MANA user has the capability to alter numerous items in a scenario; we will only cover those items which are used for our scenario. In this section, we will cover squad creation and those created for our scenario. Parameters that are varied in our scenario, including their ranges and relation to the "real world," are listed in Appendix A. For a complete listing of MANA features, the reader is referred to the MANA version 3.0.35 user's manual.

1. MANA Settings Tabs

When building a scenario in MANA there are nine tabs that the user must be familiar with in order to create a scenario. These will be detailed below. Within the tabs are four main areas where settings can be made to determine how a squad acts, shoots, communicates and moves. The reader is referred to Figure 10 where at the top of the figure the nine settings tabs are displayed.

2. Situational Awareness (SA)

Before we attempt to explain our scenario and the inner workings of MANA it is important to explain the squad SA and inorganic SA concepts. The SA map displayed in Figure 7 is used to simulate communications between agents and squads. Squads are comprised of individual agents with identical properties; multiple squads can be created that are friendly to each other using the allegiance settings. Memory is shared between squad agents using the situational map. The map is updated instantaneously when a squad member detects other agents. The situational awareness map acts as a collective picture of sensor information within the squad. Information on the squad's SA map can be shared with other squads using the inter-squad communications options. Information passed via inter-squad communications are stored on a separate map, known as the inorganic situational awareness map displayed in Figure 8. Squad agent's personality parameters can be created to determine responses based on information from both the squad SA map and the inorganic SA map. MANA utilizes a color and geometric figure scheme to portray detections on the map. Squad friends are shown as inverted triangles, other friends as upright triangles, enemies and unknowns as colored and white boxes respectively and finally neutrals by diamonds. Colors red, yellow and light greys are used to identify a contact's threat level, which is specified by the user. The inorganic SA map shown in Figure 8 is similar to the SA map, the difference being that there is no "Show Squad Friends" option. This is removed due the fact that an agent or squad receiving third party contact information cannot confirm that a contact is a squad member [Anderson et al., 2004].

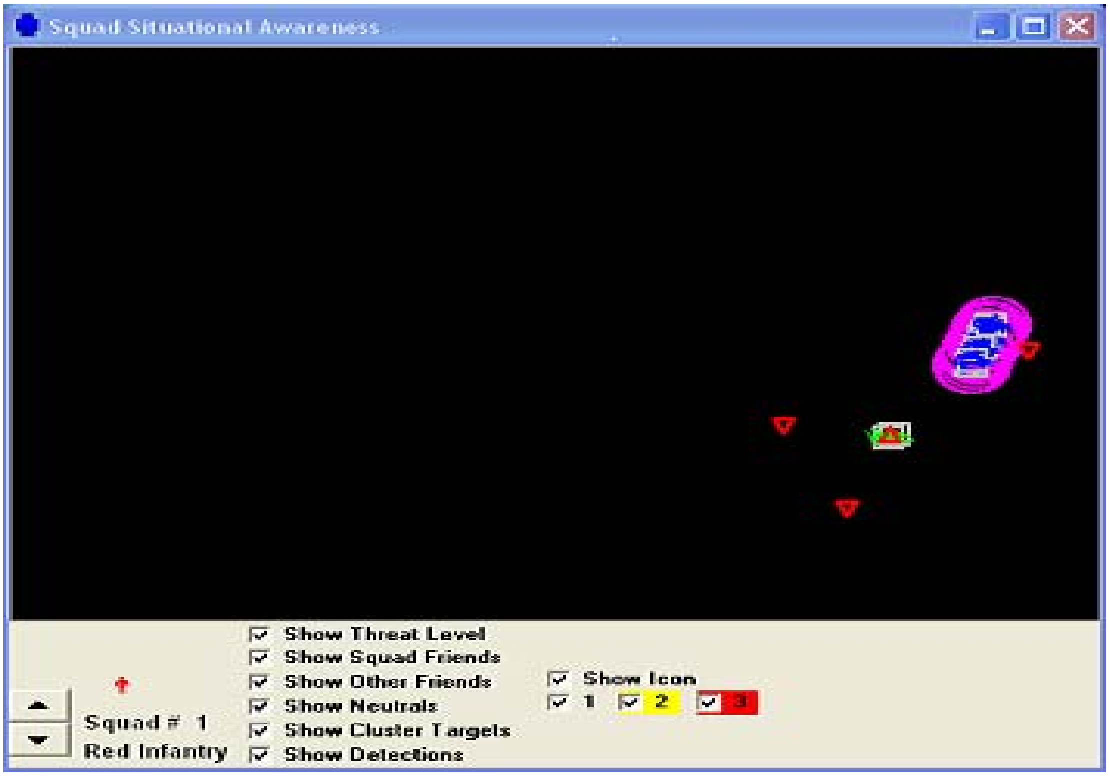

Figure 7. Squad Situational Awareness Map (Best Viewed in Color).

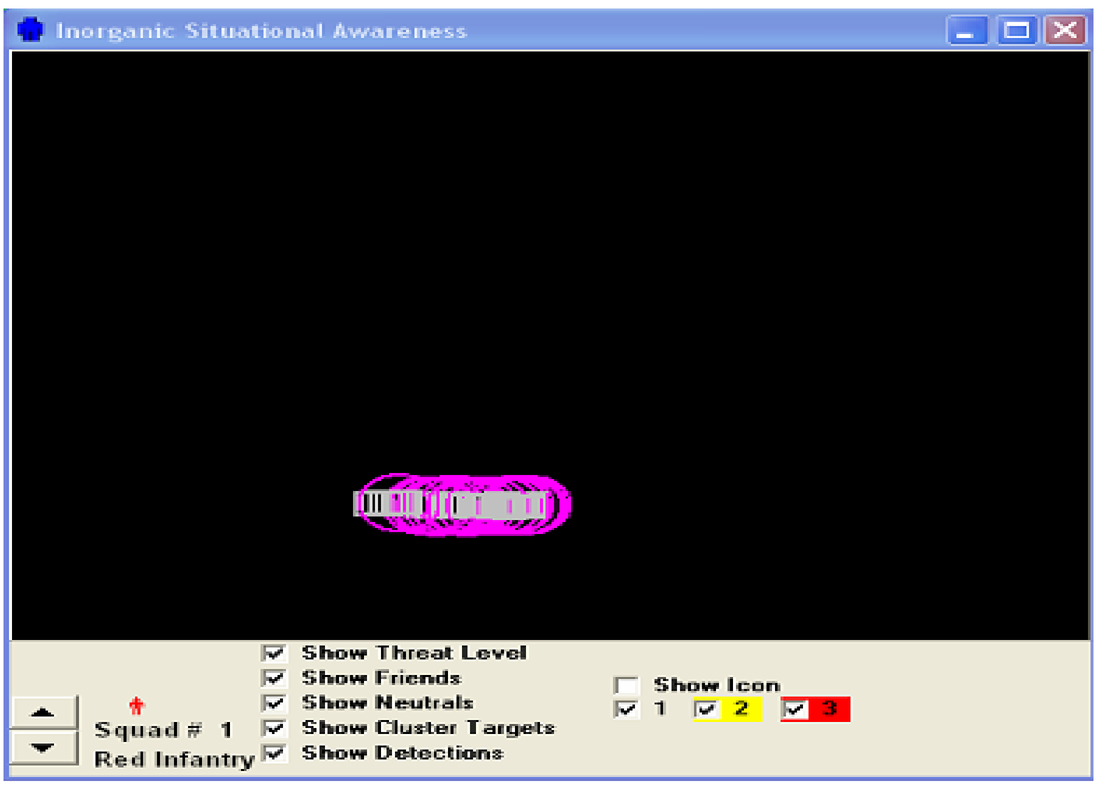

Figure 8. Squad Inorganic Situational Awareness Map (Best Viewed in Color).

3. Workings of Our Ground Convoy Scenario

Figure 9 displays the base scenario created for this thesis. The terrain represents the outskirts of an urban environment. There are no elevation changes in the terrain other than man-made structures represented by the grey polygon figures. The buildings cause line of sight and movement problems for the blue convoy. In an attempt to simulate the enemy having the advantage of home terrain, the buildings do not affect their movement or line of sight.

The blue convoy starts at the bottom left of Figure 9 and follows a prescribed route to the top right side of the screen. The scenario runs for 4000 time steps. This is not altered in any of the runs. The blue convoy consists of seven MANA squads, two squads of logistical vehicles, three squads of security vehicles, one unmanned aerial vehicle (UAV) and one squad designated as an agent to kill the red observer. The red forces consist of four MANA squads, one squad of infantry, one squad with a rocket propelled grenade (RPG), one squad depicting an observer or scout and one squad that acts as a stopping condition for the scenario. Each run begins with the blue vehicles in a relatively similar location; red forces are placed somewhat randomly within a specified area of the screen. Each squad's parameter settings will be examined more thoroughly later in this chapter.

At the start of a simulation run, the blue convoy moves across the bottom of the screen into the more urban area following the yellow road to the top right of the map depicted in Figure 9. The red agent depicted by a telephone pole icon represents an enemy observer. The observer's purpose is to detect a blue convoy moving along the route, alert other ambushers and arm an IED placed on the road, represented by an addition sign. Once the ambushers are alerted of the convoy they will move towards the road and attempt to fire on the blue agents.

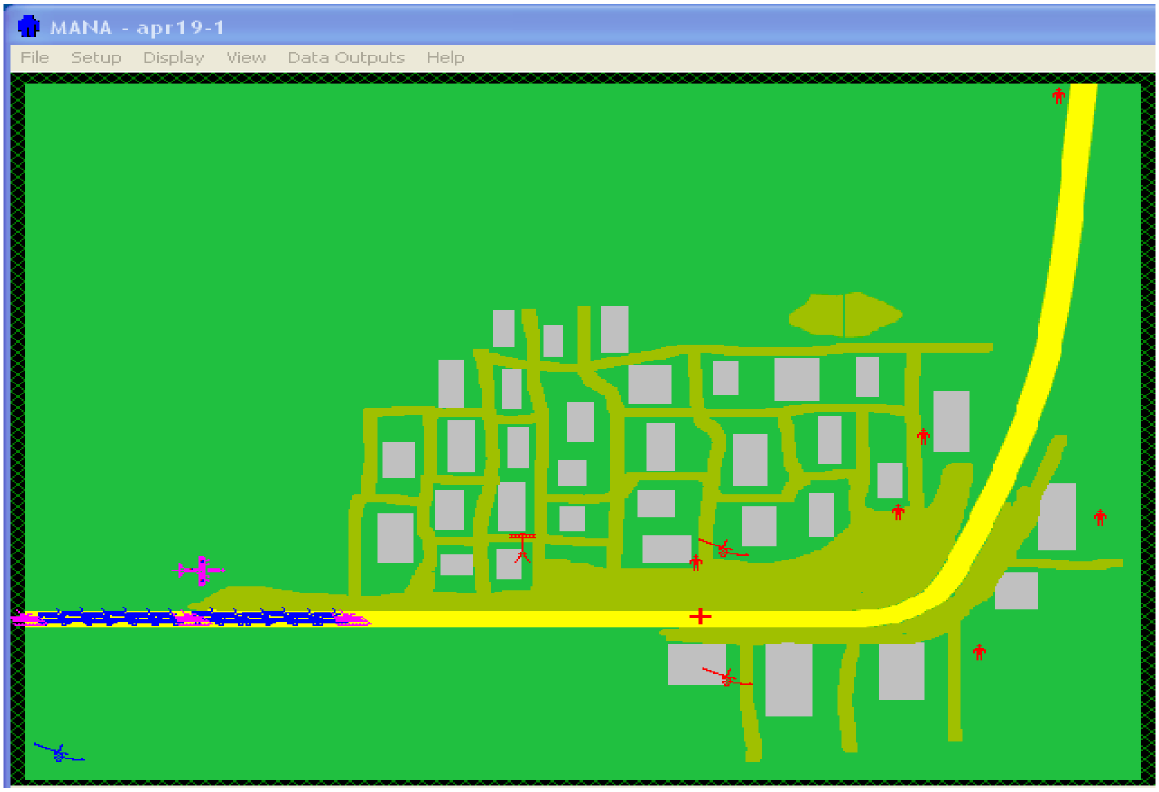

Figure 9. Ground Convoy Scenario (Best Viewed in Color).

4. MANA Squads

A squad in MANA is a group of agents with size set by the user from 1 to 1000. Agents within a squad share the same properties and can be set up to change properties in different states, where a state is simply a set of parameter values that determine an agent's desires or behaviors. The parameters altered for our squads are covered in Appendix A. The squads created for this thesis are listed in Table 1.

Squad #	Squad Name	Allegiance	# of Agents	Description	Icon
1	Red Infantry	Red	5	Infantry with AK-47	Soldier
2	Blue Back	Blue	6	Logistics vehicles	Truck
3	IED	Red	1	Explosive Device	Addition sign
4	BlueUAV	Blue	1	UAV	Airplane
5	RedRPG	Red	2	Infantry with RPG	Artillery piece
6	BlueFront	Blue	6	Logistics vehicles	Truck
7	Stop Condition	Red	1	Indicates when Blue reaches goal	Soldier
8	BlueSecurityFront	Blue	1	Armored HMMWV	APC
9	BlueSecurityBack	Blue	1	Armored HMMWV	APC
10	BlueSecurityMiddle	Blue	1	Armored HMMWV	APC
11	RedObserver	Red	1	Scout	Telephone Pole
12	ObserverKiller	Blue	1	Fires on Red Observer	Blue artillery piece

Table 1. Ground Convoy Squads.

Figure 10 displays the general properties tab of MANA, where the creation of a squad begins. On this screen, squads are given names, the number of agents in the squad is established and set to active or inactive. Also on this screen the user may perform other administrative type tasks such as saving, copying and loading squads.

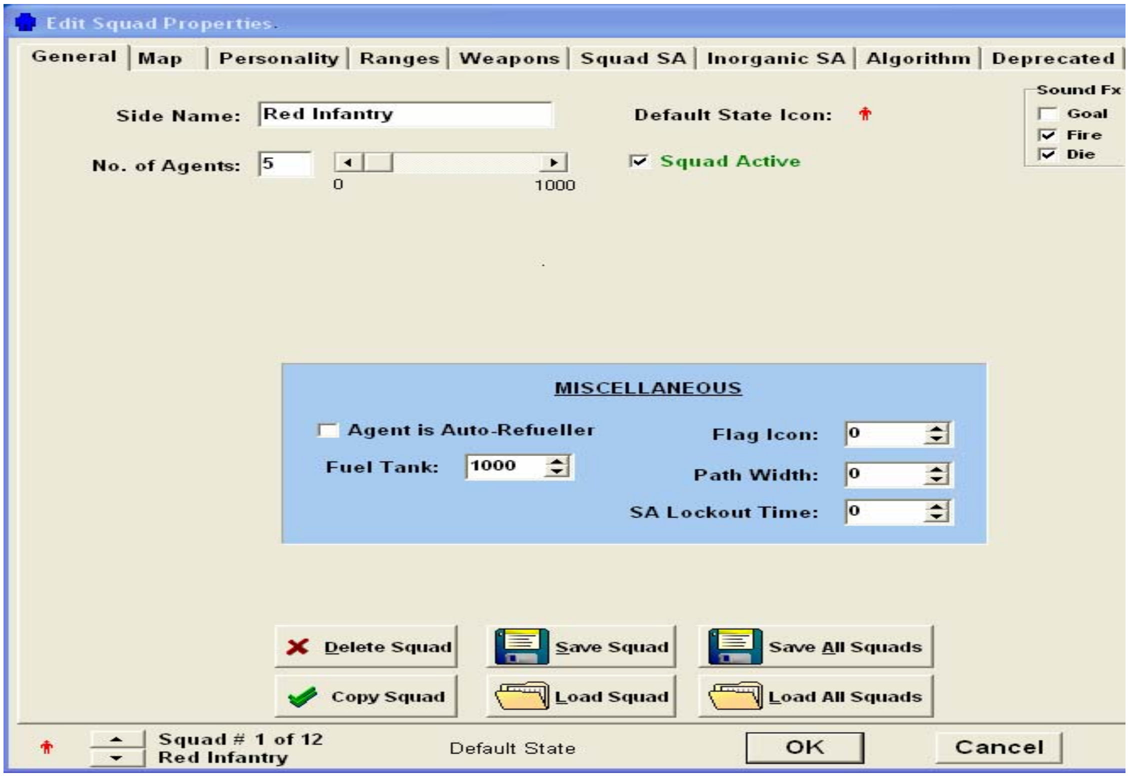

Figure 10. General Properties Tab.

5. MANA Terrain

MANA terrain is based on pixels or cells which can vary in number from 50^2 to 1000^2 pixels; the default terrain is a 200 x 200 grid, our scenario uses a 1000 x 1000 pixel grid. A MANA map file is based on a standard Windows bitmap. Cell colors can be altered to influence agent movements. The default battlefield provides five preset terrains that can be altered to affect movement. Cells can be manipulated to restrict or allow free movement, provide cover and concealment, affect lines of sight and act as barriers. In previous versions of MANA each cell could only be occupied by a single agent, this is no longer the case; the user has the option of allowing more than one agent in a cell.

Though MANA provides five preset terrains, the user can specify other terrains to achieve a desired movement or line of sight effect. We will cover the five preset terrains to give the reader an idea of how terrains affect the agents in a given scenario.

- Billiard Table – Default terrain that has no special properties affecting agents, movement and line of sight are unrestricted. Appears black in color.
- Easy Going – Terrain representing roads or other regions that are particularly desirable for agents to move along. Easy going terrain appears yellow in color. Agents can be created to have a desire to move along an easy going terrain.
- Wall – Acts as an obstacle for agents and appears grey in color. Agents can not occupy a cell that is set as an obstacle. Obstacle cells can also restrict line of sight if this option is turned on.
- Light Brush/Dense Brush – Acts as vegetation and appears green in color. Altering the density can affect speed of movement as well as providing cover and concealment from fire and observation.
- Hilltop – Terrain that offers high degree of concealment appearing dark grey in color.

It is important to reiterate that the user has the ability to specify their own terrains establishing how the terrain affects the agent. Agents can also be parameterized to either desire or avoid specific terrains. Figure 11 displays the MANA *map tab* where all terrain modifications are made.

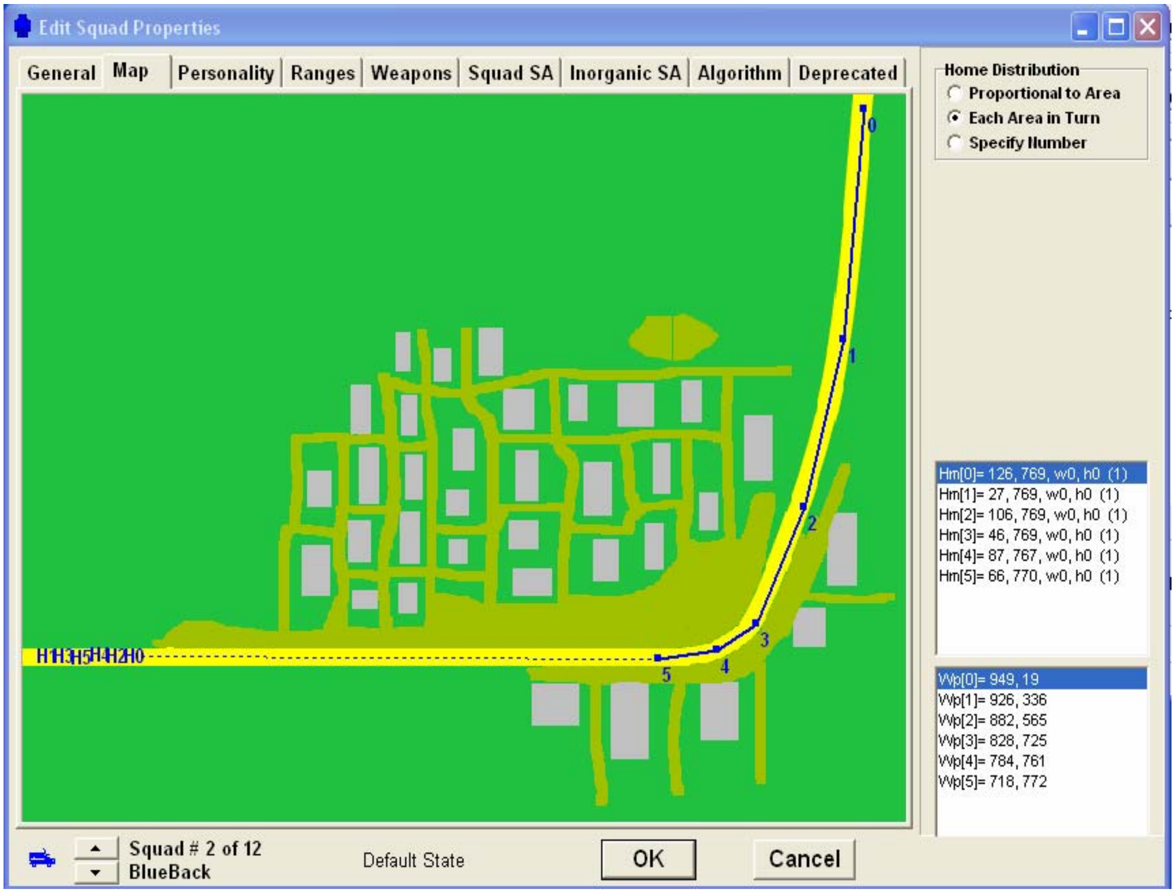

Figure 11. Map Tab (Best Viewed in Color).

The scenario map is displayed here giving the user the capability to establish starting points for each squad. The user may manually enter (X, Y) coordinates for starting locations or simply point and click with the mouse. The user also has the ability to establish exact points for the start locations or to have the agents placed randomly within an area. Once starting locations are established for each squad, waypoints can then be established for the agents to move towards if desired.

In our scenario, the convoy agents are placed on the left hand side of screen along the road in a linear formation. Each blue agent is placed in nearly the same location at the start of each run. Waypoints were established along the road identifying the convoy route. Although this seems to predetermine where the blue agents will go, this is reality. Before any real convoy hits the road, a preplanned route and order of march will be established [MCRP 4-11.3F, 2001]. The enemy agents are placed a bit more randomly within the urban area. At the start of a run the enemy agents will meander around toward set waypoints until notified of the blue convoy approaching.

6. Squad Personalities

In Figure 12 the personality properties tab is displayed. The personality tab is the primary area for establishing an agents' propensity towards certain actions. The personality settings available for manipulations are identified in four categories; agent situational awareness, squad situational awareness, inorganic situational awareness and move constraint. Under the *Agent SA* settings, the user may define how the agent as an individual performs. In the *Squad SA* area, personality weightings can be established for how the squad acts as a unit. In the *Inorganic SA* area weightings are established determining how agents act when information is received from other friendly agents outside of their squad. The *Move Constraint* settings do exactly that, they set constraints on the agents movement based on a user defined criteria.

The agent situational awareness personality weightings determine how an agent will respond to other entities appearing on the SA map. Weightings can be varied between -100 and 100. The higher the weighting value, the greater the desire an agent has towards the respective action. Alternately, the more negative a weighting the more an agent is repulsed. For example, if a value of 100 is placed in the *easy going* box, an agent will strongly desire to stay on terrain which allows for easier movement.

The squad situational values are parameters, which can be altered based on information held by an agent's parent squad. An agent can display personality traits based on what another agent within the squad detects. For example, if the enemy threat 1 box was given a setting of 10, then if any other agent within the squad detected an enemy with a threat of 1, the whole squad would have a desire to go towards that enemy detection.

The inorganic situational awareness parameter settings are similar to the squad SA settings. Detections made by all friendly agents in the scenario are placed on the inorganic map through a user created communications link. The user can then specify parameter settings for an agent's reaction to information received inorganically.

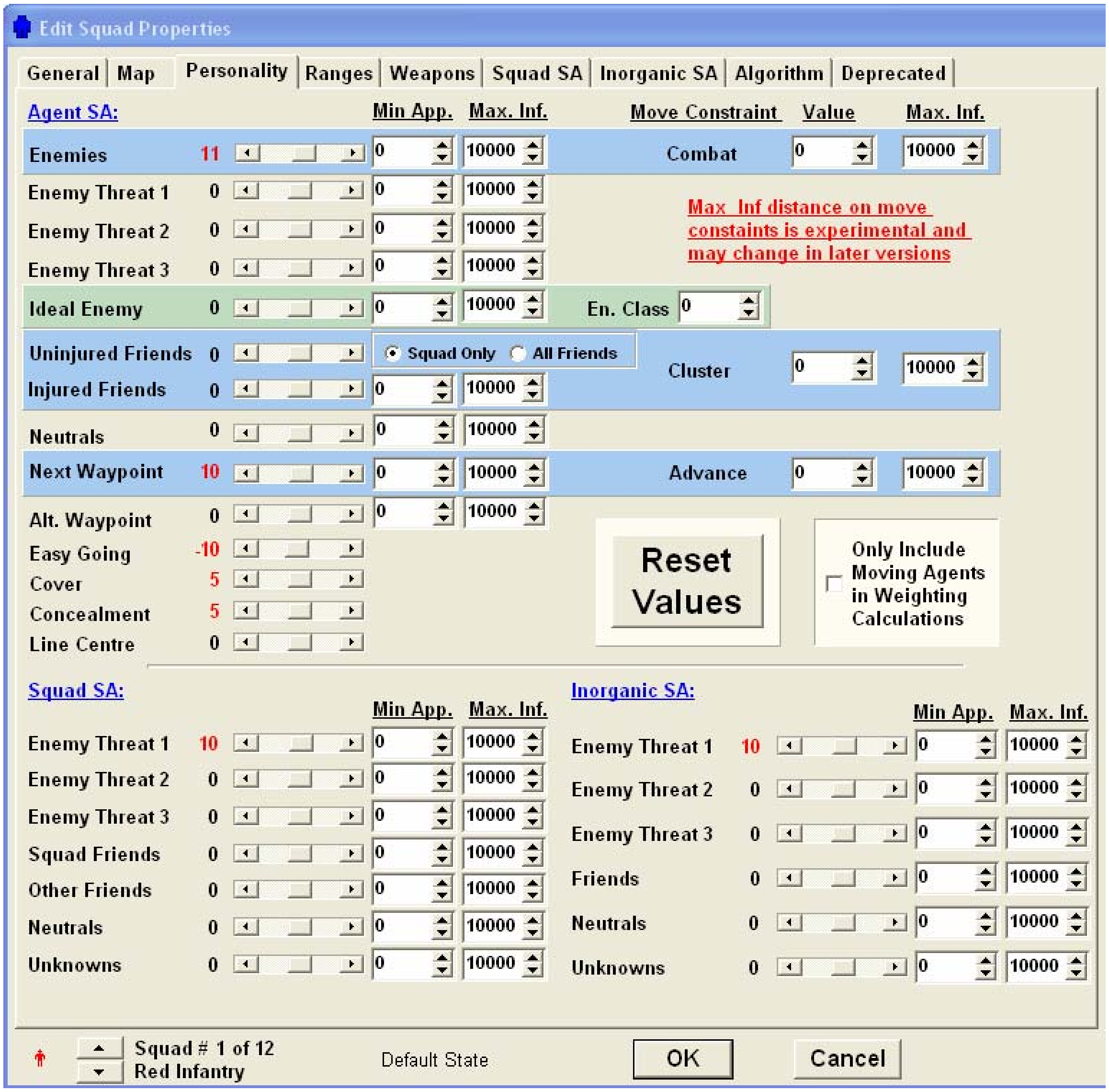

Figure 12. Personality Setting Tab.

The *move constraint* set of parameters are designed to affect movements based on a particular set of criteria. There are three selections for the user; *combat*, *cluster* and *advance*. The *combat constraint* allows the user to ensure that agents will not advance on an enemy without a numerical advantage. The *cluster constraint* allows the user to prevent clusters of friendly agents from building up beyond a specified number. The *advance constraint* is intended to prevent squads from advancing towards their next goal without a specified number of friendly agents within sensor range.

For most of the personality settings there is a selection for *minimum application distance* (Min App.) and *maximum influence distance* (Max App.). These selections are designed to set upper and lower bounds on the distance for which entities within that distance are included in the calculation for the associated personality weighting.

Also within this tab, shown in Figure 13, is the trigger state selections panel. A state can be selected and then appropriate personality weightings altered as desired by the user. For example, if the *Shot At(Pri)* state is checked, the user might want an agent to seek cover and concealment rather than stay on the road when fired upon. There are multiple trigger states available, many of which are based on how an agent is informed of an occurrence.

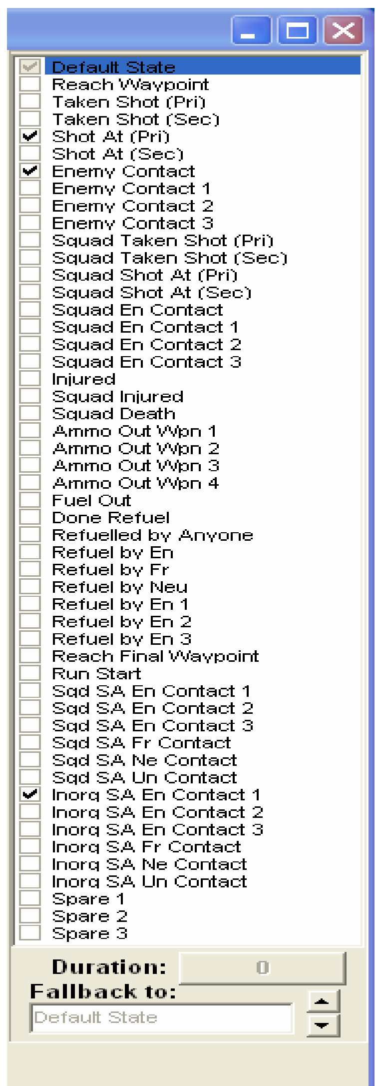

Figure 13. Trigger States.

In our scenario, blue agents begin a run with the desire to move toward the *next waypoint* while staying on *easy going* terrain and staying within an established distance of uninjured friendly agents. Trigger states are used extensively in our scenario. Logistical vehicles represented by the truck icon will move along the route until itself, their squad or another friend encounters enemy contact. If any of these state changes take place, the logistical vehicles will be kicked into the *spare 1* state where their personalities can be varied along with the time they remain in the state. Appendix A covers the weightings that are varied along with a detailed description of each factor. Blue security vehicles have similar personality weightings at the start of each run and utilize the trigger states in the same manner as the logistical vehicles. Again, Appendix A covers the personality weightings, which are varied for the security vehicles. The *cluster constraint* along with *minimum application* and *maximum application* distances of the *uninjured friends* weightings are utilized to force the convoy to travel along the route in positions relative to where they started. This option seems reasonable, as it is rare that vehicles would pass each other while traveling under normal circumstances.

Enemy ambush agents are established to begin a run desiring to meander toward established waypoints near the convoy route. It is assumed that the enemy will have a point of ambush designated and move towards it when notified of a convoy approaching. The enemy observer is placed in an area where he will always detect the convoy on the route, it is assumed that the enemy scout will locate itself on a vantage point where there is observation of the relevant route. Once the convoy is detected, ambushers are notified and are kicked into a state where they desire to locate and fire on the convoy. Located along the route is an IED, which is armed by the enemy observer. The IED will detonate at random point along the convoy.

The last two blue agents to cover are the UAV and the observer killer squad. A UAV will fly along the main supply route (MSR) in front of the convoy. The UAV's goal is to detect enemy agents and alert the convoy, kicking them into an enemy contact state. Characteristics of the UAV such as speed and detection capabilities are varied in the data farming environment. The observer killer squad has one mission, to fire on the red observer agent if the UAV detects the observer. It is assumed that an enemy scout or observer would be difficult to detect in the "real world," to model this, the red observer possesses a high *stealth* value and will rarely be detected. In the event he is detected, we needed a way to simulate the observer being neutralized by either a reaction team, air attack or some other means. In an attempt to keep the model as simple as possible an indirect fire weapon (observer killer) was set up to fire only on the red observer and only if he is detected by the UAV.

7. Ranges Tab

Similar to the personality properties tab, the ranges tab is dependent on a squad's current state. Figure 14 displays the ranges tab. The ranges tab allows for general settings such as the icon representing an agent within a squad, the *allegiance* and *threat level* of a squad and the squad's *movement speed* in the selected state. The enemy interactions selections allow for setting the *number of hits to kill* an agent, the *stealth* and *armor thickness* of an agent. The sensor capabilities selections simply control the agents sensing characteristics and will be further explained below.

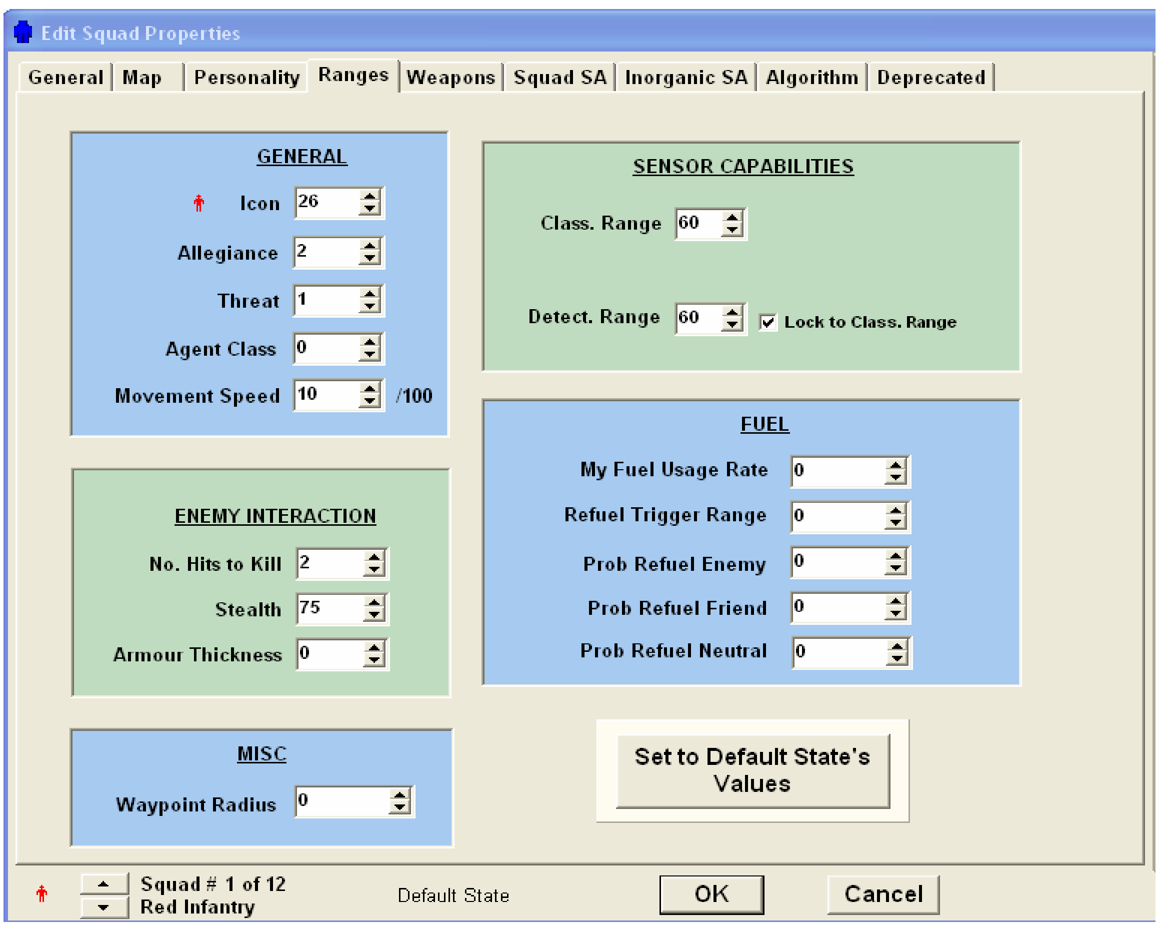

Figure 14. Ranges Tab.

Under the *General* settings, the user may establish icons for the squads, their allegiance (blue, red, neutral), their threat (low, medium, high), agent class and movement speed. *Threat* pertains to how the selected squad responds to an enemy agent, this option can be used to have agents react differently to altering threat levels. *Movement speed* refers to how many cells an agent may move in a given time step. In order to have agents move at speeds relative to each other, the blue convoy vehicles were set as baseline. We assumed that vehicles in the scenario, under normal driving conditions, will move roughly four times the speed of the foot mobile ambushers. The speed of convoy vehicles when contact occurs is varied because vehicles have the capability to move considerably faster than foot mobile agents at their top speed.

Moving on to the *Enemy Interaction* settings, the user may set the number of hits required to kill an agent, the stealth of an agent and the armor thickness. In our scenario, the number of hits to kill is varied to represent altering degrees of armor. *Stealth* was used for the red agents; it is assumed that ambushers will conceal themselves until ready to attack. The convoy agents do not have any stealth, as trucks moving down a road are easily detected.

The *sensor capabilities* settings are used to establish how many cells away (i.e. distance) an agent can detect a contact and also how many cells within that detection range can an agent classify a contact as enemy, friendly or neutral. The user may either lock the two ranges together or specify probabilities for classifying agents. In our scenario the ambusher's ranges are set larger than the convoy's due to the fact that the enemy will assume positions where they can observe the MSR. The convoy's detections ranges are varied in the scenario to uncover how much it impacts outcomes.

The *Fuel* settings were not used in this scenario. The author believes that further investigation could be made to see how much fuel consumption might play in longer convoy evolutions, where time of mission completion is a key measure of effectiveness.

The *Miscellaneous* setting of *waypoint radius* is simply how many cells an agent must be within a waypoint in order to consider it reached. The value was set at twenty for all agents to ensure that agents reach and move on to the next waypoint.

8. Weapons Tab

The weapons tab depicted in Figure 15 generally allows the user to specify how many and what type of weapons an agent possesses. Under each weapon selected the user can specify kill probabilities based on range, the shot radius and establish constraints on the number of rounds, rates of fire, penetration of the round and what type of targets the weapon can be used against. Again, weapons are dependent on the state of the squad.

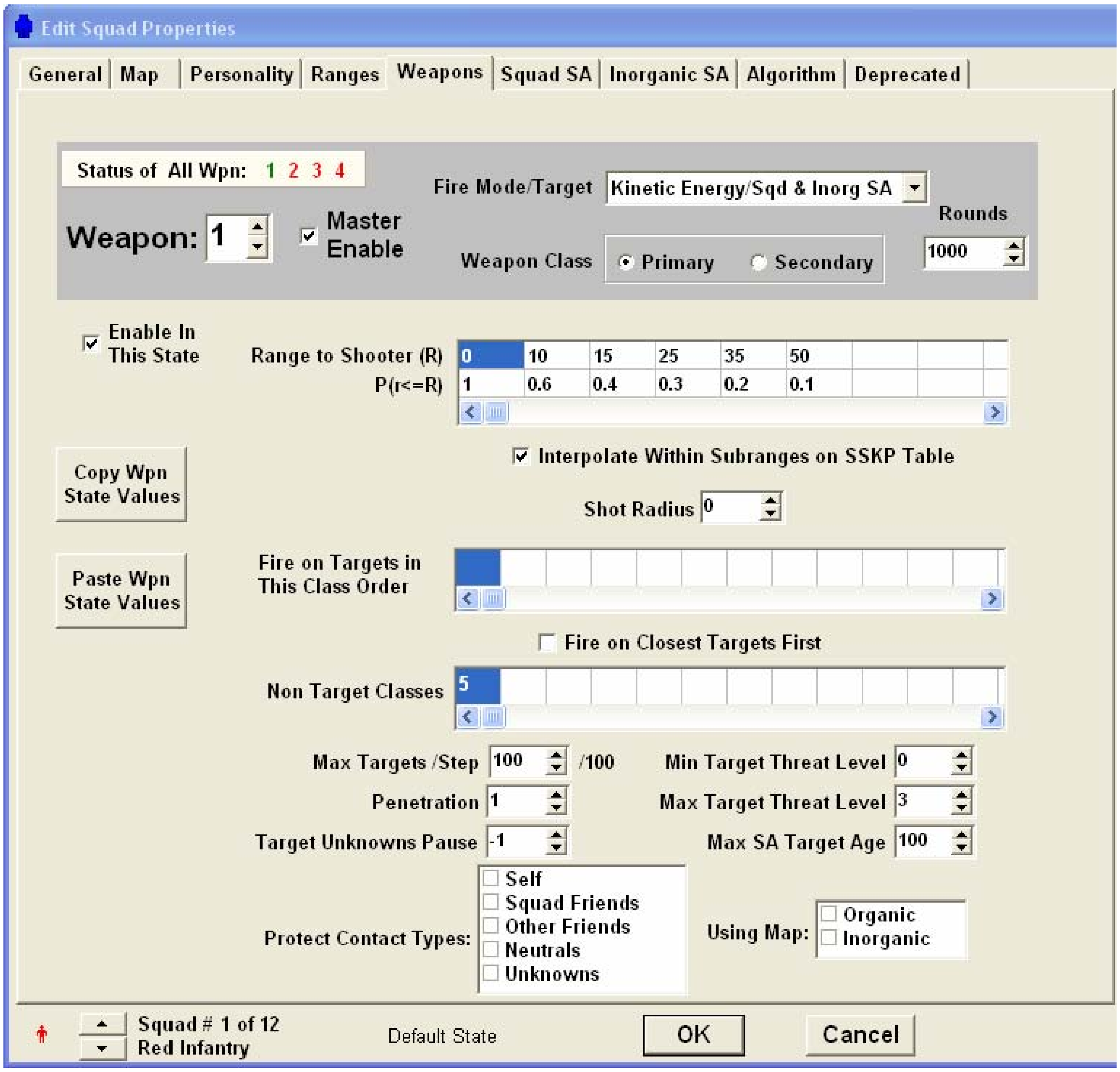

Figure 15. Weapons Tab.

A squad may have up to four different weapons. Weapons may be a kinetic energy type, such as rifles and machineguns, or be high explosive, such as mortars and artillery. Parameters for weapons may be varied in altering trigger states. The primary difference in the kinetic energy and high explosive weapons is that when setting ranges and probabilities of kill (PK), the range and PK for kinetic energy is set from shooter to target, where the high explosive range and PK is a radius from the point of round impact.

In our scenario there are four types of weapons in use; however, individual agents only possess one type of weapon each. Logistical vehicles possess a kinetic energy weapon representing an M-16. The ranges and PKs for the trucks are extremely limited and will rarely hit a target. The reason is that the accuracy of an M-16 shot from a moving vehicle is extremely inaccurate, but does provide suppressive fire. The security vehicles represent armored High Mobility Multipurpose Wheeled Vehicles (HMMWVs) with mounted M240G machineguns. The reader is advised that this is not a physics-based model to simulate the effects of weapon systems. For this reason, military experience and judgment was used to establish the ranges and PKs for the weapon systems based on their general characteristics and relation to one another, similar to how the movement speeds were established. To further model the ranges and PKs of the weapon systems we utilized, an agent-based simulation document from TRAC-Monterey was used, where ranges were established for a similar MANA scenario [Brown and Cioppa, 2003]. M-16s are less accurate and effective than the ambushers AK-47s and the M240Gs have a greater range, rate of fire and effectiveness than AK-47s. The red RPGs have a limited range but more explosive power. Since an RPG is a direct fire weapon but has an explosive round, the *shot radius* setting was used to model the destructive power of the round. Finally, the IED in the scenario was created using the *high explosive* type weapon, the kill radius was set based on observed explosive power of this type of weapon. The reader should be made aware that this is not a model designed to explore specific weapons and PKs. That being said, weapons were primarily modeled based on their relative characteristics to other direct fire weapons.

9. Situational Awareness (SA) Tab

The squad SA tab displayed in Figure 16 is used to establish characteristics of communication within a squad. Options on this panel do not vary with trigger state. The author recommends that the MANA developers explore ways to implement communications based on trigger state. It seems realistic to think that communications could be affected by such things as enemy contact. The *intra-squad comms delay* setting enables the user to establish a delay in time steps, between the time a message is sent and when it is posted on the SA map. The *squad threat persistence* option enables the user to establish how many time steps a contact will remain on the SA map. The *fuse time* and *fuse radius* settings are used to classify unknown contacts on the SA map.

In our scenario, communication limitations are not modeled, all agents are assumed to have good communications that do not vary. Though this is far from reality, the goal of this thesis is not to identify the impact of bad communications. This is an excellent area for follow on research, given that not all vehicles within a convoy will have communication assets. "Challenges to convoy movement control included inadequate communications" [EFCAT, 2003].

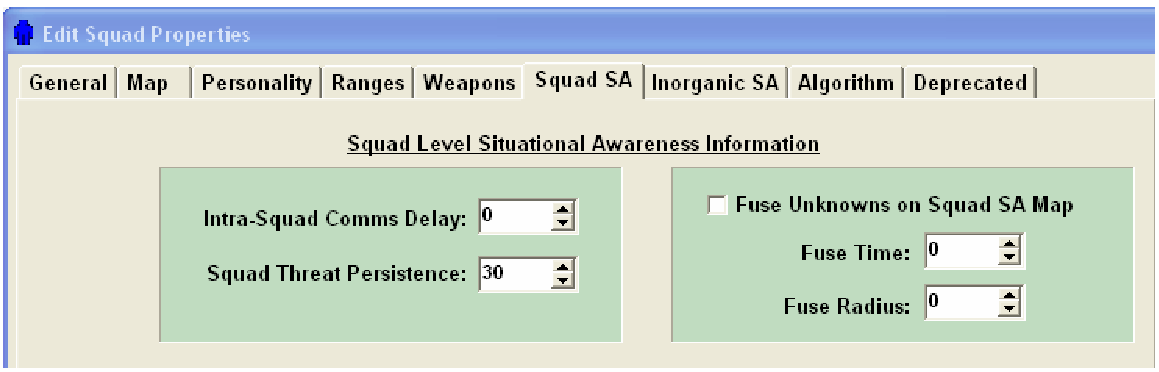

Figure 16. Squad Situational Awareness Tab.

10. Inorganic Situational Awareness

The inorganic SA map shown in Figure 17 is similar to the SA map, the difference being that there is no "Show Squad Friends" option. This is removed due the fact that an agent or squad receiving third party contact information cannot confirm that a contact is a squad member [Anderson et al., 2004]. Again, in our scenario, perfect communications is assumed, for this reason we will only briefly cover the options available on this panel.

The inorganic panel enables the user to control information from established communication links between squads. The *Inbound Inorganic Information* options provide the following options for how incoming information is handled. The *min link rank accepted* offers the ability to determine what information level (low, medium, high) of information is pasted on the squads inorganic SA map. This option could be used to model trust issues or establish hierarchical levels of communication networks. The *inorganic threat persistence* allows the user to establish the number of time steps that a contact remains on the inorganic map.

The *Outbound Communication Links* allows the user to establish communication links between the desired squads. In our scenario all blue squads are linked and all red squads are linked to the appropriate allegiance. The user has the ability to set up ranges of communications, capacity of messages a squad can handle, number of time steps required for a message to be sent and the priority level of a message sent. There are numerous options available for communications to be varied and manipulated to observe the affects of degraded communications.

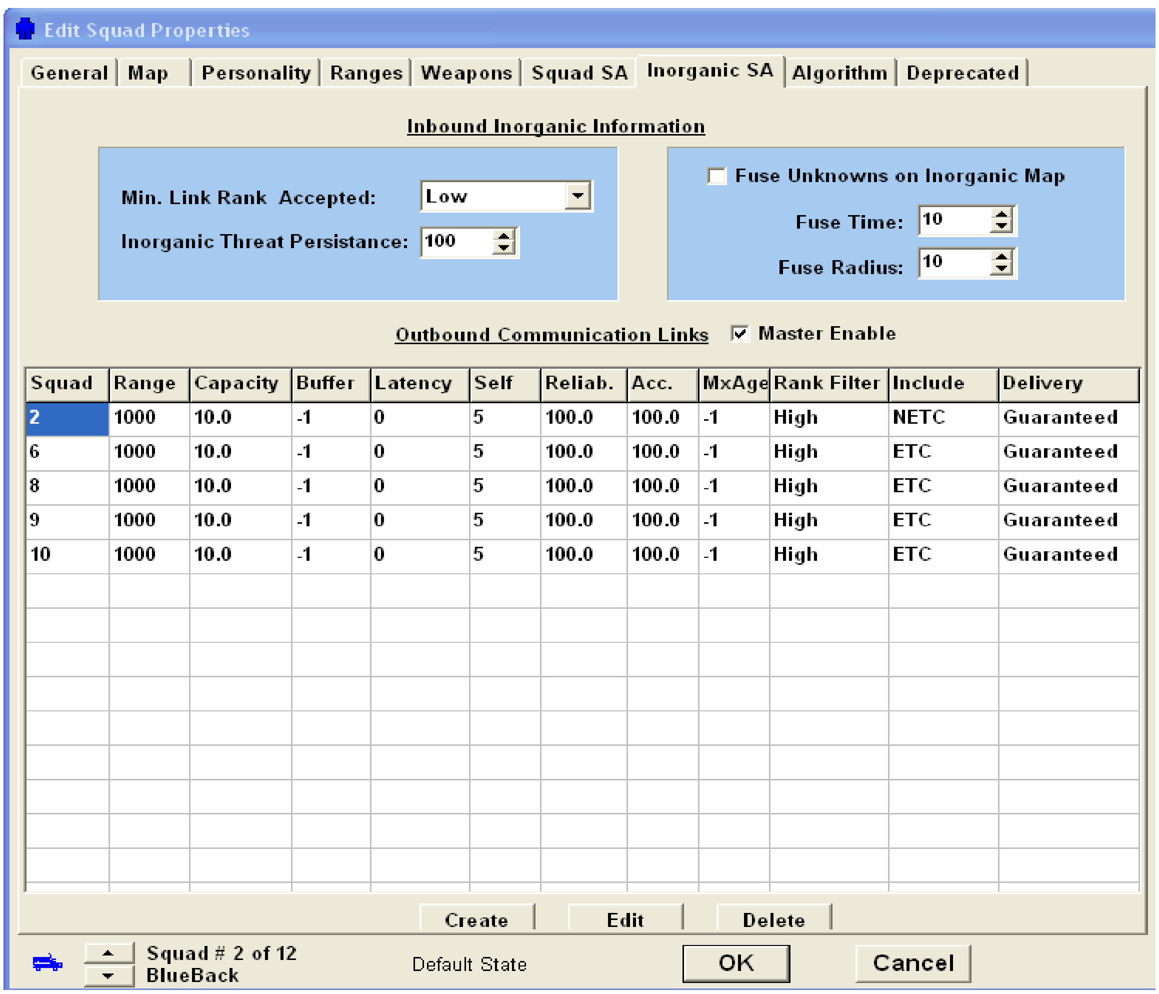

Figure 17. Inorganic SA Tab.

11. Movement Algorithm Tab

Finally, the algorithm tab depicted in Figure 18 provides the user the ability to change movement algorithm options. Options on the tab do not vary with squad state. The user can specify the type of algorithm used when agents move and establish the associated amount of precision when conducting a movement. Precision can be set to increase or decrease the amount of randomness in an agent's movement. Also on this tab are the general settings of multiple agents in a cell, diagonal movement correction, how obstacles are navigated, whether a squad moves together or not and, finally, whether the terrain affects the speed.

Our scenario uses the Stephen Algorithm, which is identified as the *standard* algorithm by the user's manual. Blue agents are set with low movement precisions, meaning there is little randomness in their selected moves. The idea is that a convoy has a set route that it will follow and not meander around towards waypoints. Red agents on the other hand were set with higher move precision, allowing them to have some degree of randomness when selecting a move.

Under the g*eneral movement settings,* the user can turn on or off several options. The *multiple agents allowed in cell* option allow for more than one agent in a cell if checked, depending on the "real world" scale, this option might want to be checked. The d*iagonal movement correction* option corrects for the time it takes an agent to move if they are moving in a diagonal direction. The *navigate obstacles* option allows the agents to move around solid terrain objects if they get "stuck." The s*quad moves together* option ensures that each squad member's fractional movement is the same at each time step. Finally, the g*oing affects speed* option will cause the type of terrain to affect the speed of agents.

In our scenario, for the blue agents all options are checked. For red agents, the *going affects speed* option is not checked. The assumption is made that ambushers on foot in a familiar area will have the ability to move somewhat freely with terrain not affecting their movement. This also allows for modeling the red agents moving in and out of structures, though this does not affect their speed, it does affect the ability of the convoy to detect them.

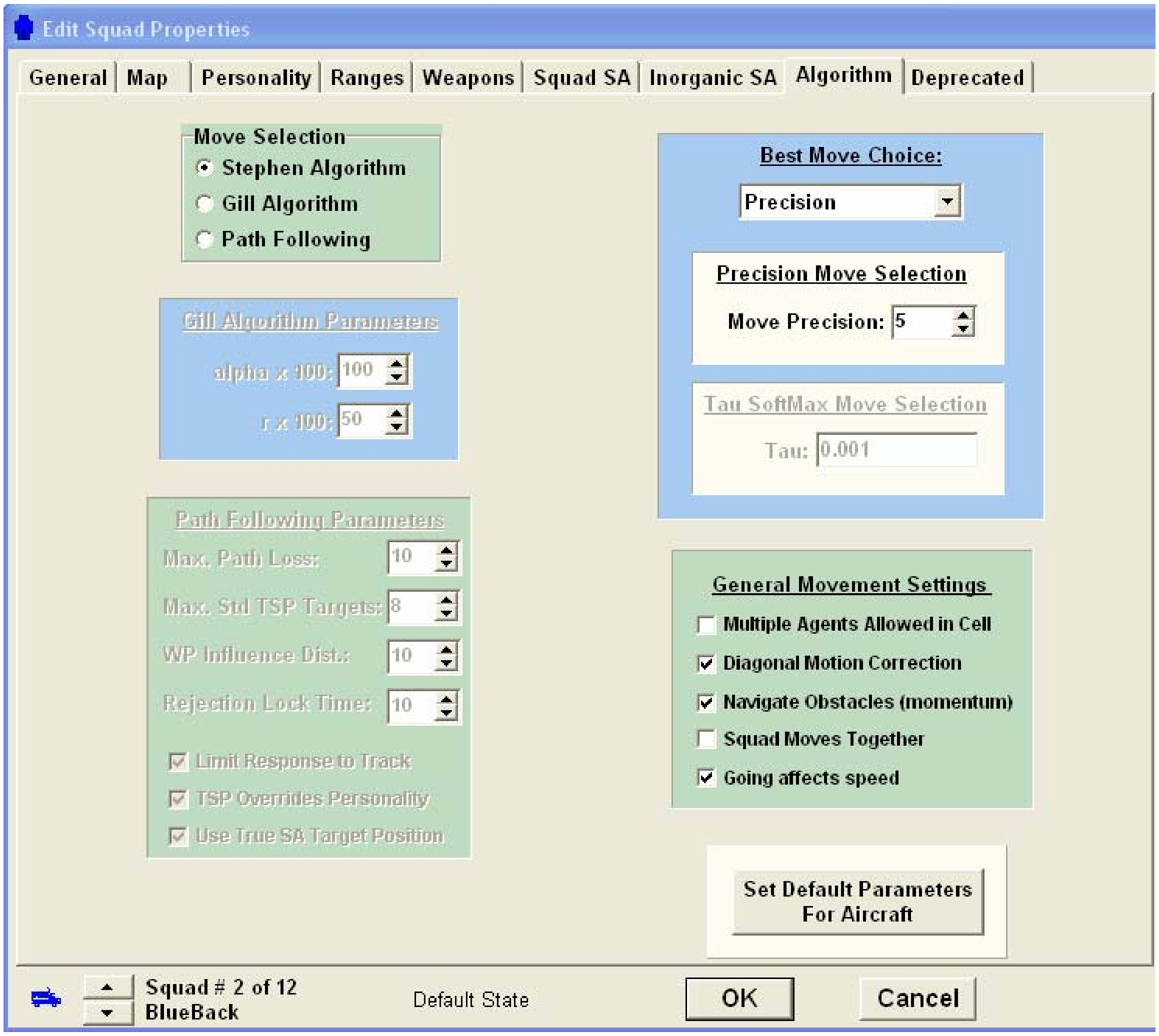

Figure 18. Algorithm Tab.

This concludes the discussion of the chosen modeling environment and the creation and characteristics of the created MANA scenario. The model was created to identify general properties of a ground convoy that determine their success in this scenario. There are hundreds of other parameters within this model that could be explored, such as communications, weapons types, ranges and PKs and the introduction of a more urban terrain. The reader is advised that all conclusions are based on the outcomes from the created scenario and could be significantly different given a different set of parameters.

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IV. ANALYSIS METHODOLOGY

This chapter presents the analysis methodology for our ground convoy simulation model. First, we will cover our selected measure of effectiveness (MOE). Second, we cover the experimental design process. Third, we cover the selected statistical software package including some of the data manipulations. Finally, we cover some of the statistical techniques used to select pertinent factors and analyze the effects.

A. MEASURE OF EFFECTIVENESS (MOE)

MOEs are quantitative measures that give insight into the performance of a measured activity. In our scenario, we chose *blue casualties* as the MOE to determine how our convoy is performing in the scenario. This MOE was chosen based on conversations with individuals involved with I MEF operations. It was stated that during the offensive phase of OIF, "time to mission accomplishment was a critical element." If our scenario was based on movements during an offensive phase, we would probably have selected time it takes the convoy to reach its goal as a possible MOE. However, our scenario is based on the stabilization phase of operations where time is less important and survivability of our troops is the priority.

B. DESIGN OF EXPERIMENT

In this section we will cover three topics relating to the experimental design. First, we will discuss the factors and how they were selected. Second, we will cover the experimental design used to generate the factor combination settings. Finally, we will discuss the data farming process for obtaining the dataset used in the analysis.

Utilizing trigger states, MANA offers the ability to examine thousands of possible factors within a given scenario. Obviously there are computing constraints and it would be impossible to examine every possible factor within a scenario in a single design. Since the purpose of this thesis is to examine the effects of actions when an ambush is encountered, the majority of the examined factors occur in one state. In order to understand where in the scenario a specific factor occurs and which squad it affects, they will be identified by the squad, then state and finally factor in the following organization squad_name/state_name/factor_name [Wolf, 2003]. To illustrate the factor for a security squad's aggressiveness, the factor will be written as, *BlueSecurityFront/Spare 1/Enemies.*

1. Factors and Ranges

Realizing the difficulty in examining every possible factor and combination of factors in a single MANA scenario, we identified the factors that logically should be important, based on experience and a literature research, such as placement of security vehicles within a convoy. Once a list of possible factors was compiled, we began to make exploratory runs in an attempt to make a preliminary assessment on the significance and to bound the ranges of those factors. Though there are literally thousands of possible factors and combinations within a single scenario, not all the factors need to be varied in every state. For example, in our scenario, we are interested in what happens after a convoy makes enemy contact, therefore, many of the factors were irrelevant in states other than the contact states. However, there are factors that are examined outside of the contact states, such as security vehicle locations, where the state does not affect the factor.

Once a baseline scenario was created, we began to zero in on those factors that logically should be significant. We began our experiment by conducting a 22 factor 129 level design. The 22 factor 129 level design refers to the Latin Hypercube technique of experimental designs and is discussed further in the next section. The results of this design displayed several factors that were expected to be significant, such as security vehicle location, security vehicle aggressiveness and logistical vehicle speed. After doing regression analysis on the results, we were able to identify 16 main factors dominating the model. Next, we ran a 16 factor, 65 level design to further zero in on the important factors. From these results, we were able to narrow the design down to 11 important factors.

Upon examination of our output from the final 11 factor production runs we found some disturbing trends. Initially it appeared that the means of each excursion were identical only differing between the scenario used for the excursion. We utilized four scenarios to vary the location of the security vehicles within the convoy. Upon further investigation it was discovered that the output for each excursion was identical in mean, standard deviation and range. We expected the means between excursions to be relatively close due to the fact there are only 16 blue agents. However, the fact that the distributions of all 129 excursions with extremely different parameter settings were identical was realized to be impossible and far too coincidental. After examining the scenario and experimental design to ensure we had not made an error, we turned to our support at the MITRE Corporation who had conducted the simulation runs. Upon further examination it was found that there was an error in the scripting of the simulation runs. It should be noted that the discovery of the problem and correction of the error took only two days. While this might seem to be a major set-back, in reality it seems to validate the power of ABMs and our chosen experimental design. The ability to produce numerous simulation runs and examine the data quickly for unlikely trends reinforces the value of ABMs and the data farming technique. Consider, for example, a large physics-based model that takes weeks to set-up and then 60 hours to run. If a similar problem had occurred, weeks of work would have been lost. In our case this was a relatively non-issue and caused only a minor set-back.

Once the error was discovered we were concerned that the error had existed in our previous simulation runs. The error was discovered to be present in our 22 and 16 factor design runs. In order to avoid taking a step back in our research we went back to previous 11 and 16 factor exploratory runs where the error was not present. These data sets, along with experience and research, were then used to select our factors for the final 11 factor production run.

The factors listed in Table 2 are the factors used in our final production runs. The factors are listed by affected squad or squads, the state of the factor, the actual factor, plus the low and high level of the settings. Recalling from Chapter III, there is one security vehicle in each of the security squads. Factors that affect the security vehicles are varied together, meaning for all practical purposes they act as a single squad with equal desires, speeds and so forth.

Squad Name	State	Factor Name	Low Setting	High Setting
Security Vehicles	Start of Run	Security Location	1	4
	Spare 1	Sec Speed	100	250
		Sec Time in State	1	132
		Sec AgentSA Enemy	-33	33
		Sec InorgSA Enemy	-33	33
		Sec AgentSA Friends	-33	33
	Default	Sec Detect Range	10	100
Logistic Vehicles	Spare 1	Log Time in State	1	132
		Lod Twd concealment	-33	33
		Log Detect Range	10	100
		Log Speed	100	250
UAV	Default	Detect Range	10	120

Table 2. Selected Squad/State/Factors.

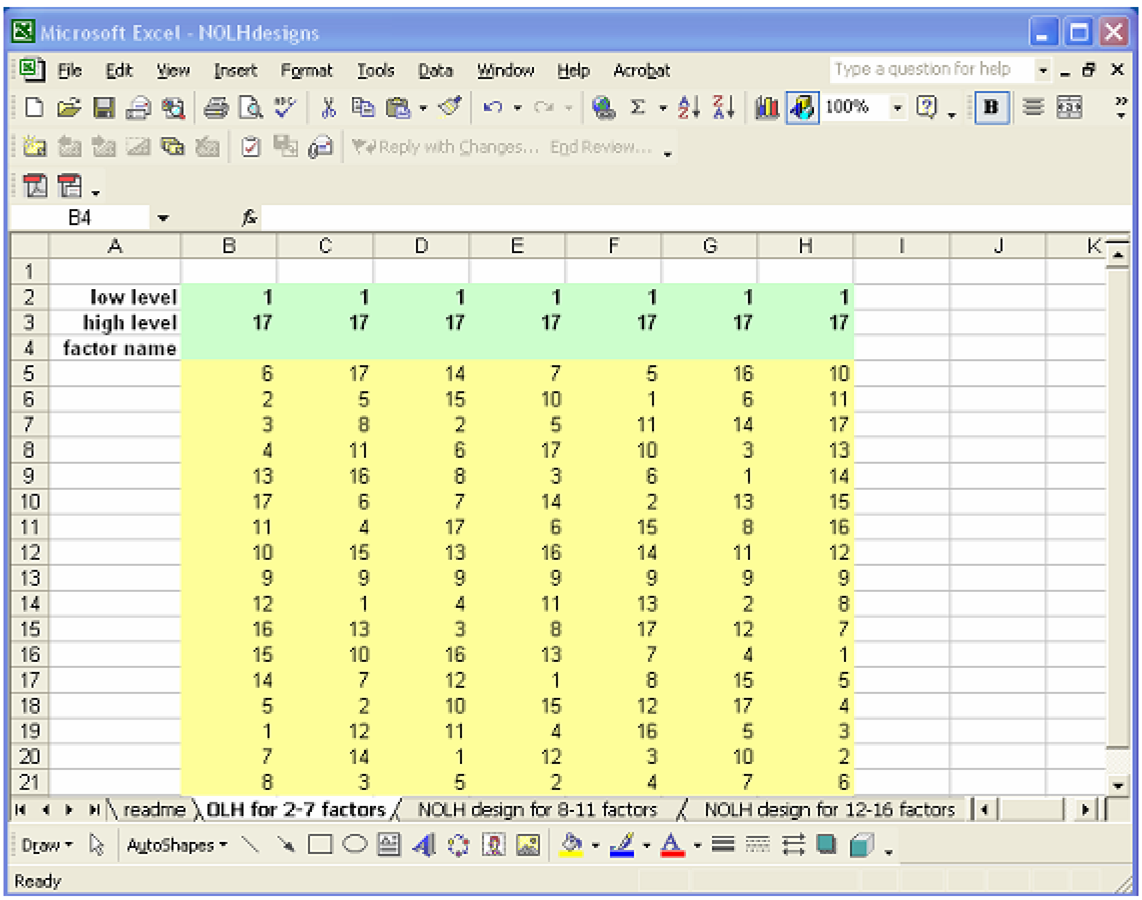
To relate the speed and distance factor settings to the "real world," the following is provided. Recall from Chapter III that the speed of the vehicles was set as a baseline, meaning all other agent speeds are relative to vehicles. A speed of 100 means a vehicle moves 1 pixel per time step, so if we assumed that a convoy was moving 30 mph then a person on foot would move roughly one-third of this or 10 mph at the maximum. Agents on foot were set up to have a speed a bit faster than would be in reality in order to model their knowledge of the terrain. Continuing with the example, if the security vehicle speed is set at 250, they can move 2.5 pixels per time step and implies they can move roughly 8 times the foot soldier or 80 mph. Eighty mph is extreme but was purposely set this high to observe any extreme effects or points of diminishing return. Detection range distances were purposely set low for the convoy in order to simulate the effects of moving vehicles in a column and to give a slight observation advantage to the ambushers. For example, if we assumed that each pixel is 3 meters then an agent's detection range would be 30 meters and if 100 then their range 300 meters.

2. Nearly Orthogonal Latin Hypercube (NOLHC)

Current and foreseeable future computing capabilities eliminate the possibility of attempting a full factorial experiment with numerous factors containing expanded levels. Suppose we wished to examine our 16 factors with each factor having 3 levels. Using 3 levels would enable the discovery of any non-linearities within the model. To create a design of this nature we would need 3^{16} design points, which would require 43,046,721 runs to get a single data point for each combination of factors. Now suppose that each run takes 30 seconds, this would require 21,523,361 minutes, 14,947 days or approximately 41 years to get a single data point for each design point. Obviously, a full factorial design was unacceptable; especially considering that the factors selected all have more than 3 levels.

Considering that our factors all contain more than 3 levels, a full factorial design was immediately ruled out as a possibility for a design; so we pursued a Latin Hypercube (LHC) design. The LHC design is a sampling technique where the goal is to sample the experimental area not only on the edges but also in the interior to maximize the space-filling of the sampled area [Cioppa, 2002]. Using an LHC design minimizes the assumptions that need to be made about the form of the response surface. The NOLHC design provides us with two desirable characteristics for examining our scenario; approximate orthogonality and good space filling. The LHC technique provides an efficient method to examine many factors each with multiple levels in an attempt to uncover any non-linearities within the response surface [Brown et. al., 2002]. To construct the LHC for this thesis, we used a Microsoft Excel spreadsheet created by Professor Susan Sanchez [Sanchez, 2004]. The spreadsheet displayed in Figure 19 allows the user to first pick either an orthogonal or nearly orthogonal design based on the number of factors required. The user specifies the low and high levels of each factor, the algorithm then divides the range into subpopulations of equal marginal probabilities. The algorithm then takes a random sample from one of the subpopulations and sets this value as the first factor setting for that particular design point. The process is repeated until all levels of the factor are filled. The resulting design is a matrix of randomly sampled, randomly assigned and uniformly distributed factor settings [TRAC-Monterey, 2003, Cioppa, 2002 and Wolf, 2003].

When using a NOLHC design, a major concern is correlation between the factor columns or the existence of multicollinearity. The process for constructing the design itself limits the amount of correlation present. However, in an attempt to gain more space filling and further reduction of possible correlations, we linked 4 NOLHCs together. This was done by randomly shuffling the 11 factor columns, placing the lower and upper level values in the excel spreadsheet and creating new design points. After the new design points were created, the columns were placed back in the correct factor order and concatenated with the preceding design. In order to gain more observations and space filling, we then took the design and ran each of our four scenarios with the entire design. The resulting design after linking was a 11 x 129 matrix with no correlations greater than 0.02 or less than -0.02. Figure 20 displays the scatter plot and Figure 21 displays the associated correlations for each pair of factors. One of the main factors we wanted to examine was the security vehicle location; this factor was removed from the matrix and replaced with another relevant factor when the actual runs were made, we were careful to ensure that the MANA scenario that this factor corresponded to was visible in the data output. When the run results were obtained, the factor was placed back in the output based on which scenario was used with the corresponding output.



	A	B	C	D	E	F	G	H
1								
2	low level	1	1	1	1	1	1	1
3	high level	17	17	17	17	17	17	17
4	factor name							
5		6	17	14	7	5	16	10
6		2	5	15	10	1	6	11
7		3	8	2	5	11	14	17
8		4	11	6	17	10	3	13
9		13	16	8	3	6	1	14
10		17	6	7	14	2	13	15
11		11	4	17	6	15	8	16
12		10	15	13	16	14	11	12
13		9	9	9	9	9	9	9
14		12	1	4	11	13	2	8
15		16	13	3	8	17	12	7
16		15	10	16	13	7	4	1
17		14	7	12	1	8	15	5
18		5	2	10	15	12	17	4
19		1	12	11	4	16	5	3
20		7	14	1	12	3	10	2
21		8	3	5	2	4	7	6

Figure 19. LHC Design Spreadsheet (From: Sanchez, 2004).

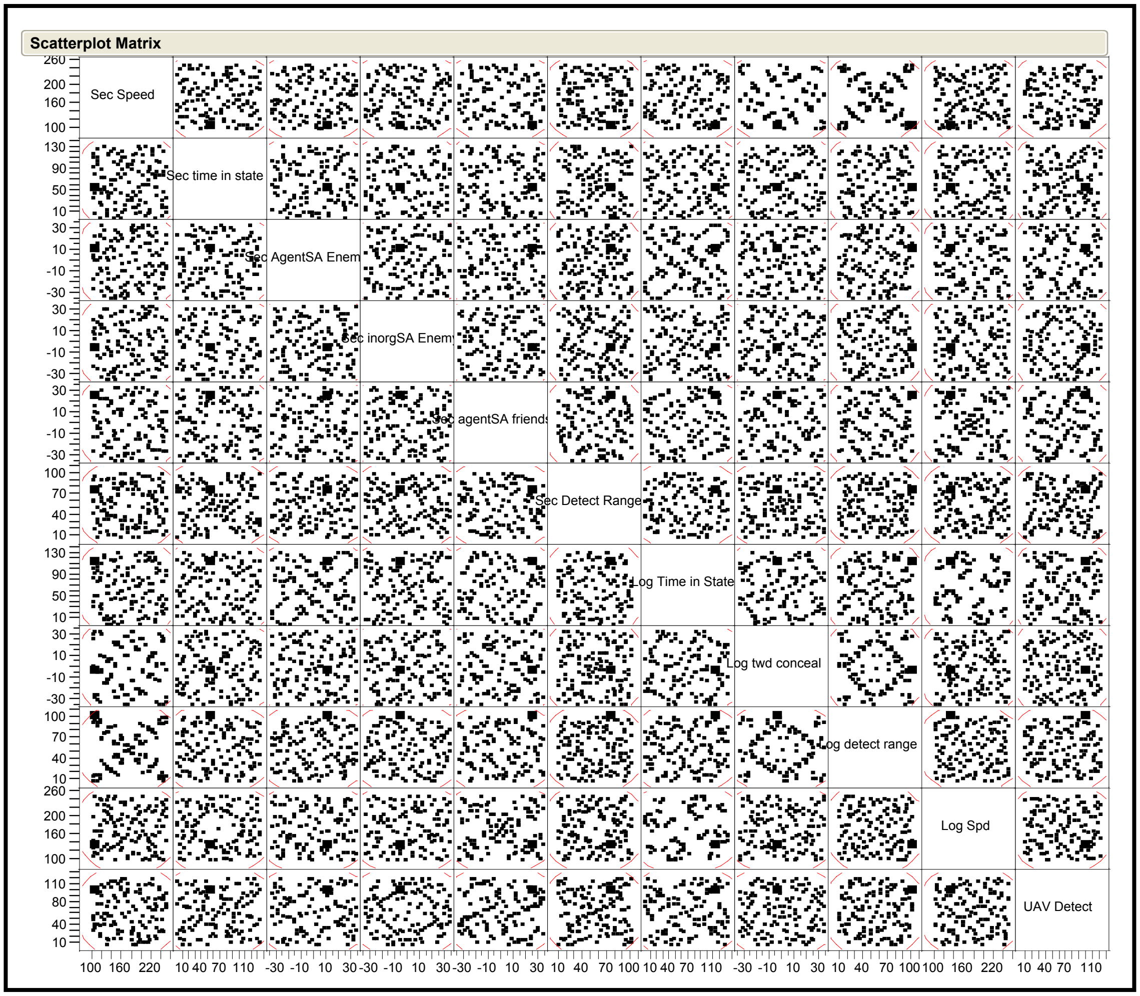


Figure 20. Scatter Plot.

Sec Speed	Sec time in state	Sec AgentSA Enemy	Sec inorgSA Enemy	Sec agentSA friends	Sec Detect Range	Log Time in State	Log twd conceal	Log detect range	Log Spd	UAV Detect
1	-0.0046	0.0023	0.0067	-0.0077	-0.0008	0.0013	-0.0057	0.0104	-0.0079	0.0089
-0.0046	1	0.0057	0.0055	-0.0018	0.0006	0.0028	-0.0013	0.0123	0.0002	0.0022
0.0023	0.0057	1	0.0033	-0.0028	-0.0113	0.0038	0.0015	-0.0055	-0.0019	0.0003
0.0067	0.0055	0.0033	1	-0.0029	0.001	0.0031	0.0023	0.0071	-0.0052	0.002
-0.0077	-0.0018	-0.0028	-0.0029	1	0.0001	0.001	-0.004	0.0091	0.0104	0.0047
-0.0008	0.0006	-0.0113	0.001	0.0001	1	0.0019	-0.0031	-0.003	-0.0036	0.0005
0.0013	0.0028	0.0038	0.0031	0.001	0.0019	1	-0.0004	0.0092	0.0096	0.0092
-0.0057	-0.0013	0.0015	0.0023	-0.004	-0.0031	-0.0004	1	-0.0105	-0.0037	-0.0018
0.0104	0.0123	-0.0055	0.0071	0.0091	-0.003	0.0092	-0.0105	1	-0.017	-0.0038
-0.0079	0.0002	-0.0019	-0.0052	0.0104	-0.0036	0.0096	-0.0037	-0.017	1	0.0018
0.0089	0.0022	0.0003	0.002	0.0047	0.0005	0.0092	-0.0018	-0.0038	0.0018	1

Figure 21. Pairwise Correlations.

3. Computing Process

The MITRE Corporation is a defense contractor that maintains an office in Woodbridge, VA, supporting PA and other Marine Corps offices. MITRE operates a supercomputing cluster that supports data farming efforts. Once a scenario and design are created and factors are ready to be data farmed, the files are simply e-mailed to MITRE. MITRE then creates a script file that establishes which factors in the appropriate trigger states are to be varied. The user specifies how many replications are to be performed at each design point; when the runs are conducted a random seed is applied to each row. Once the runs are completed the output files are returned in the form of a comma separated value (.csv) file. For our final scenario production runs we had 129 design points and conducted 50 runs at each point, this requires 6,450 runs. In order to examine the security vehicle location factor this process was conducted 4 times for a total 25,800 runs.

C. ANALYSIS OF THE DATA

There are numerous software packages available for data analysis, such as S-Plus, SAS, Clementine and JMP. The author was introduced to the JMP Statistical Discovery Software ™ during this thesis and found its user-friendly construction desirable. For this reason it was the package used for this thesis. In this section we will briefly cover the chosen data analysis software package and discuss the manipulation of the simulation results.

1. Chosen Data Analysis Software

JMP was created by the SAS Institute Inc. and possesses many of the desirable attributes of several other software packages rolled into one. "JMP is designed to be a point-and-click, walk-up-and-use product that harnesses the power of interactive statistical graphics to serve the analysis needs of the researcher" [JMP, 2002]. The author was able to learn the main capabilities of the package within a day and the extensive graphical user interface (GUI) capabilities make the manipulation of data extremely simple. JMP allows the user to view and manipulate data in a spreadsheet, produce subsets of data and provides a wide range of possible graphical, statistical and data analysis options [JMP, 2002 and Wolf, 2003].

2. Data Consolidation

The simulation output data consisted of 25,800 observations. When the data was returned each design point excursion is represented by a unique identifier code. Each identifier consisted of 50 observations. In an attempt to identify whether the factor settings or the variability within the simulation were causing particular outcomes, the data was grouped by identifier code and the mean value of the response variable (blue casualties) was taken for the 50 points in each excursion. This resulted in 516 data points representing the average of each particular excursion. Before the consolidation was made we added our 4 security vehicle locations back into the data. This was accomplished by adding a column for each location. The values of the columns were either 1 or 0 representing which location the row of settings corresponds to. The resulting matrix after this manipulation was 15 x 129.

D. ADDITIVE MULTIPLE REGRESSION

In an attempt to fully understand what factors in our scenario were contributing the greatest to the success of our convoy in the created scenario, we applied the additive multiple regression analysis technique to our data.

Regression is statistical technique that investigates the relationship between two or more predictor variables to a response variable [Devore, 2000]. For example, if we found that convoy speed was a statistically significant predictor variable, we could perform regression analysis to determine how many blue causalities we would expect to suffer based on speed. In our model, we only considered main effects, two-way interactions and 2nd degree polynomials.

1. Regression

Relatively recent advances in computing power have enabled multiple regression analysis to become a widely used technique by researchers. Linear regression fits a linear function of predictor variables to a continuous response variable using the least squares fitting criterion [Devore, 2000 and Hamilton, 1992]. The general additive multiple regression model equation is listed below:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + ... + \beta_k x_k + \varepsilon$$

Y is our response variable; x is the independent or predictor variables, β is the coefficient of the predictor variables and ε is the error term.

2. Regression Assumptions

In order to apply the statistical testing procedures of *t-tests* and *f-tests* there are a few assumptions that must hold regarding the error term in order for the tests to be valid. Errors or residuals must follow a normal distribution, residuals must be identically distributed with zero mean and constant variance and all residuals must be independent and identically distributed [Devore 2000, Hamilton 1992 and Wolf 2003].

3. Model Comparison

In our comparison of the regression models created from our data, we use the coefficient of determination (R^2) value to determine which model is providing the best fit to the data. The R^2 value can be interpreted as the proportion of observed variation in the response variable that can be explained by the linear regression model [Devore, 2000]. The equation to calculate the R^2 value is provided below:

$$R^2 = 1 - \frac{SSE}{SST}$$

Where SSE is the sum of squared deviation about the least squares line and SST is the sum of squared deviations about the mean response line.

An R^2 of 1.0 means that the model completely explains the response variable based on the predictor variables. Alternately, an R^2 of 0.0 indicates that there is no relationship between the predictor variables and the response variable [Wolf, 2003]. Although, we looked for high R^2 values in our models, there are other considerations to be made when comparing the models. Also, in multiple linear regression it is possible for the R^2 value to provide a deceptive measure, it can become greatly inflated when a large number of predictors are used relative to the number of observations [Devore, 2003]. With 11 main factors we could have a full model with 78 terms consisting of main effects, two-way interactions and polynomial terms to the 2^{nd} degree. With 78 predictor variables it would be extremely difficult to determine what is actually happening in the model. For this reason we attempted to minimize the number of predictor variables in model while still maintaining a reasonably high R^2 value.

We used an F-test to further evaluate prospective models. The F-statistics allow us to test hypotheses regarding sets of parameters [Hamilton, 1992]. Given a large complex model we can then take a subset of parameters from the large model and test whether the large model significantly improves upon the smaller model with fewer parameters [Hamilton, 1992]. Suppose we have *K* predictors in our model minus the intercept term and wish to reduce the model by *H* predictors, we can then observe whether the latter model significantly improves from the lesser. The relevant equation is listed below [Hamilton, 1992]:

$$F^{H}_{n-K} = \frac{(RSS\{K-H\} - RSS\{K\})/H}{(RSS\{K\})/(n-K)}$$

Where *RSS*{*K*} denotes the residual sum of squares for the larger model (*K* parameters) and *RSS* {*K-H*} is the residual sum of squares for the model with fewer parameters. The calculated F statistics are then compared to the F-distribution with df_1 = H and df_2 = n-K degrees of freedom.

In summary, the F-test compares the null hypothesis that all predictor coefficients in the model equal zero against the alternative that at least one of the predictors is not zero and therefore provides some useful information about prediction of the response variable.

4. Significant Terms

In order to determine which factors in the models were providing the most useful information we needed to test the individual terms of the models. Where the F-test allowed us to compare models, the *t*-tests allows us to compare individual predictor terms in the model. We used the *t*-test to accomplish this task. The t-statistic test allows us to evaluate the importance of the individual coefficient values. The *t*-statistic is calculated with the following equation [Hamilton, 1992]:

$$t = \frac{b_k - \beta_k}{SE_{bk}}$$

Where b_k is the estimation of the coefficient for parameter k, β_k is the actual or hypothesized value of the coefficient of parameter k and SE_{bk} is the estimated standard error of b_k, the estimated coefficient.

Each *t*-statistic of the predictors equals the coefficient divided by its standard error. The corresponding *p*-value for each coefficient is also provided with most statistical software packages. A *p*-value greater than .05 indicates that a term is not significantly significant [Devore, 2000].

In conclusion, we have identified our experimental design methodology, identified the process for selecting the factors and briefly explained the additive multiple regression technique. Chapter V will detail the analysis conducted on our dataset.

V. DATA ANALYSIS

In this chapter, we detail our analysis findings. We begin with an initial assessment of the data. Next, we cover the multiple linear regression models with main effects, and then examine the two-way interactions and the quadratic model. We will combine all relevant terms into a final regression model and summarize the selected factors. Finally, in each section we explore what the resulting factors suggest about our scenario and how they might relate to the "real world."

A. INITIAL ASSESSMENT OF THE DATA

We begin our analysis by doing an initial assessment of the data where we look for any obvious errors, the distributions of blue and red casualties and any obvious trends and outliers. It should be noted that the data farming process does take some manual effort that can possibly lend itself to errors. Mentioned in Chapter IV was an example of some processing errors we found in several of our datasets.

Upon receiving the data we created a distribution plot of the blue and red casualties with associated summary statistics, see Figure 22. Particular attention should be paid to the high number of runs that resulted in 12 blue casualties, we will examine this occurrence later this chapter.

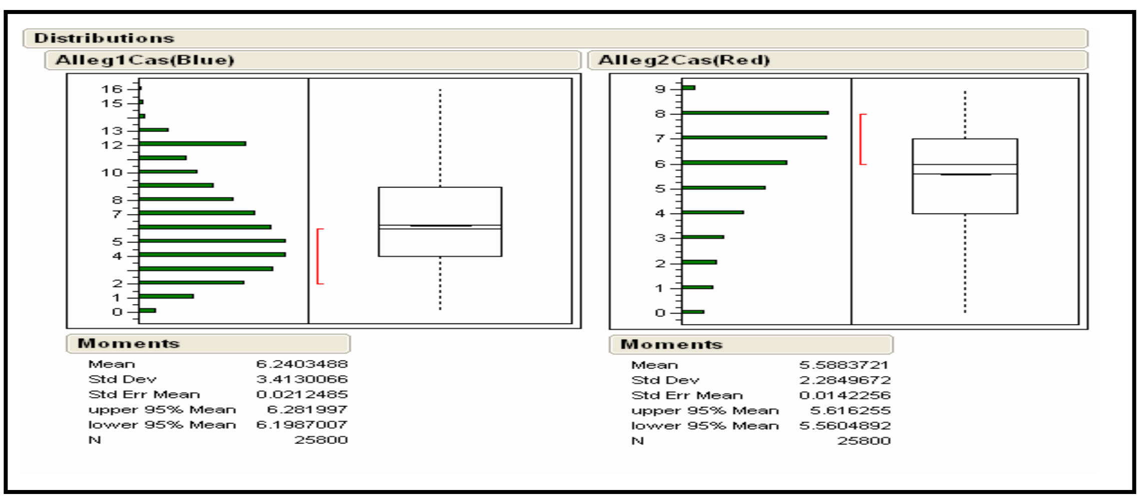


Figure 22. Blue and Red Casualty Distributions with Summary Statistics.

We then plotted the data on a scatter plot to look for any obvious trends and outliers. Figure 23 displays the scatter plot and highlights some obvious outliers that will be investigated later in this chapter.

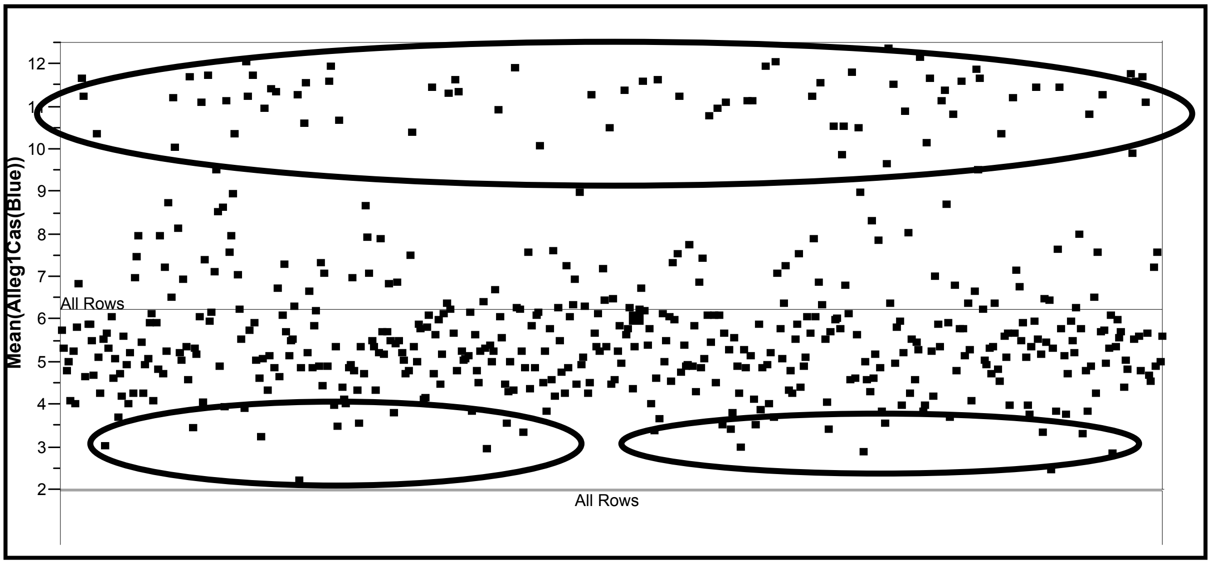


Figure 23. Scatter Plot with Highlighted Outliers. All rows on the Y axis corresponds to each design point in the data set.

After doing an initial assessment of the data, it is clear that there are some interesting effects taking place. In the next section, we cover our regression analysis.

B. FITTING THE MODELS

Our final production run consisted of 11 factors believed to be logically relevant in our scenario based on military experience, judgment and the results from exploratory runs. Security vehicle location is our 12th factor; locations were modeled using 4 separate scenarios and are used in the regressions. In this section, we detail the regression models created and relevant factors identified in each model. We then combine the dominating terms into a final model and closely examine the main effects and two-way interactions. Finally, we summarize some of the interpretations of the factors and interesting outliers.

1. Main Effects

We began the regression analysis with a model consisting of only the 12 main effects. There are actually 15 terms in the initial regression model, 4 of which represent the security vehicle locations. We used the mixed stepwise regression function in the

JMP software package to conduct the regression. The mixed function alternates the forward and backward steps, entering terms based on a specified significance level in the forward step and then removing terms with the least significance in the backward step. The resulting model contains all significant terms [JMP, 2002]. A term is initially included in the model if its p-value was less than 0.25 for a forward step. We set the criteria for a term to be removed from the model in the backward step if the p-value is greater than 0.05. A p-value less than 0.05 is generally considered to be significant [Devore, 2000].

The main effects model started with 15 terms and the initial step through resulted in 10 terms being significant with an R^2 of 0.4811. Figure 24 displays the actual value by the predicted value plot. The general trend of the data is positive indicating that the actual values of the blue casualties and predicted values of blue casualties are in general agreement. Annotated by the circles are some obvious groups of outliers that will be further examined in the analysis.

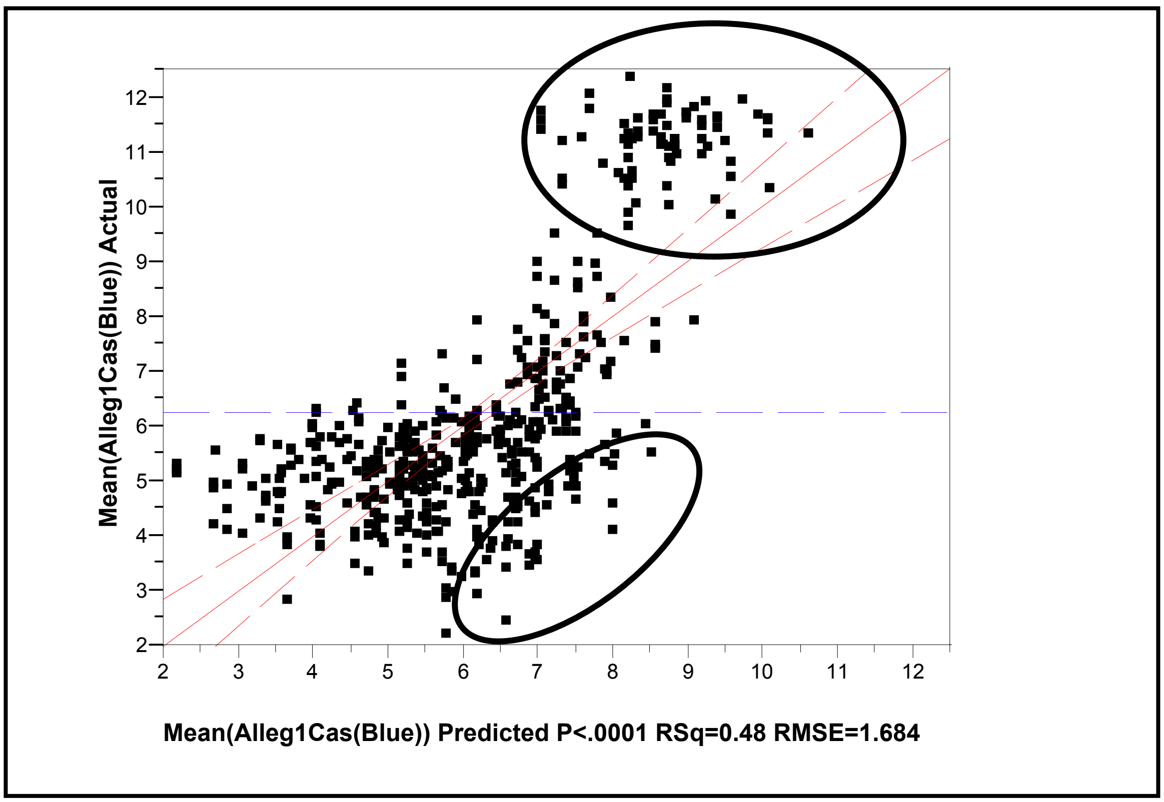


Figure 24. Actual versus Predicted Blue Casualties.

Before we move on to adding first order interactions we wanted to examine some aspects of the model a bit more closely. In previous exploratory runs security vehicle locations had dominated the models. In this model, only one location term entered in the model is significant. Security location 4, which was purposely created as an extreme case that no convoy commander in their right mind would utilize, enters as a significant term. Upon closer examination, the term has a positive slope indicating that if this location is used the convoy experiences more casualties. This was expected and reassured us that the scenario was performing as we expected. At this point, rather than eliminate any of the factors that only slightly effect the model we decided to leave them all in the model and try adding first order interactions in an attempt to improve the fit (i.e. increase the R^2 value).

2. First Order Interactions Model

Rather than start the stepwise function with only the significant terms from the main effects model, we decided to include all possible interactions. After the initial screening, the resulting model consists of 33 significant terms with an R^2 of 0.7993. Now we have 12 main effects and 21 interaction terms. Even though the explained variance in this model is much larger than the main effects model, it would be extremely difficult to understand what was happening with all 33 terms. Taking a closer look at the included terms it is evident that there are only a handful of terms that dominate the model. If we only use 3 terms; the security inorganic aggressiveness, the logistics vehicles propensity to move toward concealment and the interaction of the two, we can explain 52 percent of the variation in the model. Figure 25 displays the leverage plots of these 3 terms. Leverage plots give a graphical representation of an effect's significance test. The distance from the points in the graphs to the horizontal line (mean) show what the error would be without the term in the model. The distance from the points to the line of fit or the diagonal show the actual residual [JMP, 2002]. In a leverage plot we are primarily looking to see that the fitted line follows the data better than the horizontal line.

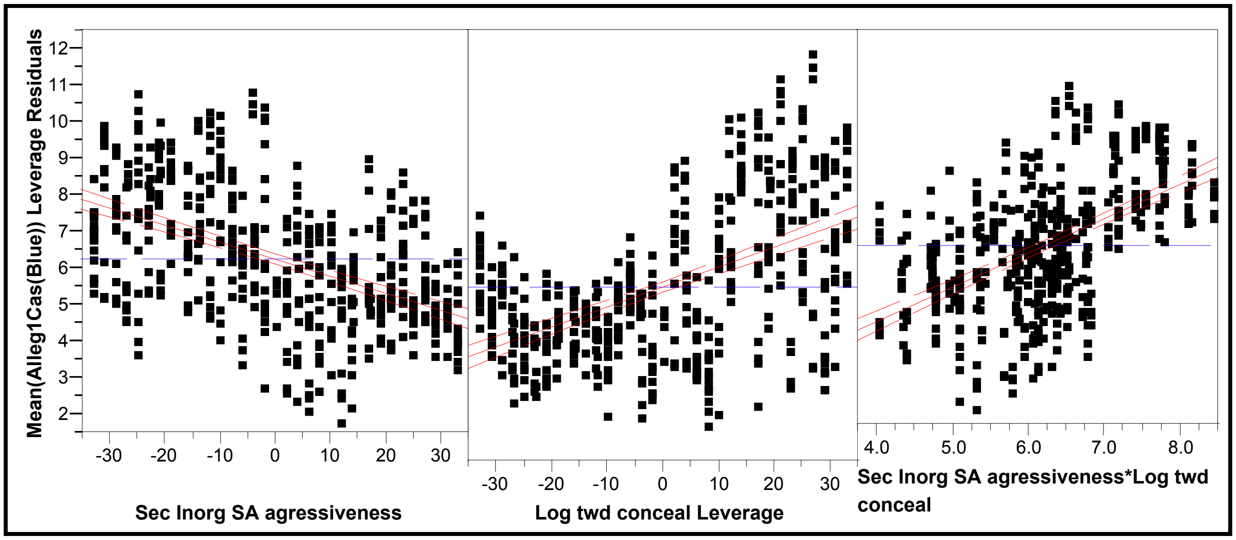


Figure 25. Leverage Plots for 3 Dominating Terms.

There are obviously some critical interactions affecting the model. Rather than dig into those interactions at this point in the analysis, we first added quadratic terms and then attempted to understand what is taking place.

3. 2nd Order Quadratic Model

Again, rather than add quadratic terms based solely on the terms from the two previous models we decided to start the stepwise function with all main effects, first order interactions and second degree polynomials. After running the stepwise function the resulting model consisted of 29 significant terms with an R^2 of 0.8075. We wanted to eliminate terms that were not providing much useful information while still maintaining a relatively good explanation of the variance. To accomplish this we reduced the criteria for terms to remain in the model by reducing the p-value level to 0.01. Only terms with a p-value of 0.01 will remain in the model. By doing this screening, the resulting model consists of 23 terms with an R^2 of 0.7927. Since this screening did not eliminate many terms we decided to look at each individual term in an attempt to whittle down the model. Viewing the step history produced by JMP, we saw that 3 terms explain 52 percent of the model. Figure 26 displays the 25 terms on the *X* axis and the R^2 value on the *Y* axis. From this plot, we can plainly see that there is a point of diminishing return. In order to increase the R^2 value of the model, we added 11 more terms to the three main terms. At this point, the model consisted of 14 terms with an R^2 of 0.7421. We feel that the R^2 value from this model is sufficiently high to be used as our final model. In the next section, we will further eliminate some irrelevant terms and produce the final model. We will then examine this model in full detail and attempt to understand exactly what is happening in the scenario based on these terms.

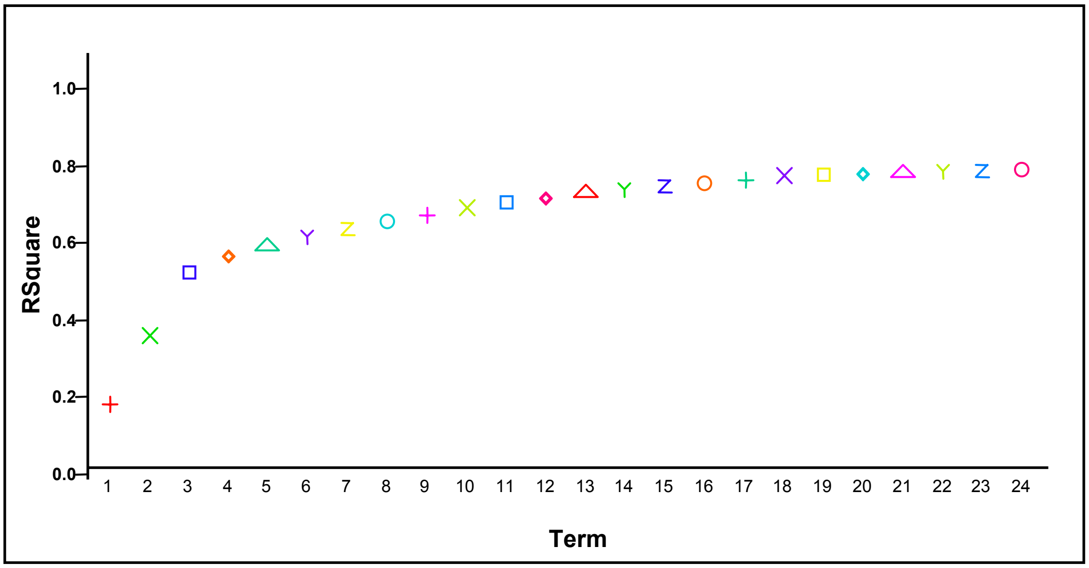


Figure 26. Model Terms vs. R Squared Value

Term	Parameter
1	(Sec Inorg SA aggressiveness-0.03101)*(Log twd conceal-0.03101)
2	Log twd conceal
3	Sec Inorg SA aggressiveness
4	Log class/detect range
5	Sec Time in State
6	(Log twd conceal-0.03101)*(Log twd conceal-0.03101)
7	(Sec stay with friends-0.03101)*(Sec stay with friends-0.03101)
8	(Sec Time in State-66.5039)*(Log twd conceal-0.03101)
9	Sec stay with friends
10	(Log class/detect range-55.031)*(UAV class/detect range-65.031)
11	UAV class/detect range
12	(Sec Time in State-66.5039)*(Sec stay with friends-0.03101)
13	Sec agent aggressive
14	Sec Loc4
15	(Security Speed-175.031)*(Log twd conceal-0.03101)
16	Log time in state
17	(Sec stay with friends-0.03101)*(Log time in state-66.5039)
18	Log Speed
19	(Security class/detection range Default-55.031)*(Log class/detect range-55.031)
20	(Sec stay with friends-0.03101)*(UAV class/detect range-65.031)
21	(Sec Time in State-66.5039)*(Log Speed-175.031)
22	(Log Speed-175.031)*(Log Speed-175.031)
23	(Security Speed-175.031)*(Sec Time in State-66.5039)
24	Security Speed

Table 3. Terms Corresponding to Figure 26.

4. Final Model

Before spending too much time looking at each of the 14 terms, we first checked the assumptions made. We plotted the actual number of blue casualties against the predicted number and the residuals against the predicted number of blue casualties. Figure 27 displays the actual vs. the predicted number of blue casualties.

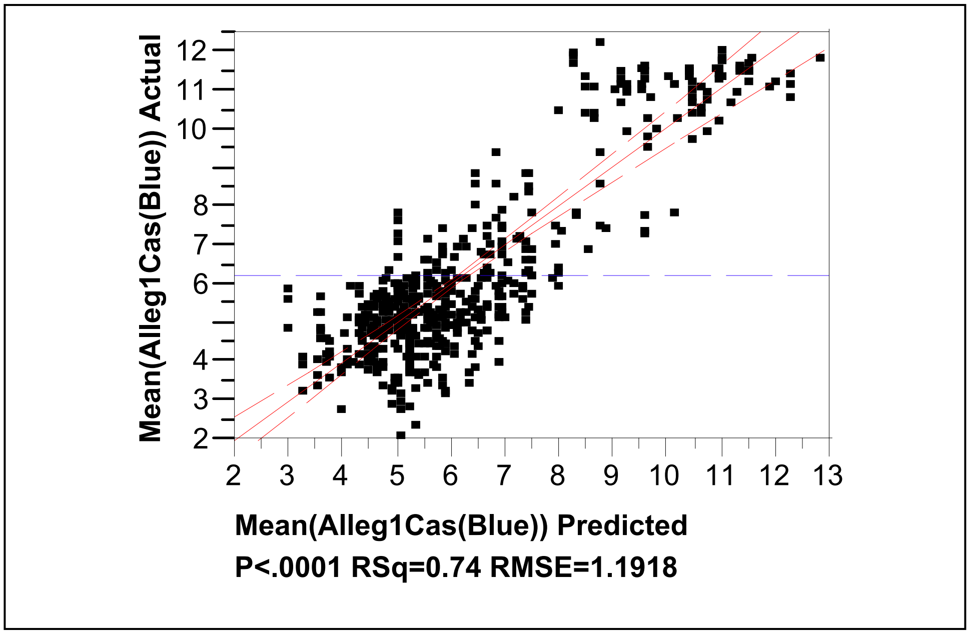


Figure 27. Actual vs. Predicted Number of Blue Casualties.

From the actual vs. the predicted number of blue causalities plot we can see a positive slope, indicating that the actual and predicted numbers of blue casualties are in general agreement.

To check the assumption of normality for the residuals we plotted the residuals against the predicted number of blue casualties displayed in Figure 28. When viewing this plot we want the residuals to have a mean of zero, constant variance and be identically distributed. At first glance there appears to be a trend in the data when the predicted number of blue casualties is greater than 8. It seems that when above 8 the model consistently under predicts the number of blue casualties. This group of points can be seen in previous plots when the number of blue causalities is greater than 8. At first this was disturbing because it indicates something is happening that is not captured in the model. After examining the scenario, it was concluded that this phenomena can attributed to an interaction between the logistic vehicles going towards concealment and the security's propensity towards the enemy when the information is received inorganically. This interaction is discussed in the next section.

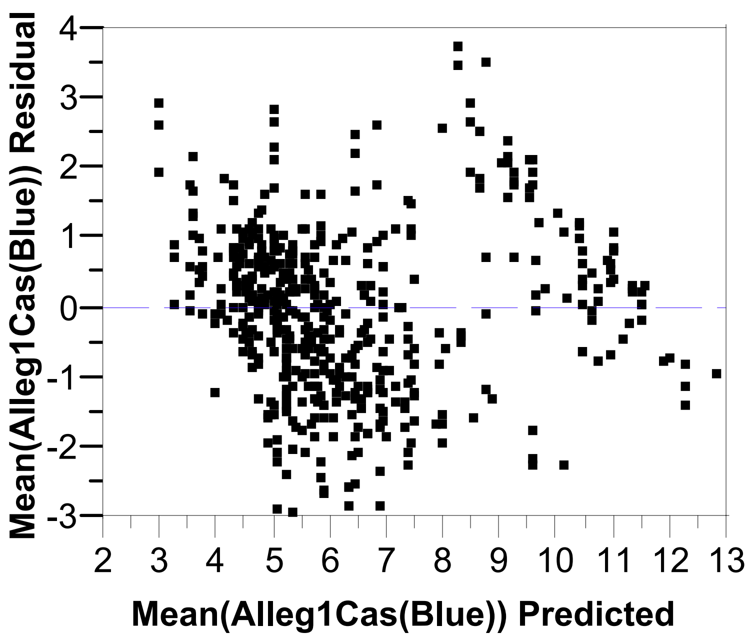


Figure 28. Residual vs. Predicted Number of Blue Casualties.

The final model consists of 14 total terms, 8 main effects, 4 two-way interactions and 2 quadratic terms. In the next section, we examine some of the most influential individual terms.

5. Significant Individual Factors

In this section, we use one-way analysis of variance tests to get an idea of which individual factors have the most significant impact on the number of blue casualties. We also identify the factor settings that contribute the most to the response (blue casualties). While we examined each of the main effects, we only present those that have the most significant impacts. We used t-tests over the entire range of each factor to determine the points where the settings are significant.

Figure 29 displays the means diamonds plot of logistics vehicles propensity towards concealment versus the number blue casualties. The variance at each factor setting shows vertically on the plot. The diamond around each column of points indicates the 95% confidence level for the predicted number of blue casualties. We notice from the plot that when the factor settings are less than 10, the variance in our predictions is much less. A negative factor setting means the logistic vehicles want to stay away from concealment and on the road moving towards the next waypoint when the convoy is ambushed. We can easily relate the setting of 10 to the scenario. In order to keep the convoy moving in a column we set the desire to stay on easy going terrain and move towards the next waypoint at 10, these factors were not varied in our final production runs. When the move toward concealment factor is set at 10, the three factors cancel each other out when MANA calculates the movement penalties. When the toward concealment factor is set greater than 10 it out weighs the others and the convoy moves toward concealment upon contact. When the factor is set less than 10, the convoy desires to stay on the road. As the toward concealment factor becomes more negative the desire to stay on the route is greater. In summary, in our scenario the convoy does better when they do not seek concealment upon contact. This is similar to doctrinal practices.

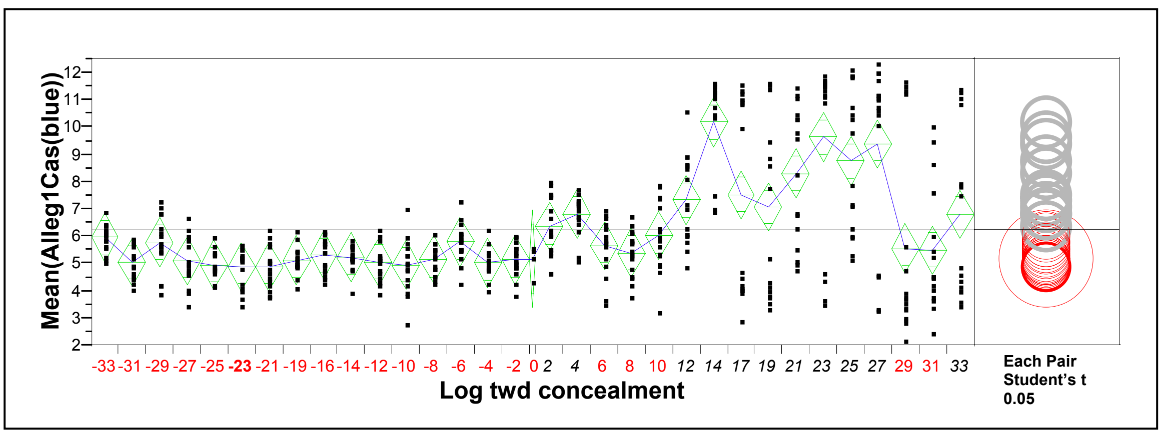


Figure 29. One-Way Analysis of Variance for Log Vehicles toward Concealment and Number of Blue Casualties.

Figure 30 displays the one-way analysis of variance plot for the security vehicles inorganic propensity of moving towards the enemy versus the number of blue casualties. The relevant factor here means that the security vehicles receive detection information from agents outside of their squad. From the plot we can see that factor settings greater than 0 are for the most part not statistically different, however, below 0 the variance becomes greater and are significantly different than positive settings. We reason that, as the security vehicles receive detection information, the more positive the setting the greater the desire to go after the enemy, hence the convoy experiences fewer casualties. With this in mind it will be interesting to view the interaction of this factor with the logistic vehicles toward concealment.

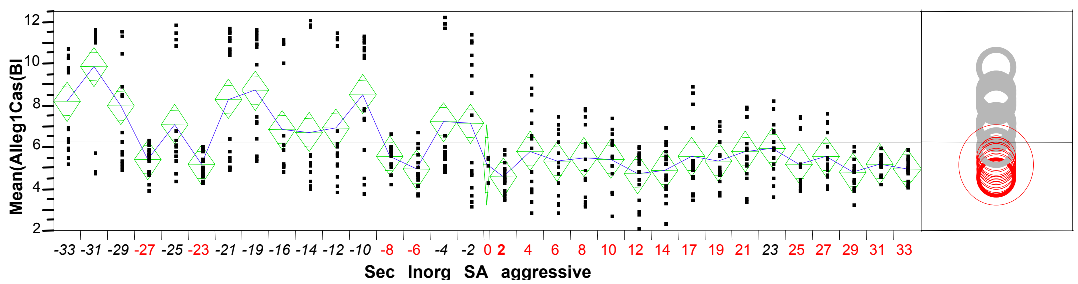


Figure 30. One-Way Analysis of Blue Casualties vs. Security Vehicle Inorganic Aggressiveness.

The last individual factor we will cover is the logistics vehicles detection range in the enemy contact state, see Figure 31. We would normally assume that as the detection ability of the convoy increases, we should see fewer blue casualties. However, that is not what we see in the plot. Several explanations could all be causing the output or individually causing. We notice in the plot that there is a general trend, as range gets larger, the blue casualties decrease. We also notice that there is a significant amount of variability throughout the plot and the mean tends to jump between neighboring settings, which we did not expect. After some careful considerations, we concluded that the variability could be due to the buildings in the scenario causing line of sight constraints on the convoy. If this was true we would expect a point in the range where blue casualties rise and stays for points thereafter, which is not the case. At this point we turned to the scenario's construction to see if this could be due to the factor settings. The logistics vehicles detection range is varied in the enemy contact state, meaning that once the convoy encounters the enemy, the factor is varied. The reasoning behind this was originally to see if a heightened state of awareness once ambushed leads to fewer blue casualties. To see if this is true we constructed a contour plot of logistic vehicle detection range and security vehicle inorganic aggressiveness against the number of blue casualties, see Figure 32. The plot shows an area towards the top right side where casualties are lower when the detection ranges are high and security vehicle aggressiveness is high. We can conclude that an increased state of awareness during an ambush seems to make a difference in our scenario.

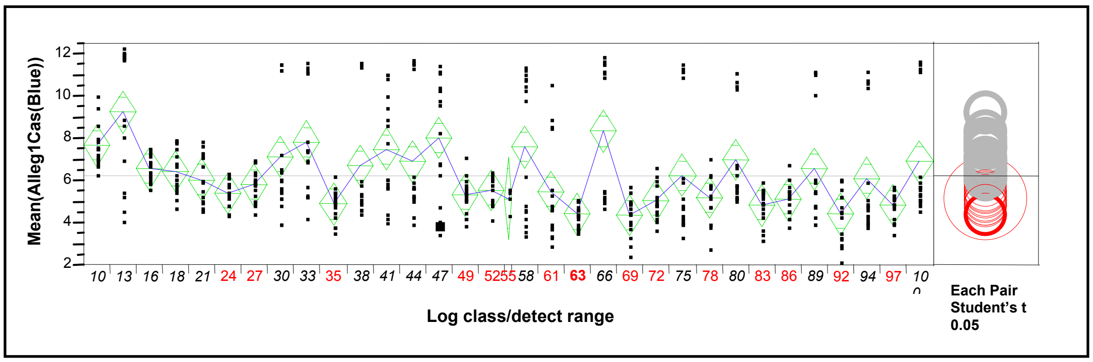


Figure 31. One-Way Analysis of Logistic Vehicle Classification Range vs. Number of Blue Casualties.

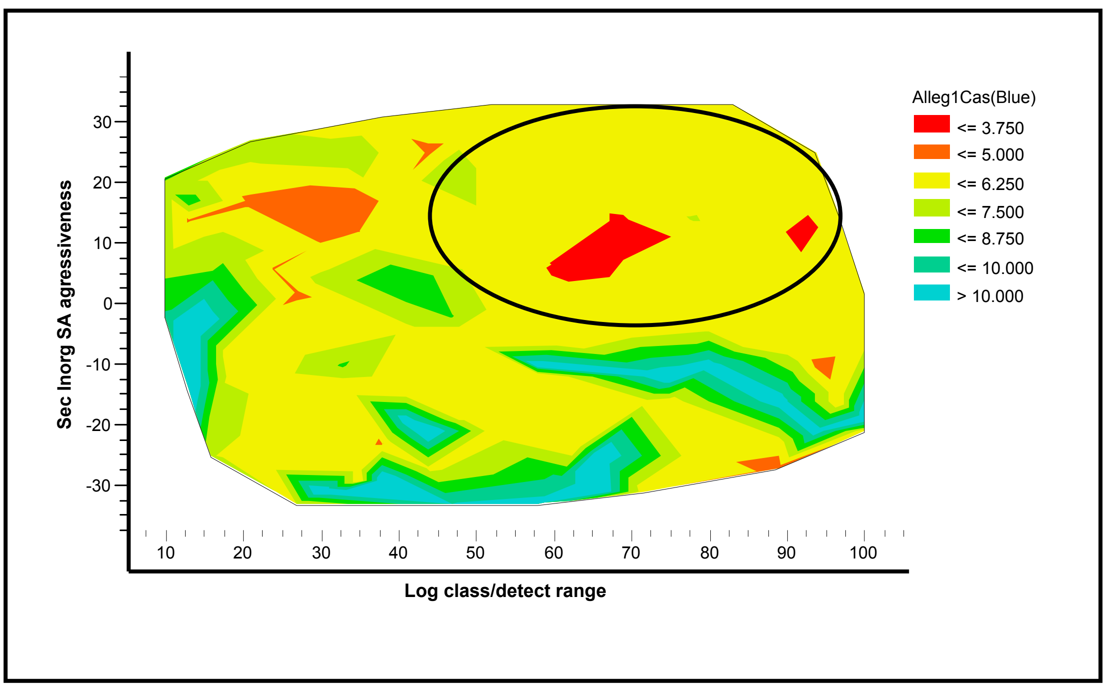


Figure 32. Contour Plot of Security Vehicle Inorganic Aggressiveness and Logistic Vehicle Detection Range vs. Number of Blue Casualties. (Best Viewed in Color)

We have identified some of the individual factor effects in our model, next we will cover some of the interesting interactions that seem to play a bigger role in our scenario than the individual factors.

6. Significant Interactions

In our model interactions between factors seem to be explaining a large portion of the variance. We use contour plots to examine the interactions more closely. In a contour plot, two factors are plotted along the axes with the response variable (blue casualties) depicted as a contoured regions within the plot.

Of the three interactions in our model, the interaction between the security vehicles inorganic aggressiveness and the logistics vehicles desire to seek concealment is by far the most influential explaining roughly 20 percent of the variance in the model. Figure 33, displays this contour plot. Areas of interest are highlighted with ovals and numbered 1, 2 and 3. We can plainly see in oval 1 when concealment is greater than 10 and aggressiveness less than 10, the convoy suffers high casualties. In oval 2, when concealment is still high but aggressiveness less than 10 casualties drop to about 5 and fewer. In oval 3 where concealment is less than 10 and aggressiveness positive, casualties are again relatively low. Relating this to our scenario provides some interesting perspectives. It should be noted that the value of 10 can be related to the scenario construction, agent personality traits that are not varied were set at 10, so when our varied factors are altered, we see differences outside of that value. In some aspects, the value of 10 can be thought of as a baseline. In oval 1 our logistics vehicles are seeking concealment upon enemy contact while simultaneously the security forces are not seeking to engage the enemy; intuitively we are suffering high casualties. In oval 2 the logistics vehicles are seeking concealment, but now the security forces are engaging the enemy, again, intuitively we are suffering fewer casualties. However, and more interesting in oval 3, the logistics vehicles seek to continue along the route upon contact while the security forces engage the enemy. This in itself is not that interesting but if we look closer at the plot, we see that even when the security aggressiveness is negative we still suffer roughly the same number of casualties. Although, the convoy does better when security vehicle aggressiveness is high, the plot suggests that the actions of the logistic vehicles play a bigger role than does the actions of the security vehicles. This occurrence could play a role in training logistic vehicle operators, by emphasizing their procedures upon enemy contact.

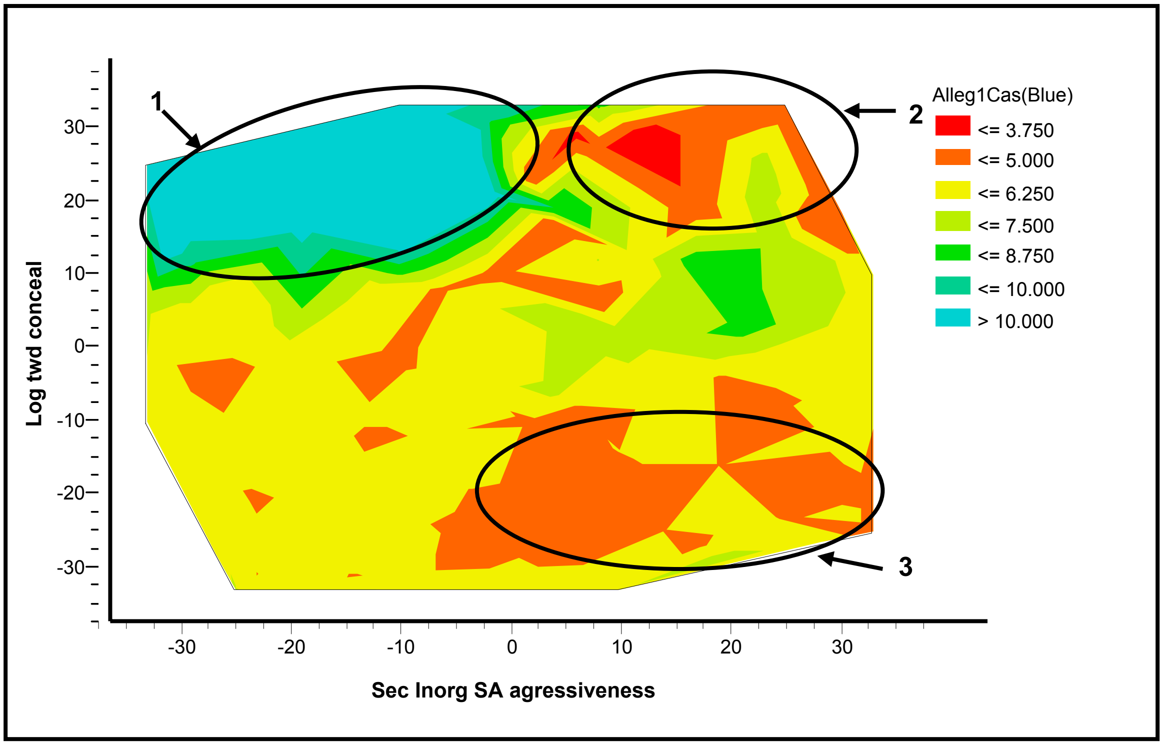


Figure 33. Contour Plot of Security Vehicle Inorganic Aggressiveness Against Logistic Vehicle Towards Concealment. Ovals 1, 2 and 3 Represent Areas of Interest. (Best Viewed In Color)

In Figure 34, we examine the interaction between the security vehicles time in state and the logistic vehicles' propensity towards concealment. In our scenario construction, the default state acts as a baseline where the logistic vehicles stay on the route and keep moving and the security vehicles only slightly desire to engage the enemy. Enemy contact state *spare 1* was established to vary the convoy's tactics upon enemy contact. If the time in state is high, there can be several effects, the security will either pursue the enemy for an extended period or stay away from the enemy. The scenario was purposely designed so we could see the effect of the security vehicles pursuing the enemy rather than simply firing and moving on to the next waypoint. In order to understand what is happening we need to look at several different plots. In Figure 34, we see that the convoy does the best when the logistic vehicles stay away from concealment regardless of the security time in state, as seen in oval 2. In oval 1 we see that the casualties are high when time in state is high and the logistic vehicles desire to move toward concealment high. This is explained by the fact that the security will pursue a contact for an extended period while the logistic vehicles hide; this leaves the convoy vulnerable to enemies who have not yet been detected.

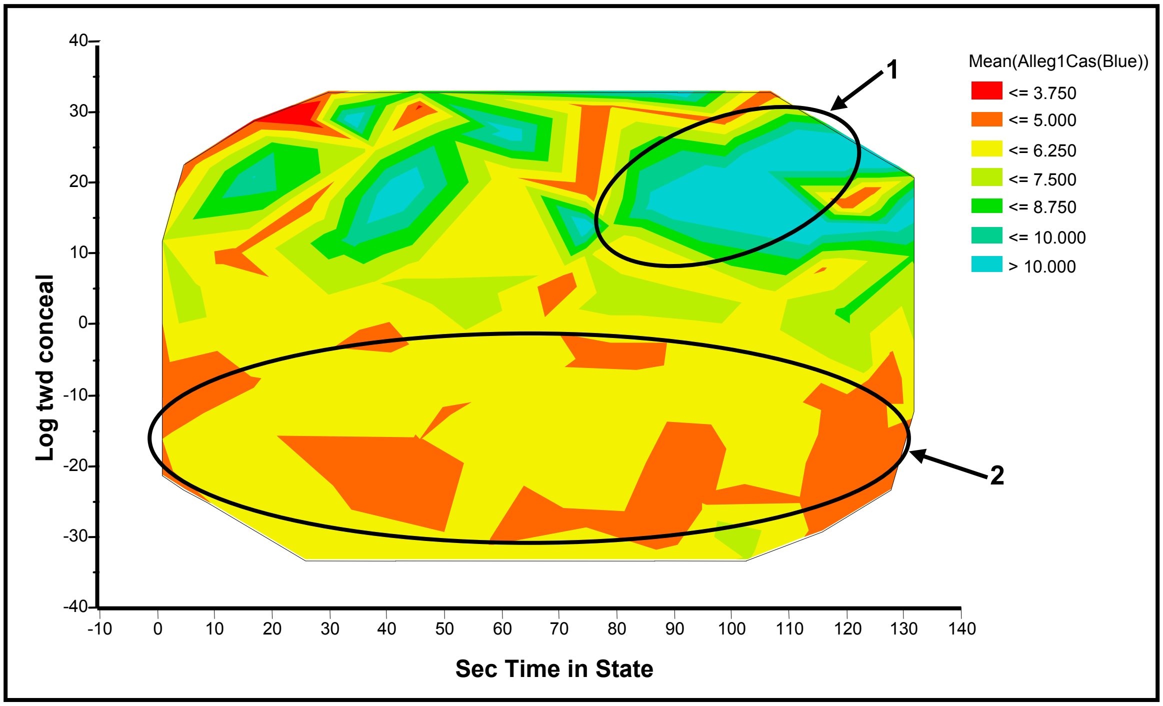


Figure 34. Contour Plot of Security Vehicle Time in State vs. Logistic Vehicles Propensity Towards Concealment. Ovals 1 and 2 Highlight Areas of Interest. (Best Viewed in Color)

To interpret what is happening in the scenario we looked at a contour plot of the security inorganic aggressiveness vs. security time in state, see Figure 35. As expected, as security aggressiveness increases, casualties decrease regardless of the time in state. In addition, as aggressiveness decreases and time in state increases, there are a high number of casualties. After careful consideration of the scenario, we conclude that this could be caused by the inner workings of the scenario. For example, when time in state is low and aggressiveness high, the security will pursue the enemy every time there is a detection, which has the same effect as increasing the time of the contact state. This explains why we see the same outcome across the range of the time. However, when aggressiveness is low and time in state is high we see the opposite effect. The security stays away from contacts and does so for the duration of the respective time. This explains why we see high casualties in the lower right corner of the plot. Though this might seem intuitive, in our scenario it suggests that the success of the convoy is not affected by the security pursuing the enemy or by staying with the convoy and providing suppressive fire.

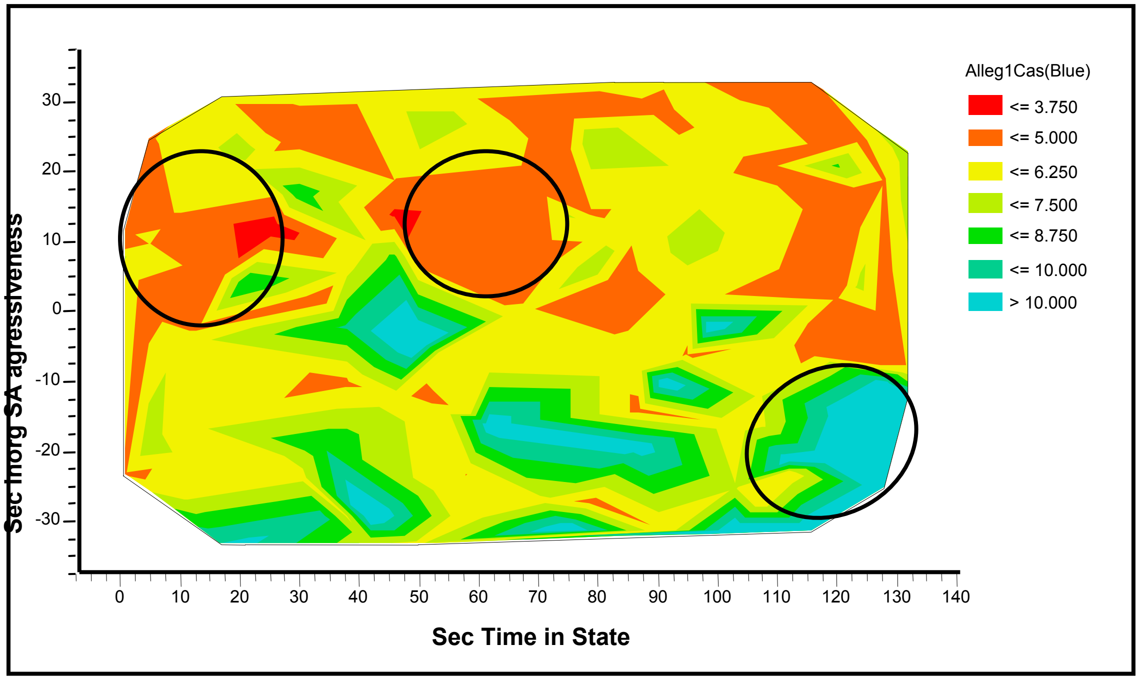


Figure 35. Contour Plot of Security Vehicle Time in State vs. Security Vehicle Inorganic Aggressiveness. Highlighted Circles Identify Areas of Interest. (Best Viewed in Color)

In this section, we have identified some of the critical interactions in the model. In the next section, we will look at some of the outliers that we saw in Figures 23 and 24.

7. Outliers

To begin examining the groups of outliers we refer the reader back to Figures 23 and 24 on pages 54 and 55 respectively. To take a closer look at some of the outliers we use a regression tree to see where the main effects of the model make significant splits in the data. Viewing Figure 36, we can easily see that our splits occur in our outlying areas. The first split occurs at the logistics vehicles toward concealment term, 340 of the 516 observations are identified when the factor is less 12. When the logistic vehicles stay away from concealment, we see the mean drops to 5.4 blue casualties. When towards concealment is greater than or equal to 12 the mean rises to 7.8, and there is obvious variance in the data. The next split begins to explain our outliers. When the security vehicles' inorganic aggressiveness is greater than or equal to 2 the mean drops to 5.21 blue casualties, when less than 2 the mean makes a big jump to 10.9 and dissects the group of outliers in the top right of Figure 36. The final split occurs when the logistic vehicles detection range is 58 pixels. When greater than or equal to 58 the mean casualties are 4.03 and when less than 58 the mean is 6.61. Consequently, these splits produce an R^2 of 0.828 and explain our three groups of outliers. In our scenario, we can conclude that a convoy experiences the greatest success at these factors settings.

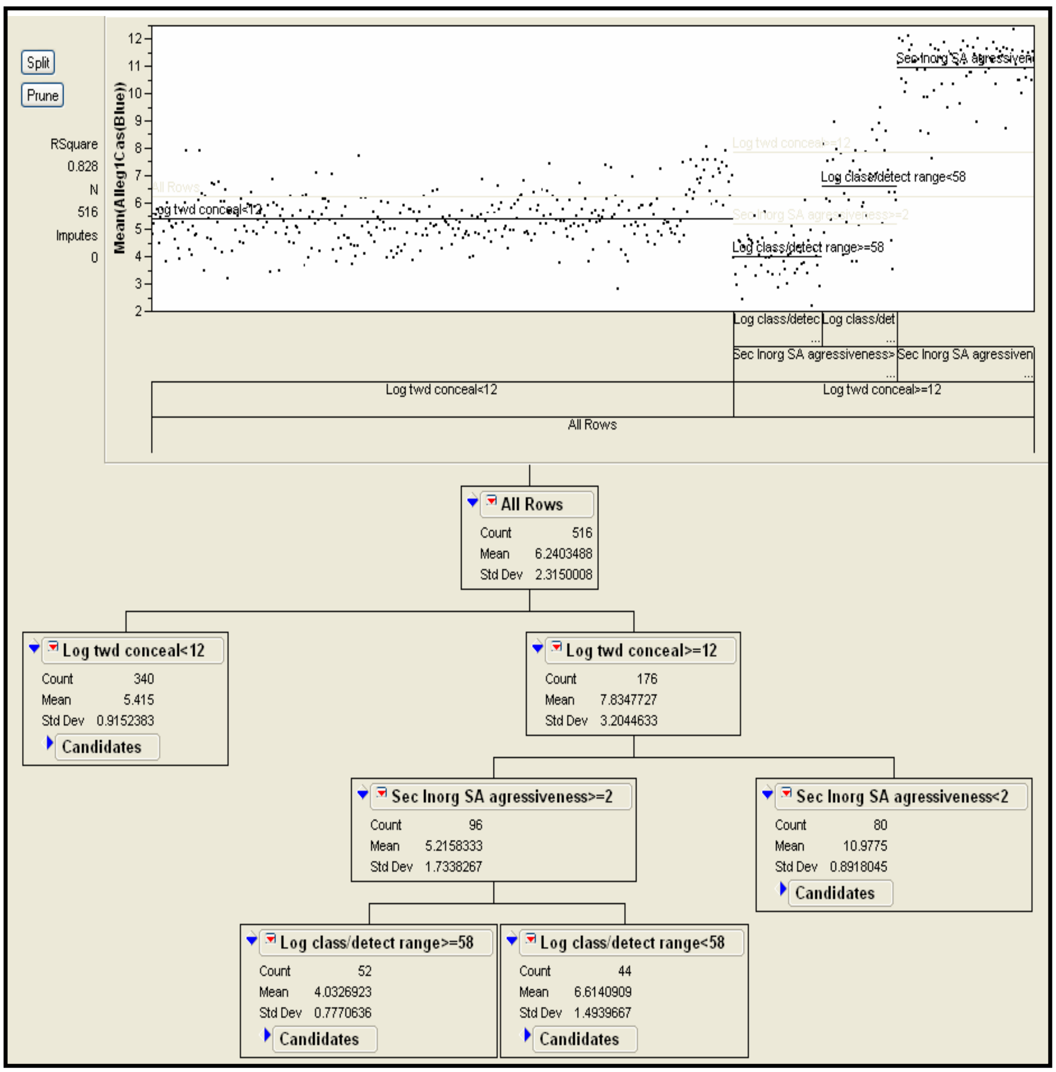


Figure 36. Regression Tree of Main Effects.

8. Interesting Observations and Interpretations

In this section we look at some of the interesting observations learned while examining the data and scenario. We will look at the location of security vehicles within the convoy, how the UAV helped in the scenario, the relationship between inorganic aggressiveness and the organic aggressiveness and finally how vehicle speeds impact the model.

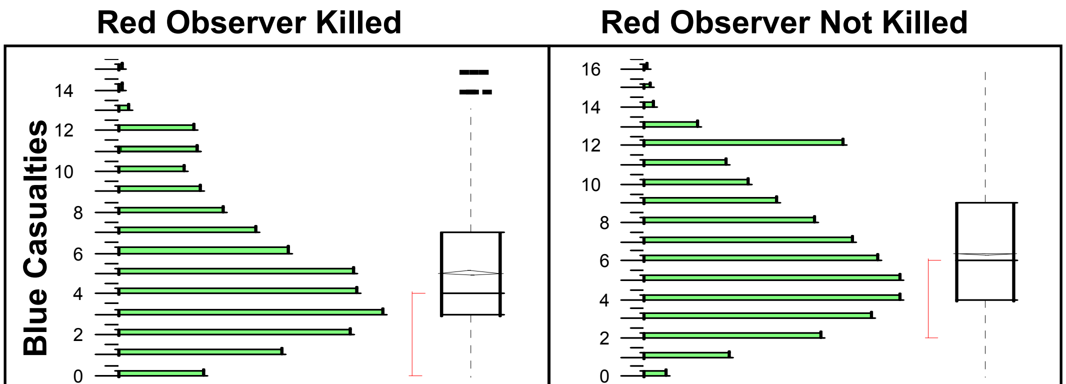
When we began building the scenario, one of the key factors we wanted to examine was the location of security vehicles within the convoy. Though three of the four locations did not survive the screening process for the final model, there are some interesting observations to be made from the 4 locations. Security location 1 evenly distributes security amongst the convoy, location 2 places 2 vehicles in the front and 1 in back, location 3 places 1 in the front and 2 in back and, finally, location 4 places all 3 security vehicles in the center of convoy. Location 4 is the only placement that made it to the final model. As we expected, location 4 has a positive slope, which indicates more casualties when used. Although we expected location to play a bigger role in the outcome, we are pleased to see that location 4, which would be absurd in real life, exhibited this outcome in the results. After observing the scenario and watching the 4 locations run we concluded that the inability of MANA to constrain agents maneuvering amongst each other caused the differing locations to produce similar results. We attempted to utilize the *cluster constraint* and the *max and min influence* settings to inhibit the vehicles when moving near each other, but it did not seem to affect the outcome. This could be because we set the movement precision selection low in order to keep the vehicles in a column on the road. We must remember that there are only 16 possible blue casualties in the scenario, with 6450 observations for each location our means will tend to be similar.

To this point, we have not examined the value that the UAV provides in the scenario. Recall from Chapter III that the UAV moves along the route searching for enemy agents, if the UAV spots the enemy observer, it will call for long-range fire to eliminate the observer. We want to see how the convoy does when the observer is eliminated. Of the 25,800 observations, there are 2,203 where the observer is detected and eliminated. In Figure 37, we compare the distributions and summary statistics of when the red observer is killed and when not killed. We can plainly see that there is a statistical difference in the two means, suggesting the convoy does better when the observer is eliminated. Of more interest is the larger proportion of observations where casualties were less than or equal to 4. When the observer dies, 50 percent of the observations result in 4 or fewer casualties versus the alternate where only 25 percent of the observations were 4 or fewer. A final point to make regarding the importance of the UAV is the fact that out of the 25,800 total observations there were only 334 where the convoy suffered no casualties, of the 334, 97 occurred when the UAV detected the observer. We used the following hypothesis test of population proportions to determine if there is a statistical difference between the two cases.

$$H_0 : p_1 - p_2 = 0$$
$$H_a : p_1 - p_2 \neq 0$$
$$Test\ statistic : z = \frac{\hat{p}_1 - \hat{p}_2}{\sqrt{\hat{p}\hat{q}(1/m + 1/n)}}$$

Where p_1 is the proportion of convoys with no casualties if the observer is killed and p_2 is the proportion of convoys with no casualties when the observer is not killed. From the test we get a z test statistic of 10.445, using an α of .005 the corresponding z value is 2.58. From this test, we get a *p-value,* which is the probability that the null hypothesis is true, of 1.296 x E^{-25}. This *p-value* is so minuscule that at any reasonable level of α the null hypothesis should be rejected. The two proportions are clearly not equal and we reject the null hypothesis that the two proportions are equal.

From the test we can conclude that the UAV does provide a significant advantage to our convoy and that usage of UAVs for convoy route surveillance should be closely examined.



Red Observer Killed

Moments

Mean	5.018611
Std Dev	3.2584855
Std Err Mean	0.0694238
upper 95% Mean	5.154754
lower 95% Mean	4.882468
N	2203

Quantiles

100.0%	maximum	15.000
99.5%		13.000
97.5%		12.000
90.0%		10.000
75.0%	quartile	7.000
50.0%	median	4.000
25.0%	quartile	3.000
10.0%		1.000
2.5%		0.000
0.5%		0.000
0.0%	minimum	0.000

Red Observer Not Killed

Moments

Mean	6.3544095
Std Dev	3.4048411
Std Err Mean	0.022165
upper 95% Mean	6.3978544
lower 95% Mean	6.3109646
N	23597

Quantiles

100.0%	maximum	16.000
99.5%		14.000
97.5%		13.000
90.0%		12.000
75.0%	quartile	9.000
50.0%	median	6.000
25.0%	quartile	4.000
10.0%		2.000
2.5%		1.000
0.5%		0.000
0.0%	minimum	0.000

Figure 37. Comparison of Data When Red Observer is Eliminated to When Not Eliminated, Using Histograms and Summary Statistics.

From the data set, we notice the relevance and irrelevance of the security vehicles inorganic aggressiveness and organic aggressiveness, respectively. Recall that inorganic aggressiveness refers to a security vehicles' desire to pursue the enemy when the detection is received from outside its squad. Organic aggressiveness refers to an agents' desire to pursue the enemy when they make the enemy detection themselves. We were surprised to see that organic aggressiveness is not a significant factor in the model. After careful consideration of the scenario it became apparent what is actually happening and seems to be a remnant of the scenario construction. Recall that our security vehicles are all separate squads, each with one vehicle. When we conducted our runs, we locked the security vehicles together when their relevant factors were varied. This causes them to act as a single squad with the same desires. Since an inorganic communications link was established between the three squads, in essence if one detects the enemy, they all detect and respond similarly. We reason that due to the model construction the effects of the inorganic aggressiveness were dampening those of the agent aggressiveness. In hindsight, if we wanted to examine the effects of each security vehicle acting independently we should have unlocked the factor settings for organic aggressiveness. Though this might seem to be a waste of a factor, it seems to demonstrate the importance of the communications links between the blue squads.

From our exploratory runs and logical thinking, we presumed that vehicle speeds would have a significant effect in the scenario. We varied both the security vehicle speeds and the logistic vehicle speeds upon enemy contact. One would think that the faster the security can close on the enemy and the logistics vehicles can move from the kill zone, the fewer casualties we would suffer in the scenario. Neither of the terms provide a significant impact on the final model. However, looking closer at the data, we can see from the contour plot in Figure 38 that convoy success depends on the speeds of the vehicles being relatively close to each other. Meaning that if the security is fast but convoy is slow we do bad, and vice versa. The oval in Figure 38 shows a trough on the diagonal of the plot that justifies this conclusion. Consequently, in our scenario, the security vehicles staying close to the convoy plays a bigger role than speed alone.

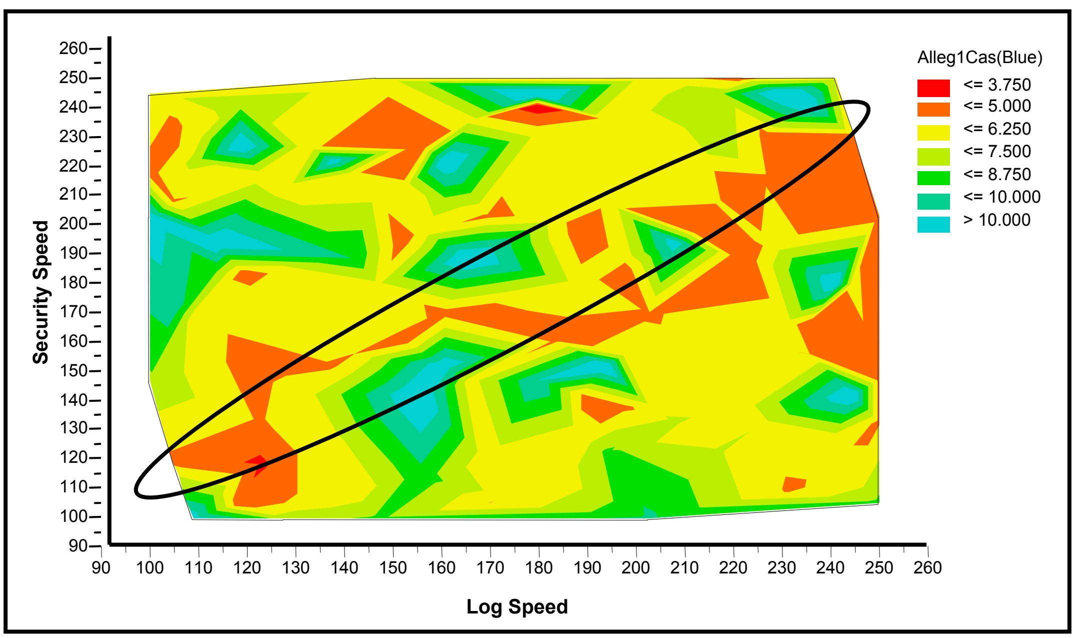
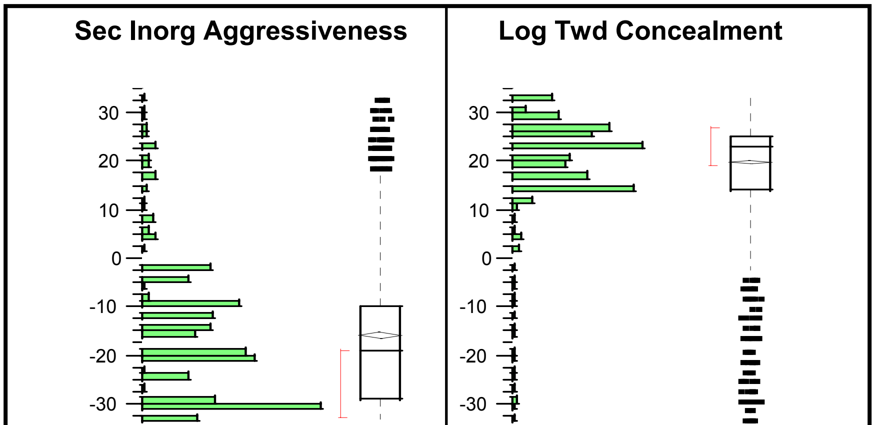


Figure 38. Contour Plot of Log Speed vs. Security Speed. (Best Viewed in Color)

Earlier in this chapter we noted the high number of runs that resulted in 12 blue casualties. Looking closer at the instances where this occurred we find it can be explained by several occurrences. We plotted the distributions of parameter settings against the number of blue casualties when they are 12 and 12 or greater. From the plots, we were able to identify the factors that are biased towards a range of settings. Of the 12 factors, 2 show a significant bias towards a range of settings, see Figure 39. When security inorganic aggressiveness is negative and logistic vehicles toward concealment is positive, we see the 12 blue casualties occur. In order to figure out why there is a spike at 12 blue casualties in the data we plotted the same factors against when casualties were 12 and greater. In Figure 40, nearly the same distributions appear for the two relevant factors. At this point, we are convinced that the spike at 12 is an artifact of the scenario and not by something occurring out of the ordinary. There are 15 vehicles in the convoy that can be killed, three of which are security vehicles that can only be killed by the IED or an RPG shooter. When the casualties are 12 or greater, the security tends to avoid contact while the logistic vehicles look for concealment. In most cases, it appears that either the RPG or the IED at the start of an ambush hits the first security vehicle. At the same time, the other two security vehicles fall to the rear of the convoy away from the enemy. This causes the RPGs to attack the logistical vehicles seeking concealment. Each RPG shooter has only three rounds, and are used on the logistics vehicles in these cases. By the time the surviving security vehicles resume movement, there are no other weapons capable of killing the security and we see the result of a spike at 12. In most cases this resulted in 2 security vehicles and 1 logistics vehicle surviving. Worth mentioning, is the fact that fewer red agents are killed in these runs, specifically the RPG, who after firing all 3 rounds will retreat. We believe that the spike at 12 is not significant and can probably be shifted by a small change in the scenario, for instance, increasing or decreasing the number of RPG rounds. Of more importance is what causes the high number of blue casualties, which was explained previously in this chapter.



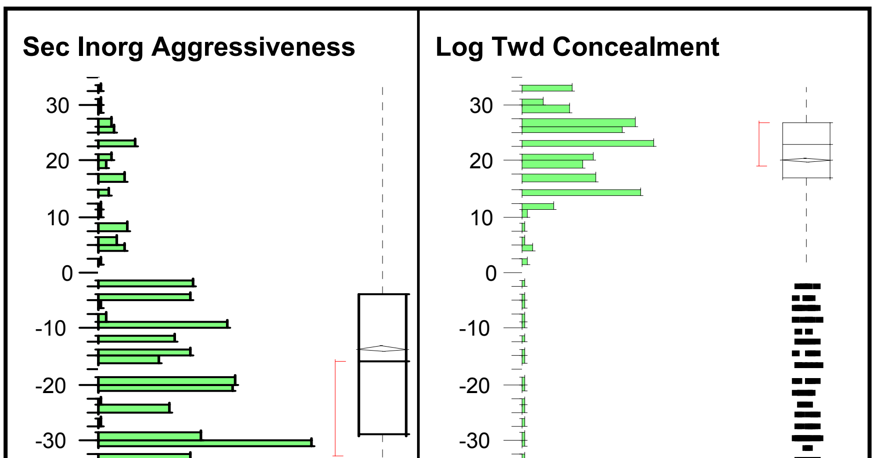
Moments (Sec Inorg Aggressiveness)

Mean	-15.86961
Std Dev	14.138188
Std Err Mean	0.3029457
upper 95% Mean	-15.27551
lower 95% Mean	-16.4637
N	2178

Moments (Log Twd Concealment)

Mean	19.755739
Std Dev	10.270482
Std Err Mean	0.2200705
upper 95% Mean	20.187309
lower 95% Mean	19.324169
N	2178

Figure 39. Distributions of Security Inorganic Aggressiveness and Logistic Vehicle Toward Concealment when there are 12 Blue Casualties.



Moments (Sec Inorg Aggressiveness)

Mean	-13.74481
Std Dev	15.959366
Std Err Mean	0.2920591
upper 95% Mean	-13.17215
lower 95% Mean	-14.31747
N	2986

Moments (Log Twd Concealment)

Mean	20.185532
Std Dev	9.9815108
Std Err Mean	0.1826633
upper 95% Mean	20.543691
lower 95% Mean	19.827374
N	2986

Figure 40. Distributions of Security Inorganic Aggressiveness and Logistic Vehicle Toward Concealment when there are 12 or greater Blue Casualties.

9. Conclusions

In this chapter, we have built a model that explains 75 percent of the variance in our data set when predicting blue casualties, we have thoroughly examined the significant terms in the model and we have highlighted some of the other interesting observations found in the data set. Though most of our conclusions are intuitive regarding convoy operations, we have shown that it is possible to model convoys using agent-based models. We have come to this conclusion by observing extreme effects that were purposely planted in the scenario to help validate the outcomes. In the final chapter of this thesis, we will summarize our findings and try to relate them to the "real world." Appendix B provides the actual summary statistics from our final regression model. It should be noted that interpreting the terms as they relate to our scenario is relevant, using an actual regression equation from this scenario to predict in the "real world" is not.

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VI. CONCLUSIONS AND RECOMMENDATIONS

Over the course of this research, we have seen the end of offensive operations and the beginning of the nation building process in Iraq. As the nation building process has evolved over the past several months we have witnessed an insurgent force in Iraq establish themselves and continually find the means to inflict casualties on the coalition forces. The insurgents are evolving and are constantly honing their tactics, techniques and procedures. We know that the majority of attacks occurring are directed at coalition vehicle convoys. We can assume that future enemies will realize the success of this tactic.

This thesis has taken a simulation and modeling approach to examining the tactics, techniques and procedures employed during convoy operations. We have examined historical considerations, reviewed the current doctrinal practices, explained the chosen modeling environment, data farmed over numerous possible factors and applied some common statistical techniques to analyze the results. In this chapter we summarize our findings and provide recommendations for each of major phases of this thesis.

A. CONCLUSIONS

1. Convoy Operations

We have observed insurgents in Iraq consistently attacking our convoys. We can assume that this trend will continue in Iraq and future enemies will adopt the tactic. Movement of supplies is an integral part of any military operation and we cannot afford to be limited in our movements by small forces with minimal resources.

In this thesis we have identified some of the important factors surrounding convoy operations based on our scenario. We understand that convoy operations in hostile situations are subject to an extremely chaotic environment where millions of varying factors can produce a wide range of outcomes. It would be impossible to model every minute detail of a convoy operation in a single scenario, but this was not our intent. We wanted to identify global effects of prominent factors and determine if it was possible to model convoys using an ABM.

From our scenario we cannot say that traveling at a certain speed is optimal or that surveying a convoy route with a UAV will always guarantee positive results. However, there are few areas of interest we can conclude from information obtained from our scenario:

- Use of a UAV dramatically reduces the number of casualties suffered.
- Communications between all parties involved, including the UAV significantly increases the probability of success.
- The convoy composition (i.e. positioning of security vehicles) is important. For example, while having combat power massed in most combat operations is a benefit, we found in our scenario, when security vehicles are massed in one location of the convoy it leads to more casualties.
- The tactics of the logistic vehicles is a bigger determinant of success than that of the security vehicles.
- Speeds of vehicles are relative, it is more important for the convoy to operate as unit than as individuals.

To the operators in the field, we pose these observations as areas to examine in the hope that through practical real world experimentation we can find better ways to conduct convoy operations.

2. Agent-Based Models

Agent-based models provide us with a modeling environment to quickly create scenarios based on an abstraction of a complex problem. Coupled with the data farming process, the tool is extremely powerful in providing us with insights into a larger and more complex problem. Though a powerful tool, caution should be exhibited in their use, definitive conclusions and predictions should not be made from the outcome of an ABM. Rather, we should seek to increase our understanding of the relevant problem and hopefully gain insights from the global behaviors exhibited in the outcomes. Combat operations exist in a dynamic and fluid environment where human interactions control outcomes. ABMs offer us a tool that attempts to simulate these interactions.

B. RECOMMENDATIONS

1. Convoy Operations

In our research, we have only scratched the surface of the possible factors that can be examined to gain insights into convoy operations. If further research is conducted on this topic using ABMs, we highly recommend that subject matter experts (SMEs) be intimately involved in creating the scenario. We were able to gain some input but not at the level required. Adding SMEs to the process helps to validate the assumptions made when modeling and also provides a much needed reality check on the outcomes. It is the opinion of the author that SME input and constructive criticisms, coupled with the statistical knowledge of an analyst will pay dividends for the Armed Services.

2. Agent-Based Models

Though we were successful in modeling a convoy in MANA, there are some constraints that could skew some of the output. We found it difficult to model the effects of vehicle movements. Unlike the movements of humans on the ground, the movement of vehicles is much more constrained by their surroundings. A major factor in convoy operations is the dispersion distances between vehicles, we attempted to model this factor, but in the end, we do not believe it was effectively modeled providing any useful information. Dispersion distances can severely influence the effectiveness of enemy weapons and IEDs on convoys, as well as the effectiveness of the convoy weapons on the enemy. The low resolution of ABMs inhibits us from examining these types of details, but we should remember that ABMs are not designed to look at very detailed physical effects.

It was found that current convoy sizes are relatively small, around 20 vehicles, however, during the offensive operations of OIF the logistical convoys tended to be well over 50 vehicles. If we wanted to model a larger convoy over bigger terrain area in MANA, it would be difficult due to the constraints of the graphical MANA battlefield. Perhaps this type of modeling environment is not quite ready for examining a larger convoy.

We pose these observations to the ABM developers not as criticisms, rather as insights for them to contemplate in future development of follow-on versions of the models.

C. AREAS FOR FOLLOW ON RESEARCH

There are thousands of problems within the military that can be examined using ABMs. During the course of this research, we found numerous topics within the area of convoy operations that can and need to be examined. The following is a list of topics that could be examined either independent of this thesis or as a follow-on to this thesis.

- Alter the size of convoys with varying numbers of security vehicles and weapon mixes.
- Examine convoy operations in a more urban terrain.
- Thoroughly model and examine the effects of communication amongst the convoy vehicles. We assumed perfect communications in our scenario, this is far from reality.
- Model convoy operations using emerging technologies, such as gunfire detection and location (GDL) devices and frequency jamming systems to counter IEDs.

We leave the reader with one final thought; during the Cold War, control of the skies was of the utmost importance during a conflict. In the current global environment, control of the roads is now at the top of our list.

APPENDIX A. FACTORS EXPLORED

Listed are the 11 factors that where explored in this thesis. We identify the factor, state in which it is varied, the range of the factor, the MANA definition from version 3.0.35 user's manual [Anderson, et al., 2004], and finally our interpretation of how the factor relates to the "real world."

A. SECURITY LOCATION

- State – Security vehicles are placed in their respective positions (listed below) at the start of each run. We use four separate scenarios to examine locations.
  - Location 1 – Per doctrine [MCRP 4-11.3F, 2001], security is evenly distributed within the convoy, 1 front, 1 middle and 1 in the rear of the convoy.
  - Location 2 – 2 in front and 1 in the rear of convoy.
  - Location 3 – 1 in front and 2 in the rear of convoy
  - Location 4 – All 3 security vehicles in middle of convoy. This location was used to identify the validity of the scenario; we expect this location to result in more blue casualties.
- Range – Not applicable for this factor.
- MANA Definition – Not applicable for this factor.
- Real World Interpretation and Justification – In our research we had seen reports from the AOR instructing the use of security vehicle locations that were not in agreement with doctrinal practices. We wanted to identify if altering security vehicle locations would impact mission success in our scenario.

B. SECURITY SPEED

- State – Spare 1, which is the enemy contact state.
- Range – (90 to 250)
- MANA Definition – The number of cells an agent can move in a single time step divided by 100. Speed can be set between (0-1000) and can change in altering states.
- Real World Interpretation and Justification – Security vehicle movement speed. We wanted to see if the security vehicles were able to close on the enemy faster, if it would make a difference in results. A speed of 100 was set as the baseline for vehicles. We assumed the average convoy speed

would be around 30 mph. A speed of 250 would represent 80 mph, which is extreme, but we wanted to see if extreme cases make a difference. A convoy speed of 100 is roughly 3 times the speed of the enemy ambushers.

C. SECURITY VEHICLE TIME IN STATE

- State – Spare 1.
- Range – (1 to 132)
- MANA Definition – Number of time steps a squad will stay in a state once it has been triggered. If a state of 0 is set the state will never be entered. The time can be set between 0 and 99,999,999.
- Real World Interpretation and Justification – The duration of time security vehicles will pursue an enemy or act on the corresponding tactics of the relevant state. Time in state was used to identify if a prolonged pursuit of the enemy contributed to mission success or failure.

D. SECURITY VEHICLE AGENT SA AGGRESSIVENESS (ENEMY)

- State – Spare 1.
- Range – (-33 to 33)
- MANA Definition – Agent SA refers to an agents' propensity towards personalities based on information it has obtained in the current time step.
- Real World Interpretation and Justification – Corresponds to how much the security wants to engage an enemy. We used a negative value to identify extremes, where the security actually stays away from enemies.

E. SECURITY INORGANIC SA AGGRESSIVENESS (ENEMY)

- State – Spare 1.
- Range – (-33 to 33)
- MANA Definition – Inorganic SA refers to a squad's response based on contact information received from agents outside of the relevant squad.
- Real World Interpretation and Justification – Corresponds to how much the security vehicles want to engage an enemy based on information received from other squads or units, could be from other security vehicles, logistical vehicles or a UAV. Our reasoning was that this factor would show the value of communications and situational awareness.

F. SECURITY VEHICLES STAY WITH AGENT SA FRIENDS

- State – Spare 1.
- Range – (-33 to 33)
- MANA Definition – Refers to an agent's propensity towards other agents of the same allegiance within sensor range.

- Real World Interpretation and Justification – Represents how much the security vehicles want to stay with and protect other vehicles in their proximity. The negative value was used to show extreme cases where the security leaves the logistical vehicles. However, if this factor is coupled with a negative propensity towards the enemy we see an extreme case that would never happen in the "real world."

G. SECURITY VEHICLE CLASSIFICATION/DETECTION RANGE

- State – Default
- Range – (10 to 100)
- MANA Definition – Refers to the radius in cells that an agent can see other entities around them. Classification refers to the radius in cells that an agent can classify detections as friendly, enemy or neutral. In our scenario the two are locked together.
- Real World Interpretation and Justification – Represents the visibility limitations that vehicles in a column coupled with terrain, weather and movement might cause the convoy. The default state for security vehicles was used to see if earlier enemy detections by the security vehicles cause a significant difference.

H. LOGISTIC VEHICLES TOWARD CONCEALMENT

- State – Spare 1.
- Range – (-33 to 33)
- MANA Definition – Refers to an agents desire to seek terrain areas that provide concealment.
- Real World Interpretation and Justification – Can be interpreted as the logistical vehicles within the convoy wanting to seek out a concealed area rather than drive through an ambush upon contact. A negative value will cause the logistical vehicles to remain on the route and drive through an ambush while a positive value will cause them to seek concealment upon enemy contact.

I. LOGISTIC VEHICLE SPEED

- State – Spare 1.
- Range – (90 to 250)
- MANA Definition - The number of cells an agent can move in a single time step divided by 100. Speed can be set between (0 and 1000) and can change in altering states.
- Real World Interpretation and Justification – Upon enemy contact this can relate to the logistical vehicles speeding up through an ambush. Selection of speeds is same as reasoning for security vehicle speeds.

J. LOGISTIC VEHICLES TIME IN STATE

- State – Spare 1.
- Range – (1 to 132)
- MANA Definition - Number of time steps a squad will stay in a state once it has been triggered. If a state of 0 is set the state will never be entered. The time can be set between 0 and 99,999,999.
- Real World Interpretation and Justification – Similar to the security vehicles time in state factor. If a convoy is ambushed and seeks out concealment, this factor determines how long they will wait before proceeding along the route. We wanted to identify if it was better for the logistical vehicles to give the security time to pursue the enemy or better to quickly resume travel along the route.

K. LOGISTIC VEHICLES DETECTION/CLASSIFICATION RANGE

- State – Spare 1.
- Range – (10 to 100)
- MANA Definition - Refers to the radius in cells that an agent can see other entities around them. Classification refers to the radius in cells that an agent can classify detections as friendly, enemy or neutral. In our scenario the two are locked together.
- Real World Interpretation and Justification – Similar to the security vehicles detection and classification range with one exception. This factor was varied in the enemy contact state to determine if good situational awareness when ambushed significantly impacted the results. It should be noted that when this range is high, the security vehicles are also benefiting from the detections made through the inorganic communication links.

L. UAV DETECTION AND CLASSIFICATION RANGE

- State – Default. The UAV does not remain in an enemy contact state for any prolonged period.
- Range – (10 to 120)
- MANA Definition - Refers to the radius in cells that an agent can see other entities around them. Classification refers to the radius in cells that an agent can classify detections as friendly, enemy or neutral. In our scenario, the two are locked together.
- Real World Interpretation and Justification – Simply represents how much a UAV can see below them on the ground. A value of 10 is extremely limited, but a value of 120 as it relates to the "real world' would be an extreme case. The intent was to identify whether or not an increased awareness of enemy locations assisted the convoy.

APPENDIX B. FINAL MULTIPLE LINEAR REGRESSION MODEL SUMMARY STATISTICS

Summary of Fit

RSquare	0.7421
RSquare Adj	0.7349
Root Mean Square Error	1.1918
Mean of Response	6.2403
Observations (or Sum Wgts)	516

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	14	2048.3292	1.46E+02	1.03E+02
Error	501	711.6735	1.42E+00	2.22E-137
C. Total	515	2760.0027		

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	6.7827	0.2022	3.35E+01	3.44E-130
Sec Loc4	0.5343	0.1212	4.41E+00	1.27E-05
Sec Time in State	0.0100	0.0013	7.49E+00	3.04E-13
Sec agent aggressive	0.0137	0.0026	5.20E+00	2.91E-07
Sec Inorg SA aggressiveness	-0.0467	0.0026	-1.77E+01	5.16E-55
Sec stay with friends	-0.0144	0.0026	-5.48E+00	6.73E-08
Log twd conceal	0.0482	0.0026	1.83E+01	9.96E-58
Log class/detect range	-0.0183	0.0019	-9.42E+00	1.61E-19
UAV class/detect range	-0.0086	0.0016	-5.41E+00	9.63E-08
(Sec Time in State-66.5039)*(Sec stay with friends-0.03101)	-0.0004	0.0001	-5.24E+00	2.41E-07
(Sec Time in State-66.5039)*(Log twd conceal-0.03101)	0.0005	0.0001	6.69E+00	5.83E-11
(Sec Inorg SA aggressiveness-0.03101)*(Log twd conceal-0.03101)	-0.0029	0.0002	-1.94E+01	9.31E-63
(Log class/detect range-55.031)*(UAV class/detect range-65.031)	0.0004	0.0001	5.95E+00	5.15E-09
(Sec stay with friends-0.03101)*(Sec stay with friends-0.03101)	-0.0010	0.0002	-6.21E+00	1.14E-09
(Log twd conceal-0.03101)*(Log twd conceal-0.03101)	0.0015	0.0002	9.20E+00	1.00E-18

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LIST OF REFERENCES

Army Transportation Association website, http://134.198.33.115/atav/default.html, accessed 27 May 2004.

Anderson, Mark A., Lauren, Michael K., and Galligan, David P., *MANA: Map Aware Non-Uniform Automata Version 3.0.35 User's Manual,* New Zealand Defence Technology Agency, April 2004.

Brown, Lloyd P., *Agent Based Simulation as an Exploratory Tool in the Study of Human Dimension*, Masters Thesis, Naval Postgraduate School, Monterey, California, March 2000.

Brown, Lloyd P. and Cioppa, Thomas M., *Objective Force Urban Operations Agent Based Simulation Experiment,* Technical Document TRAC-M-TR-03-0211, U.S. Army TRADOC Analysis Center, Naval Postgraduate School, June 2003.

Cioppa, Thomas M., *Efficient Nearly Orthogonal and Space-Filling Experimental Designs for High-Dimensional Complex Models*, Ph.D. Dissertation, Naval Postgraduate School, Monterey, California, September 2002.

Devore, Jay L., *Probability and Statistics for Engineering and the Sciences,* 5th Edition, Duxbury Press, 2000.

Diamond, John and Moniz, Dave, *Hard Lessons Applied to Convoy Protection; US Military Report Warns of Changing Guerilla Tactics, Offers Ways to Counter Them,* USA Today, December 2003.

Dibb, Brian, Captain, USMC, Operation Iraqi Freedom (OIF) Forward Analysis and Collection Team (FACT), EFCAT Safety Team, *Summary of MARCENT G-1 Personal Casualty Reports,* 15 May 2003.

Donald, David Herbert, *Why the North Won the Civil War,* Louisiana State University Press, 1960.

Enduring Freedom Combat Assessment Team (EFCAT), *Initial Observations Report: Convoy Operations,* Unclassified, Marine Corps Studies and Analysis, August 2003.

Enduring Freedom Combat Assessment Team (EFCAT), *Initial Observations Report: Sustainment Training,* Unclassified, Marine Corps Studies and Analysis, October 2003.

Hamilton, Lawrence C., *Regression with Graphics: A Second Course in Applied Statistics*, Duxbury Press, 1992.

Hart, Liddell, *Strategy,* New York, Praeger, 1967.

Horne, Gary and Johnson, Sarah, *Maneuver Warfare Science 2002,* USMC Project Albert, September 2002.

Horne, Gary and Johnson, Sarah, *Maneuver Warfare Science 2003,* USMC Project Albert, December 2003.

Ipekci, Arif Ilker, *How Agent Based Models Can be Utilized to Explore and Exploit Non-Linearity and Intangibles in Guerrilla Warfare*, Master's Thesis, Naval Postgraduate School, Monterey, California, June 2002.

JMP® Statistics and Graphics Guide, Version 5, SAS Institute Inc., 2002.

Killblane, Richard*, Presentation: Hardened Convoy in Vietnam, 8th Transportation Group,* US Army Transportation Museum, Fort Eustis, Virginia, December 2003.

Krane, Jim, *Iraqi Fighters Learned Tactics from Chechens, Officer Says,* The St. Petersburg Times, The Associated Press, January 2004.

Krulak, Charles C., General, USMC(Ret), *Operational Maneuver From the Sea (OMFTS),* Headquarters Marine Corps, Washington, D.C.

Project Albert Website, http://www.projectalbert.org, accessed December 12, 2003.

Riccardi, Nicholas and Sanders, Edmund, *Road Perils in Iraq Add To Chaos, Shortages,* Los Angeles Times, April 2004.

Sanchez, S. M. (2004) Excel Spreadsheet for Generating Nearly Orthogonal Latin Hypercube Designs. Available online at http://diana.gl.nps.navy.mil/~susan/, accessed 27 May 2004.

Sinclair, Wayne A., Major, USMC, *The Last Defense; Vehicle Survivability for Guerilla Mine Warfare,* November 2003.

United States Marine Corps publication FMFRP 12-40, *Professional Knowledge Gained From Operational Experience in Vietnam, 1965-1966,* Washington D.C., 1991.

United States Marine Corps publication FMFRP 12-41, *Professional Knowledge Gained From Operational Experience in Vietnam, 1967,* Washington D.C., 1989.

United States Marine Corps Publication MCRP 4-11.3F, *Convoy Operations Handbook,* Headquarters United States Marine Corps, Washington, D.C., September 2001.

U.S. Army Transportation School, Tactical Transportation Branch, *Tactical Convoy Handbook,* Extract from FM 55-15, Ft. Eustis, Virignia, April 2003.

Van Riper, Paul K., Lieutenant General USMC(Ret), *Ship To Objective Maneuver (STOM),* US Marine Corps Combat Development Command, Quantico, July 1997.

Widdowson, Brian, MITRE Corporation, *Convoy Operations Working Group Synopsis,* Project Albert, February 2004.

Wolf, Eric, *Using Agent-Based Distillations to Explore Logistics Support to Urban, Humanitarian Assistance/Disaster Relief Operations*, Masters Thesis, Naval Postgraduate School, Monterey, California, September 2003.

181st Transportation Battalion, *Presentation: Convoy TTPs, Operation Iraqi Freedom, Road Warriors,* July 2003.

501st Forward Support Company, *Presentation*: *Enemy Tactics Techniques and Procedures (TTP) In Attacking Convoys,* November 2003.

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