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THESIS

MODELING AND SIMULATION IN SUPPORT OF OPERATIONAL TEST AND EVALUATION FOR THE ADVANCED AMPHIBIOUS ASSAULT VEHICLE (AAAV)

by

Jesse A. Kemp

September 2001

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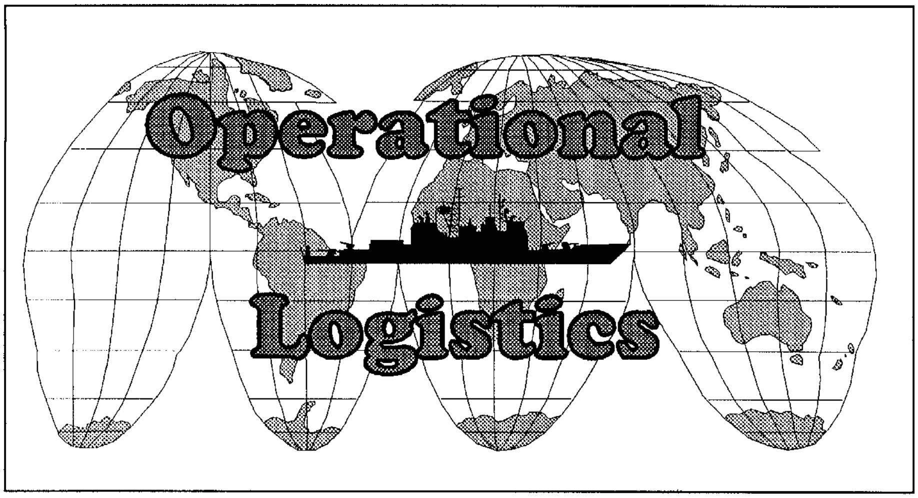
Amateurs discuss strategy, Professionals study logistics



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This thesis documents a simulation model developed to assist in the planning of Operational Test and Evaluation (OT&E) of the Marine Corps' Advanced Amphibious Assault Vehicle (AAAV). The model simulates a platoon of AAAVs in an amphibious assault, using Operational Maneuver From the Sea (OMFTS) techniques, supported by elements of a Marine Expeditionary Unit (MEU) aboard amphibious ships offshore.

The emphasis of the model is on suitability issues, specifically operational availability, maintainability, and supportability. In particular the effect of logistical support for one AAAV on the ability of the platoon to complete a mission. The purpose of the simulation is to gain insight into important and highly sensitive factors that, when changed slightly, have large effects on the platoon of AAAV's ability to perform its mission.

The results of the model show that, the assumed form of the distribution of failure times for a single AAAV is the most important aspect of reliability test data. Simply calculating the mean time to failure (MTTF) from data and using an exponential model is inadequate. Even if an observed or estimated MTTF is within an acceptable requirement threshold level, if it is characterized by a high or even moderate number of infant failure times, then the platoon's ability to perform its mission is substantially impeded. Other factors that are of importance are the procedure by which a failed AAAV is rescued and repaired, and the average length of each repair.

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MODELING AND SIMULATION IN SUPPORT OF OPERATIONAL TEST AND EVALUATION FOR THE ADVANCED AMPHIBIOUS ASSAULT VEHICLE (AAAV).

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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THESIS DISCLAIMER

The reader is cautioned that the computer model developed in this thesis may not have been fully exercised for all cases that may be of interest. While every effort has been made within the available time to ensure that the computer programs are free of computational and logic errors, they cannot be considered validated.

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EXECUTIVE SUMMARY

This thesis develops a simulation model to assist in the planning of Operational Test and Evaluation (OT&E) of the Marine Corps' Advanced Amphibious Assault Vehicle (AAAV). The AAAV is a vehicle under development that will replace the Marine Corps' current amphibious assault vehicle, the AAV7-A1. The new vehicle is designed to transport Marines over water and land faster, as well as to provide improved armor protection and fire support.

The model simulates a platoon of AAAVs in an amphibious assault, using Operational Maneuver From the Sea (OMFTS) techniques, supported by elements of a Marine Expeditionary Unit aboard amphibious ships offshore. The scenario has the platoon of AAAVs move from ship to shore, followed by a distance on land. After launching from the ship, each vehicle in the platoon is subject to failures. The times to failure are random and drawn independently for each vehicle from an adjustable distribution of times such as Exponential or Weibull. Depending on the distribution of individual times to failure used, parameters that determine the mean time to failure (MTTF) are also adjustable. If failures occur during the water transit phase, the vehicles must be towed back to the ship or to the shore (whichever is closest), either by other working members of the platoon, or designated auxiliary tow vehicles belonging to the MEU. When the failed or quiescent vehicles are towed to their respective locations they are repaired if repair assets (i.e. mechanics, parts, helicopters for transport to the failed AAAV) are available. Failed vehicles are subject to multiple delay times such as the time to locate parts and mechanics, the time to transit to where the failed vehicle is located, and, of course, the time to make the repairs. The model simulates many of these times by independently drawing random numbers (that represent times) from a respective distribution of times. These distributions and the parameters that determine their means are able to be adjusted.

Once the platoon reaches land (the specific locations of which depend on the scenario modeled) it waits, before proceeding, for some or all of its members to be repaired and rejoin the platoon if failures occurred along the way. Because AAAVs operate as part of a combined amphibious and air assault force, it is vital to mission success that there be enough combat power provided by the AAAV platoon, and that that combat capability be delivered on time. For this reason, the statistical characteristics of the time to get part or all of the platoon to a designated location is one of the primary MOEs of this thesis.

After the platoon obtains the required number of operational vehicles at the designated location, it proceeds into an area designated as the objective area (OA). The OA is usually several miles from a location designated as the attack objective (AO). Upon reaching the AO, the platoon pauses for a randomly generated period of time that is intended to represent conducting an attack, or carrying out some other mission. At *all* times, the vehicles in the platoon are subject to failure. If failures occur while the platoon is anywhere on the land, the MEU located offshore must provide the needed support to make repairs. This can either be accomplished by delivering maintenance support via helo from the ships offshore, or by providing it from a logistics base inserted via LCACs after operational forces have been delivered by those same LCACs. Again, many of the delay times associated with what happens from the time a vehicle fails to when it rejoins the platoon are random. After the time to reach a designated location has been measured and the platoon has entered the objective area, the ability of the platoon to maintain availability is measured while it conducts operations in the OA. This MOE is simply a time average of the number of vehicles that are operational during the time the platoon is in the OA, expressed as a fraction of the total platoon.

The emphasis of the model is clearly on suitability issues, specifically operational availability, maintainability, and supportability. As explained, the model represents the recovery and repair of failed AAAVs under various proposed procedures. The focus is on the ability of the platoon of AAAVs to complete a mission subject to the ability of support assets to provide timely assistance to failed single AAAVs. The use of simulation to portray the evolution of such an operation will assist decision makers in gaining insight into important and highly sensitive factors in the logistics procedures that, when changed, may have large effects on the platoon of AAAV's ability to perform its mission.

To test which factors are indeed important or sensitive, a series of factorial design experiments is conducted on both MOEs under different scenarios. The factors considered most likely to be important are varied at different levels, while all other factors not explicitly tested remain constant. Although many of these factors are held constant across all observations, their individual observations can be randomly distributed. Each combination of factor levels is replicated over 200 simulations to provide a mean observation. These factor level means are then tested for their ability to affect the MOEs, both statistically and, more important, practically. These factorial experiments are used as a preliminary and exploratory tool for each test conducted.

Because using population means in factorial design experiments does not say anything about the variability between runs, when all factors are held constant, other tools for analysis are used. These tools include histograms to plot the distribution of the observations of each replication, the variance between runs, and plots of the platoon's availability over time.

The results of the models show a considerable amount of sensitivity to the assumed form of the distribution of failure times from which a mean time to failure (MTTF) is calculated. Specifically, if the distribution of times to failure allows a high or even moderate number of short, or otherwise known as *infant* failure times, balanced by very long failure times, it can cause large variability in the model's measures of effectiveness (MOE).

Using specific results from the model, the importance of the assumed distribution of failure times and the inadequacy of simply calculating a mean time to failure (MTTF) is illustrated: A MTTF = 72 hours (a value within the ORD-specified threshold level for this operational requirement), is held constant while the form of the distribution is varied. This is measured for its effect on the mean time to get 12 AAAVs to a point 25 nm inland from the beach, which is 25 nm from the ship (50 nm total distance). The result is a 95% confidence interval that runs from a short time of 2 hours (the minimum time required to get there) to up to over 7 hours, with individual observations of up to 50 hours.

Another result of analysis is that the procedure by which a failed AAAV is rescued and repaired is an important factor. Another factor found to be highly important is the mean corrective maintenance time (MCMT). If the fact that not all failures require only 2nd echelon (unit level) type repairs is considered in calculating an overall MCMT, the effects of long, complicated repairs on the MOEs are highly significant.

Many different scenarios are modeled; however there are likely to be many more important aspects of AAAV platoon operations that are not modeled or tested. Thus, the intent of this thesis, beyond the analysis of the scenarios simulated, is to allow operational testers the ability to fully simulate specific operational tests, prior to actually conducting them, in order to gain insight as to what aspects of those tests are the most critical.

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I. INTRODUCTION

A. GENERAL

The Marine Corps, in an effort to improve its amphibious assault capabilities, is developing a new amphibious assault vehicle to replace the current, and aging amphibious assault platform, the Assault Amphibious Vehicle (AAV7-A1). The new system, the Advanced Amphibious Assault Vehicle (AAAV) is in many ways a revolutionary product, capable of much faster speed and overall mobility, and much improved firepower over the currently fielded system. Along with these and other performance improvements, however, comes increased system complexity, which could make system failures more common and harder to correct.

Before the AAAV goes into full production and fielding, it must first undergo rigorous and extensive testing. Testing, specifically Operational Test and Evaluation (OT&E) of a new weapon system, is part of the acquisition process that determines whether new equipment is operationally effective and operationally suitable for the environment for which it was designed while being operated by typical military personnel. OT&E is strictly defined and regulated by DoD procedures. Each system under development has an Operational Requirements Document (ORD) which details what should be tested as well as how it should be evaluated. However, even with all the emphasis and guidelines that there are on testing, the high cost of operational testing results in the testers being unable to field test every possible scenario for every requirement listed in the ORD. Because of this, testers must be focused on the most important and highly sensitive operational issues involved with each testable requirement. Sensitive operational issues, or parameters, are those that, when changed slightly, cause subsequent, significant changes in the operational effectiveness or suitability of the system. Knowing what those influential parameters are before conducting operational tests allows testers to make more efficient use of limited test runs and scenarios by combining several critical issues into single tests rather than conducting several tests to obtain the required data for analysis. Modeling and Simulation can be used to help find these influential parameters and thus enhance the effectiveness of the overall acquisitions process.

B. PROBLEM

Operational testing is designed to reveal a system's operational sensitivities and their effects on mission accomplishment. This is done by specifically testing whether or not the system meets the requirements listed in the ORD, with the objective of ensuring that the platform is able to meet or exceed the stated specifications. However, some of the issues listed in the ORD may be unrealistic to test in the field. In particular, a system's maintainability and logistics supportability are hard to test realistically because of numerous but unavoidable artificialities in the tests. Normally, the requirement to maintain a certain level of system availability is tested by examining the ability of typical military mechanics to make repairs, often under simulated conditions that are less than ideal. However, the full logistics infrastructure that would actually provide the support in combat cannot be exercised in the tests because of funding constraints. Thus, aspects such as the ability of the logistics support organization to maintain availability while providing that support from offshore and at great distances from the operating forces is not literally examined even though this may be a highly sensitive issue that could have drastic effects on the AAAV's ability to successfully complete a mission. By simulating the effects of providing support under such conditions and determining the highly sensitive issues of providing such support, testers can have a better understanding of how to analyze and interpret the results of the limited, artificial tests they are able to conduct regarding maintainability, supportability and availability during OT&E.

C. PURPOSE

The purpose of this thesis is to develop a stochastic simulation to suggest sensitive aspects of operating and maintaining a system of armored assault vehicles, specifically the Marine Corps' new Advanced Amphibious Assault Vehicle (AAAV), in order to focus its Operational Test and Evaluation. The implemented model simulates a platoon of 12 AAAVs conducting amphibious missions while being supported by elements of a Marine Corps Service Support Group operating in that same amphibious environment. By varying input parameters and observing their effects on selected measures of effectiveness (MOEs), this model can help identify how vehicle failures and the environment in which the Marines operate affect the platoon's maintainability, supportability, availability and ultimately, its ability to perform the mission.

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II. BACKGROUND

A. EMPLOYMENT AND TACTICS

Operational Maneuver from the Sea (OMFTS) is the Marine Corps' concept for projecting naval power ashore in support of strategic objectives. The concept applies maneuver warfare principles to the maritime portion of a theater campaign. OMFTS relies on fundamental and technological advances in the capabilities and platforms of naval expeditionary forces today and those projected for the future. It calls for forces to be projected from over the horizon (OTH) to the shore and beyond as rapidly as possible. The key to these operations is to deceive the enemy as to intentions, forcing him into a mobile defense, and facilitating the achievement of tactical surprise. This breaks the cohesion and integration of enemy defenses while avoiding attrition-oriented attacks. The main emphasis is on speed, mobility, deception, surprise and other means so as to confuse and create uncertainty for the enemy.

The implementation of OMFTS is achieved through tactics known as Ship to Objective Maneuver (STOM). STOM builds on many of the themes introduced in OMFTS such as the use of the sea as a maneuver space, sea basing the force's logistics, and the elimination of the traditional beachhead. STOM assaults use both surface and vertical lift platforms to launch from over the horizon to the beachhead, and beyond, to the objective, which could be as much as 100 miles inland. The concept calls for the exploitation of navigational systems and information-sharing technologies to allow commanders to control the maneuver of their units from the moment they leave the amphibious ships to arrival at the objective. The salient requirement of the amphibious operation is the necessity to rapidly amass cohesive, tightly-coupled combat power ashore from distances great enough to avoid enemy detection, as well as to provide the Naval Task Force its needed standoff.

The Marine Corps intends to achieve OMFTS using three types of delivery platforms to forcibly insert their adjustable combat unit, the Marine Air Ground Task Force (MAGTF). Together these three platforms are known as the "Amphibious Triad". The "Triad" is made up of the following platforms or platform types: the new MV-22 Osprey variable-pitch propeller aircraft, the Navy's Landing Craft Air-Cushioned (LCAC), and finally, amphibious assault vehicles. Within the concepts envisioned in OMFTS and STOM, the Marine Corps' current surface platform, the present existing and operational Assault Amphibious Vehicle (AAV7-A1), has many shortfalls. These shortfalls are outlined in Mission Area Analyses (MAAs) conducted by the Marine Corps Combat Development Command and are found in detail in the Operational Requirements Document (ORD) for the new replacement system, the AAAV. The MAAs report that the AAV7-A1 has been significantly deficient during water and land operations in offensive and defensive firepower, water speed, land speed, agility and mobility, armor protection and overall system survivability. These deficiencies gave birth to the AAAV program.

B. THE AAAV

A single AAAV will be capable of carrying up to 18 combat-loaded Marines (vice 25 in the current AAV7-A1), from distances offshore of up to 45 miles, at speeds of up to 25 knots. Once on land, the AAAV will have the same speed and mobility as the current M1A1/M1A2 main battle tank. In addition to being much faster and more mobile than the current AAV7-A1, the AAAV will have a much more powerful and effective weapon system. The primary weapon is a 30mm chain gun capable of destroying dismounted infantry or any light-armored system from a range of up to 1500 meters while on the move. The gun system also includes a secondary weapon, a 7.62mm Machine Gun.

One of the requirements of the AAAV is that it be compatible with current U.S. Navy Amphibious shipping. Thus, the basic dimensions of the AAAV has to be comparable to the current AAV. Therefore the AAAV's much larger and more powerful engine, and larger gun turret, requires that interior space must be traded for this faster, more lethal system. While the AAV7-A1 is relatively roomy inside, allowing ample room for the 25 troops plus each of their large packs and individual weapon systems, space in the AAAV is much more at a premium. Even with 18 Marines instead of 25, conditions inside the AAAV are cramped, which means the Marines aboard must go into combat much lighter (i.e. less ammunition and gear). Combined with the fact that the AAAV can cover much more ground, much more rapidly than is currently available, the end result is a system that is likely to need support sooner, and from a much greater distance.

While this "support" can be pre-planned into the amphibious assault plan (i.e. by having vertical lift assets pre-loaded with critical items such as water and ammunition), planning for and accomplishing unscheduled maintenance is more difficult. The AAAV is a much more mechanically complex system than the AAV7-A1 and thus likely to be more vulnerable to harsh operating conditions. To ease the burden on its operators of maintaining such a complex system, most of the AAAV will consist of pull-and-replace subsystems. Without having to worry about the detailed trouble-shooting of computerized equipment, a new subsystem can be put in quickly, under combat conditions, and the failed subsystem then repaired in the rear using diagnostics equipment. With barely enough room in the vehicle for the embarked Marines, the operators cannot carry any subsystems or critical spare parts on board.

Once again the speed, range, and mobility performance feature of the AAAV create potential problems for its logistics support. The Marine Corps does not have any support assets able to follow and keep pace with the AAAV. Therefore almost all the support, planned and unplanned, must come from the MAGTF's air assets. Thus limited vertical lift assets, particularly early in the amphibious operation, when most available helicopters are being used to carry troops inland in a combined assault with the AAAV's, becomes a critical vulnerability in the ability to support the AAAV should it incur a catastrophic failure. These supportability issues as well as many others must be extensively tested and resolved before the first AAAV is ready for the Marines in the Fleet. The following is a brief description of where the AAAV program is now in the acquisition process, what type of testing it must still undergo, and how the results of this thesis will be able to aid in the operational test and evaluation (OT&E) process.

C. TEST AND EVALUATION

At the present time (2001), the AAAV program has built three prototypes and all are undergoing Developmental Test and Evaluation (DT&E). In December of 2000 the program went through the MILESTONE II decision process, ending the program's prototype development phase. The next (and current) phase, formerly referred to as the Engineering Manufacturing and Development (EMD) phase, now called the System Design and Demonstration phase, allows the manufacturer, General Dynamics, to begin planning for and eventually executing the second half of this phase known as Low Rate Initial Production (LRIP). Current and additional prototypes, and later, production models will undergo continuous DT&E as well as several scheduled Operational Test and Evaluation (OT&E) events over the next six years. The final graduation exercise, known as the Initial Operational Test and Evaluation (IOT&E) event, is scheduled for the year 2006. This test will take place using the LRIP vehicles. If the AAAV is found to be operationally effective and suitable, the program will then begin full rate production and fleet fielding.

Developmental Test & Evaluation (DT&E) is conducted to measure progress, usually the Effectiveness and Suitability of components and subsystems, to assist the engineering design and development process, and to verify attainment of technical performance specifications and objectives. DT&E is normally conducted under controlled or laboratory conditions. On the other hand, Operational Test & Evaluation (OT&E) is usually defined as a field test under realistic combat conditions for the purpose of determining the effectiveness and suitability of the system in combat by typical military users, and the evaluation of the results of such a test (DoDD 5141.2, 1989). OT&E is performed to ensure that, before authorizing full rate production and delivery of a system, the DoD has tested the product to ensure that it is operationally effective and operationally suitable in its intended combat environment when operated by typical users.

Operational Effectiveness is defined to be the overall degree of mission accomplishment of a system when used by representative personnel in the environment *planned for operational employment of the system considering organization, doctrine, tactics, survivability, vulnerability, and threat*. (DoD 5000.2R 2001)

A system's Operational Effectiveness is usually easier to test, because it simply asks, "is the system effective in performing its intended mission?" A much more difficult-to-measure, and more encompassing metric, however, is Operational Suitability, which quantitatively assesses how well a system can be incorporated into, and supported by, its intended organization. Strictly defined, *Operational Suitability is the degree to which a system can be placed satisfactorily in field use with consideration being given to availability, compatibility, transportability, interoperability, reliability, wartime usage rates, maintainability, safety, human factors, manpower supportability, logistic supportability, natural environmental effects and impacts, documentation, and training requirements*. (DoD 5000.2R 2001)

D. USE OF MODELING AND SIMULATION

Although all of the standards within the definition of Operational Suitability must be tested during OT&E, there are very often time and budget constraints that do not allow the comprehensiveness required to effectively test and evaluate each aspect of the suitability definition, or each "ility", to its needed level. A stochastic simulation designed to conduct sensitivity analysis on multiple input parameters can give testers insight into important and highly sensitive operational issues affecting Operational Suitability. These issues can then guide the choice of specific field test run profiles and test scenarios. As explained before, sensitive parameters are those that, when their levels change slightly, have relatively large and important effects on measured measures of effectiveness (MOE) or measures of performance (MOP). Those sensitive parameters and their corresponding levels should then be physically measured in operational settings in order to make more likely the fielding of a new system that is fully operationally suitable.

Some of the more difficult areas in which to operationally test a system, and are the focus of this thesis, are Reliability, Maintainability, Logistics Supportability, and Availability. Supportability, Reliability and Maintainability are the "independent variables", the measures of the factors that determine Availability (A). For the AAAV platoon, availability is a quantitative measure of the number of platoon members that are able to perform effectively when ordered to do so for a mission of a certain length, in a region of operational importance. For individual AAAV systems to be effectively applied in combat, it should go without saying that they must be and remain available in an operable condition during combat. In order for this, the *overall* system (in this case a platoon of AAAV's) must be reliable to the extent that it can carry out its intended mission over the time duration required with an acceptably high probability. When this system does experience failures, the supporting organization must be able to carry out needed repairs in a timely manner.

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III. METHODOLOGY

A. THEORY AND BACKGROUND

This thesis will develop methods similar to those in master's theses by Stoneman (1998) and Schmidt (1999). Both of these theses used modeling and simulation to identify influential parameters involved in operating and maintaining reconnaissance aircraft in order to aid in Operational Test and Evaluation. Although these theses looked at two different types of platforms, both used the same MOE, expected time on station. This MOE is not literally valid for the AAAV because reconnaissance is not one of its missions; however, if effective time on station is translated into the time it takes a platoon to muster effective combat power at a specific point, or the platoon's combat availability during a specific time during the mission, the evaluation is strikingly similar. Ultimately, both Stoneman and Schmidt evaluated the effectiveness and suitability of a mobile platform that carries payload, while on a military mission. The same methods for determining effectiveness and suitability can be used for the AAAV, although the specific MOEs and input parameters are different, and the AAAV force is made up of a number (12) of vehicles which may interact.

A platoon of AAAVs in an amphibious assault should reach the stated objective and thus start the mission (the mission may be an attack on a known enemy location, or simply a "movement-to-contact" in an area where the enemy is thought to be located) with a certain number of vehicles in an operational state. (i.e. in working order, or, not failed). With an unacceptable number of vehicles failed, and thus not available to start the mission, the commander might have to wait until enough of those "downed" vehicles are once again operational. This is because each AAAV in the platoon not only contains the firepower of its main weapon system, the turret gun, but it also contains 1/12 of the combat power of the infantry company embarked aboard the vehicles. With too many vehicles failed, or in a *quiescent* state, the combat effectiveness of the platoon might be degraded to the point where the prudent commander would feel uncomfortable going into battle.

B. DEVELOPMENT OF MOES

With this in mind, the first MOE for this thesis will be the time required to launch an attack. Obviously, with no failures from the time the platoon launches at the amphibious ship, to when it reaches the beach or the "objective area", the time required to launch the attack would simply be determined by the total distance traveled, divided by the average speed of the platoon (time = distance/velocity). However, if too many vehicles fail in transit from the ship to the objective area, the time required to launch an attack would be dependent on other factors, such as how quickly the vehicles are able to be repaired in an operational environment, or how long a quiescent vehicle has to wait before assets can be made available to make repairs.

Once a commander, possessing at least a minimum required number of operational vehicles (e.g. 8, 10, 11, or whatever the commander feels is prudent— this is a setting of the simulation) moves into the objective area, thus starting the "mission", a secondary MOE will be the system's (the platoon of AAAV's) ability to maintain a certain level of availability *during* the mission. Depending on the length of a mission and the size of an objective area, it could be that vehicles fail but are able to be repaired and put back into operation during the mission. Thus, in order to measure the MAGTF's ability to support a platoon of AAAVs from an offshore seabase or other means, this secondary MOE will, more specifically, be the *time-average* availability of the platoon during a portion of the mission.

For the purposes of this thesis, this type of measurement of availability will be referred to as "platoon availability" or A_p. $A_p(t)$ then, is simply measured as the number of vehicles out of the original platoon (in this case 12) that are in an operational state during any given instance of time *t*. As AAAVs fail and are repaired then rejoin the platoon, $A_p(t)$ is decreased and increased respectively. For the 2nd MOE described above, A_p will be explicitly measured during the period the platoon is operating in the "objective area" (OA). The time-average platoon availability or $\overline{A}_p$ is then the average number of AAAVs (out of the original 12) in an operational state over the duration of the "mission". For the sake of clarity the 2nd MOE $\overline{A}_p$ in the OA will be referred to as the "mission availability" or A_m. Strictly defined: $A_m = \frac{1}{t}\int_s^{s+t} A_p(u)du$ where s = the start of the platoon's time in the objective area and t = the total time in objective area. Finally, in order for A_m to be expressed as a percentage of availability (out of 100%), the number from the equation above is divided by the number of vehicles in the platoon (12).

Input variables can be adjusted to determine how they influence these and other MOEs. Parameters such as the mean times to failure (TTF) for a single AAAV, the mean times to repair (TTR) for an AAAV, the method of transport for quiescent vehicles in the water, and many others, can be adjusted to determine their effects on the time to start the attack, and the A_m (as defined above). In addition to adjusting the mean TTF for individual AAAVs, the *form* of an assumed distribution of times to vehicle failure can be specified and its effects on the stated MOEs analyzed.

C. MODELING INDIVIDUAL AAAVS

In order to conduct this analysis, this thesis simulates a platoon of AAAV's in an amphibious environment. Each AAAV of the platoon is modeled individually and is subject to failure independently of other vehicles in the platoon. The vehicles move together, in a tactical platoon formation until one or more of the vehicles fails and becomes quiescent. At that time, the platoon loses those failed vehicles, but continues on until it reaches a designated "rendezvous point", such as the beachhead or some other objective further inland.

The scenarios used for this thesis focus primarily on a deployed Marine Expeditionary Unit (MEU) conducting combat operations using OMFTS employment techniques. A MEU generally consists of three Navy amphibious ships carrying a Battalion Landing Team (BLT), or a battalion sized landing force. One company of the battalion is normally designated as the AAAV assault company and embarks aboard a platoon of 12 AAAVs for transport to the shore and objectives beyond. The typical mission that is simulated calls for an OTH amphibious assault followed by an overland transit to objectives up to approximately 100 miles inland. As stated above, the platoon of AAAVs, after launching from at least 25 nautical miles offshore, has individual vehicles that can fail (conditionally) independently of one another (high sea states, transit speed required, etc. can simultaneously induce higher failure rates for all the AAAVs that experience thesis environmental conditions). Once a vehicle fails, the platoon loses that vehicle's firepower as well as the Marines it carries, and thus the system's (the platoon's) $A_p(t)$ is decreased. The $A_p(t)$ is not increased again until the repaired AAAV has re-joined the platoon. This measurement of mission availability requires a different and generalized assessment of down time, and how it affects individual vehicle availability, than is traditionally used.

The MOE, Operational Availability (A_o), is used to measure the percentage of time that a piece of equipment or a system is capable of performing its designated mission. The usual definition of Operational Availability (A_o) is: TBM/(TBM + TDT). Where TBM = mean time between unscheduled maintenance actions, and TDT = mean total down time. Total down time is usually further broken down into mean Time To Repair (TTR) and mean Administrative and Logistics Delay Time (ALDT). This relationship of TDT and its component times is intended to provide a simple measure of equipment availability when the equipment is deployed and functioning in a combat environment. However, this definition of A_o often only applies to a single piece of equipment and is also a long-run average time the piece of equipment is up. This thesis will be concerned with the time average measure of availability for the platoon of AAAVs being modeled. As stated above, however, the new, more customized term A_p has been created for this thesis. The above discussion of individual A_o is provided, however, because the model will simulate each AAAV individually and each AAAV's A_o will affect the A_p.

Note: A_o is most appropriate for a machine that is in constant operation and alternates between being operative or "up" or inoperative and "down". Certain items such as weapons, sensors, or communications equipment should also be tested after experiencing rigorous transport (i.e. in an AAAV). These effects, however, are not modeled explicitly in this thesis.

Another difference between a model that uses A_o, and this model is that, in this model, the time starting from when the vehicle fails to the time it rejoins its platoon is considered *total down time*. This is a longer period of time than that in a model using A_o in which an individual system is considered available again immediately after it is repaired. This modified measure of total down time for each vehicle is needed because the platoon, along with the company of Marines it is transporting, acts as a single combat unit. Thus, it is re-emphasized, a recently-repaired AAAV operating independent of the platoon does not positively affect $A_p(t)$ until it re-joins the platoon. The following is an explanation of the various failure-repair scenarios that can be expected, and thus will be modeled in this thesis.

D. BASIC SIMULATION SCENARIOS

The AAAV is considered a multi-mission system, so the assessment of A_p requires detailed techniques to characterize the associated mission states corresponding to different failure-repair scenarios. For instance, if an AAAV fails during its amphibious phase, it must be towed back to the ship, or ashore by another AAAV, or, if such assets are available, a designated tow vehicle. This effectively reduces the average speed of the two platforms dramatically and doubles the decrease in the platoon's availability (in the case where another AAAV must be used for towing). $A_p(t)$ is decreased when an AAAV fails, and again when a second AAAV must stop and tow the failed vehicle.

Note: The simulation will model the towing of quiescent vehicles with operational AAAVs but will also be able model a different scenario where Navy LCUs are used to transport quiescent vehicles to the ship or shore. These auxiliary vehicles, when modeled are not subject to failure when towing. AAAVs towing other AAAVs are subject to failure.

This forced slow towing movement allows the remainder of the platoon to gain that much more distance on the two effectively degraded vehicles (or in the second case, just the one quiescent vehicle when LCUs are used to tow), thus increasing the time until the platoon's $A_p(t)$ is increased by a return of an AAAV. A failure in the amphibious phase of an operation leads to one of the two failure-repair (water) scenarios, depending on how far away the AAAV is from the ship when it fails in the water. A third scenario occurs after a vehicle has successfully made the transit from ship to shore.

In the first scenario, the vehicle fails relatively close to the ship after launch, so that it is easier to tow the disabled vehicle back to the ship. In this case, the vehicle enters what can be considered a "repair queue" as soon as it gets back to the ship. The time in the queue, in this case, is considered ALDT, and is measured as the time from when the AAAV returns to the ship, until mechanics can be made available for making the repairs. Once parts, tools and mechanics are located, repairs begin and continue until the vehicle is operationally capable again. This portion of down time is the Time To Repair (TTR). After the vehicle is repaired, it re-launches and attempts to re-join the platoon. Again, *even though the vehicle has been successfully repaired, the platoon's* $A_p(t)$ *is still not increased*. The repaired vehicle must then make its way back to rejoin the platoon. In effect, to the platoon, a vehicle is considered "down" until it has rejoined the ranks. This time from repair to re-join will simply be called Return Time (RT). Thus for the purposes of this thesis, down time is comprised of three sub-elements: ALDT, TTR, and RT. This first scenario is described visually below in Figure 1.

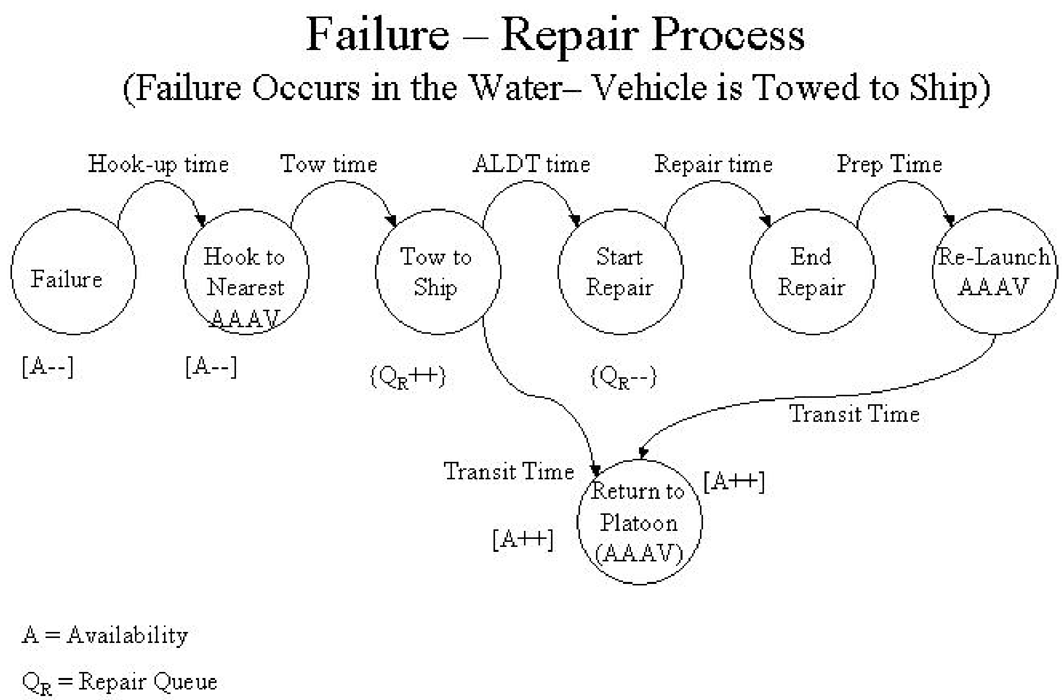

Figure 1. Event Graph of Failure-Repair Scenario 1

Figure 1 above, is known as an *Event Graph*. Event Graphs are used as a way of graphically representing discrete event simulation models. For this thesis, Figure 1 and the other Event Graphs used in this section are graphical paradigms that model the events described in each basic simulation scenario into event list logic (Buss 1996).

The next two scenarios and their respective Event Graphs become increasingly more complicated. When an AAAV fails while conducting an amphibious assault using

OTH and STOM tactics, the logistics system that supports the mechanized platoon is located on the ship from which the AAAVs launched. If the failure occurs too far away from the ship to make Scenario 1 feasible, the support for making repairs must go to the downed AAAV. The part(s) that is (are) needed for the repair must be determined, and the part(s) and mechanics on the ship must be located, and be free to participate in the repairs, otherwise the vehicle must wait. A vertical lift asset (helicopter) is then launched, if available, to rescue the downed vehicle. This portion of time, for this particular situation, can be considered ALDT. If multiple tasks are being assigned to a limited number of vertical lift assets, there may not be a helicopter immediately available for the repair mission. This could add substantially to ALDT. Since ALDT also includes the transit time from the ship to the vehicle, the distance the AAAV is from the ship when it fails will also have a substantial effect.

Once the helicopter reaches the AAAV (provided it is not attrited along the way), the mechanics must either repair the problem or replace the subsystem (all diagnostics of the failure and the required repair is assumed to be perfect). This portion of down time for this situation is the Time To Repair (TTR). Then, once again, even when the vehicle has been successfully repaired, the platoon's availability is still not increased—this occurs only when the AAAV has re-joined the platoon after the required RT.

After repairing the vehicle the helicopter must then return to the ship, be refueled and possibly undergo some maintenance before it is ready to be launched again in support of another downed vehicle, or some other need such as resupply or evacuation of casualties. It is likely that, if many missions are demanded of a limited number of vertical lift assets, there will be long periods of time during which no helicopters are available, leading to long delays in the repair queue and causing long ALDT times for newly failed vehicles. This kind of event could induce periods in which the platoon is inoperative, waiting for enough vehicles to be repaired before proceeding.

For the above problem description, several possible simulation scenarios can be derived. Two are now described. In what we will call Scenario 2, the failure again occurs in the water. This time, however, the failed vehicle is closer to the beach, and is towed there by another AAAV, or transported by an LCU vehicle. At the time the AAAV fails, a helo is launched from the ship (if one is available), to the beach (where the downed AAAV is headed) in order to make the needed repairs. In Scenario 3, the failure occurs after the AAAV has reached the beach. No "tow vehicle" is needed now, but, just as in Scenario 2, a helo must be launched from the ship to deliver the needed repair parts and mechanics. Figures 2 and 3 below visually describe Scenarios 2 and 3 respectively. During the course of the simulation, each failure of an AAAV could trigger one of these first three *basic* scenarios. Which scenario is carried out is based on the location of the AAAV when it fails.

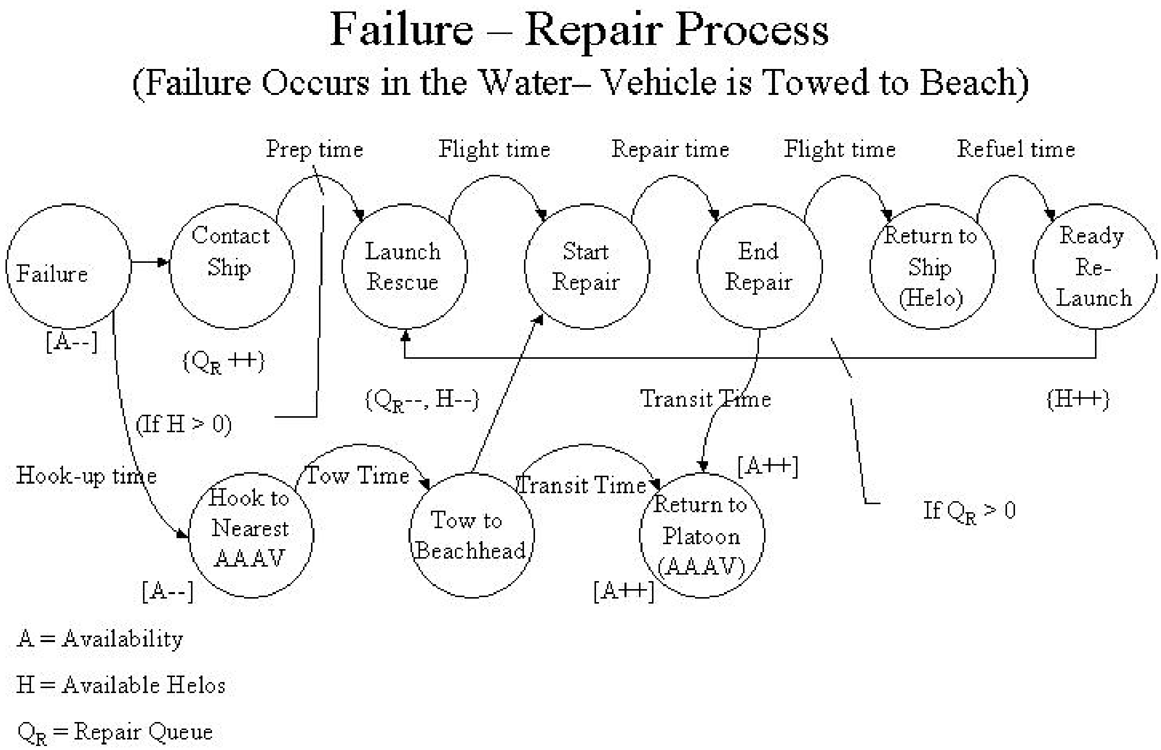

Figure 2. Event Graph of Failure-Repair Scenario 2

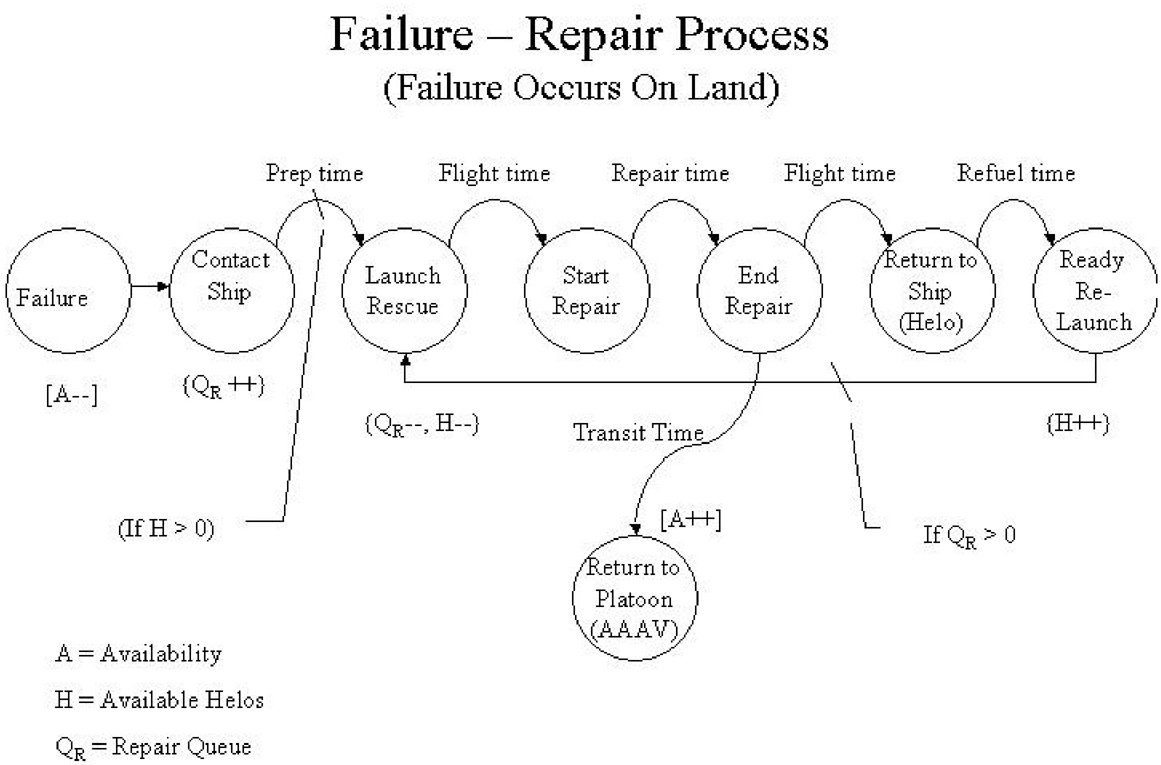

Figure 3. Event Graph of Failure-Repair Scenario 3

E. MODELING MORE COMPLICATED SCENARIOS

The three scenarios explained above are important, and in many cases, realistic situations to consider. They will be investigated in the Results section of this thesis. However, these three scenarios stop short, in many ways, of accurately modeling the MEU and the environment in which AAAVs might be called to operate in. The above three scenarios should be considered basic *templates*. They represent the basic methodology that the overall model is based on. Additional scenarios will build off these templates, but the basic determinations of availability states for individual AAAVs will not change. Each AAAV, upon failure, will be subject to ALDT, TTR, and RT before being able to rejoin the platoon and thus affect $A_p(t)$. Additional scenarios, building off the three basic templates, will attempt to model a MEU conducting an amphibious assault as accurately as possible. The following discussion explains these "reality enhancements".

A MEU possesses a limited number of vertical lift assets (normally 12 CH-46 helicopters and 5 CH-53 helicopters—the MV-22 will eventually replace the CH-46, it is assumed, at a rate of one-for-two). At roughly the same time the AAAV platoon launches, a majority of the MEU's air assets (about 70% of the total number) is needed to transport the air-assault echelon (one company of the battalion landing team (BLT)) to the objective. Until the air-assault echelon returns from delivering its Marines to the objective, there is probably only about two or three helos available for logistics recovery missions. When the air assault echelon returns, only then is there an ample number of helicopters standing by for logistics rescue missions. The simulation, therefore, models an air assault echelon with an adjustable number of helos that launch with the AAAVs in a combined air and amphibious assault. The helos fly to a designated landing zone (LZ), pause to offload the Marines they carry, and then fly back to the ship. Once back on the ship, they must be refueled and serviced, just as after any flight, before they are designated as "ready" for logistics rescue missions. The refuel times are random, independently distributed with distribution of times and their parameters adjustable.

Another level of reality that appears in the simulation is the fact that a MEU begins amphibious operations with a finite (limited) number of vertical lift assets. Helos, particularly ones operating in a STOM environment where pockets of enemy resistance may be bypassed, are very vulnerable to shoulder-fired (or otherwise) surface-to-air missiles (SAMs). Therefore, before starting a simulation, a level of helo vulnerability (a probability of helo attrition) is adjusted from zero to 100%. All helo flights are then subject to attrition by enemy forces when they enter the area designated as hostile. Each flight, upon entering the hostile area, is subject to a simple probability that it is shot down, regardless of the time in flight it spends.

Finally, it may the case that a MEU commander does not want to put the full burden of logistics support on his vertical lift assets, particularly when the MEU deploys with various types of trucks for the purpose of providing logistics support on the ground. Navy LCACs could eventually be used to transport these truck assets to the beach in order to establish a mobile logistics base ashore, specifically for the purpose of supporting the AAAV platoon. Just as with the vertical lift assets, however, initially, the LCACs are needed to deliver the mechanized company ashore, or those Marines aboard LAAVs. Therefore, before a mobile log base can be established ashore, the LCACs must first deliver the MEU's other mechanized assets ashore, then return to the ships and load the logistics assets, then deliver them ashore, when it is deemed safe enough to do so. Once ashore, however, all logistics support for the AAAV platoon is provided by the mobile log base. This scenario can become even more complicated if only some of the needed repair parts are delivered ashore. In some cases (the simulation allows an adjustable probability of a repair part being with the log base) the log base would have to call back to the ship for a needed part to be delivered via helo before being able to conduct repairs. If no helos are immediately available, then, once again, ALDT is likely to be greatly affected. As is the case with normal logistics doctrine, the mobile log base maintains a designated standoff distance from the operating forces. LCAC load and unload times are random with adjustable distributions and parameters. The LCACs start the simulation loaded with assault force equipment (i.e. Tanks or LAAVs). They travel from ship to shore just like the AAAV platoon. Once on shore they unload the equipment aboard, then return to the ship. Depending on the number of round trips necessary to deliver ashore all assault equipment, the logistics base equipment is then loaded and brought to shore.

The capability to add the above-described levels of reality to the three basic scenario templates does exists in the simulation model for this thesis. Stochastically Modeling these first three basic scenarios, as well as the other, more complicated and realistic ones, effectively represents, within the context of the AAAV's designated mission, the way in which each platform's reliability affects the MAGTF's ability to support a platoon of AAAVs. The effectiveness of the support, constrained by the operational environment, ultimately determines the platoon's availability (A_p) at any given time *t*, or its $A_p(t)$. This information can be used to determine whether or not the platoon is able to proceed on to the objective, or whether it has to wait in order to re-build combat power. Likewise, simulating an operation that lasts for a relatively long period of time, and has a large objective area, will further allow the model to generate situations that could have major effects on the capability of a Service Support Group to provide adequate support. The Service Support Group is defined as the logistics command structure and all its available assets for logistical support of the MAGTF. If a large number of constraints are placed on these limited assets at once, it could drive the platoon's A_p down sharply *during* the mission, when it is needed most, and affecting A_m.

The purpose of the three MOEs (time to the beach (TTB), time to start an attack (TTS) and A_m) is to quantitatively answer the question, “is the equipment available in working condition when it is needed?” Using $A_p(t)$ as a basis for these two MOEs supports the establishment of reliability, maintainability and logistics supportability parameters and trade-offs between these parameters. Availability is itself a summary parameter that translates system reliability, maintainability and logistics supportability characteristics into an index of effectiveness. The objective of this thesis is to develop a useful model that simulates possible scenarios in order to assess A_p and how it affects the platoon’s ability to start an attack in a timely manner, and maintain combat power once in an objective area by conducting sensitivity analysis on varying levels of basic input parameters. The overall purpose is to guide data acquisition and analysis during the OT&E process.

IV. MODEL DEVELOPMENT

A. GENERAL

In order to assess the stated MOEs, a simulation of an amphibious attack conducted by a MAGTF located aboard Navy amphibious assault ships is created. The model is developed as a stochastic, event-driven computer simulation, the objective of which is to represent an operation that sends a platoon of AAAVs from an amphibious ship (seabase) at a specified distance offshore to one or several objectives via specifiable waypoints. While in transit from the ship to the objectives, the AAAVs are subject to mission-affecting failures. This simulation is focused primarily on assessing the time it takes to get a certain number of AAAVs to a specified location, which is affected by reliability, maintainability and supportability. Furthermore, during a mission the simulation assesses the platoon's ability to maintain an average level of availability. Attrition of AAAVs by enemy action is not modeled. This assumption is unrealistic, but conservative in that its adoption in the models tends to stress the maintenance-logistics system maximally.

B. MODEL CLASSES AND THEIR DESCRIPTIONS

The model is programmed in Java using the simulation package Simkit, developed by Arnold Buss and Kirk Stork (Stork, 1997). The model consists of the following Java classes:

<u>Classes (entities) of the Model</u>

1. AAAV

2. Helo
3. LCU
4. LCAC
5. Truck
6. Amphibious Ship
7. Mover Manager
8. Failure Manager
9. Flight Manager
10. Random Pause Generators
11. Platoon Manager
12. Log Base Manager
13. Failure Dispatcher
14. Land Repair Process
15. Land Repair Process (Log Base)
16. Beach Repair Process
17. Ship Repair Process
18. Tow Manager
19. Tow LCU Manager

1. Entity Classes

The entity classes consist of the AAAV, LCAC, LCU, Helo, Ship, and Truck classes. These classes store information pertaining to the individual vehicles. All entities are given their speed, current locations, and vehicle numbers when they are created. In addition, some vehicles, such as AAAVs and Helos, temporarily store information such as what Helo is assigned to what AAAV in a rescue situation. When an AAAV fails, that AAAV's entity class records the time it fails. When it is repaired and rejoins the platoon, the entity class for that AAAV records the time it is once again operational. These "recordings" are sent to various Manager Classes that store the information. When a Helo, or Truck is conducting a logistics rescue, it is designated to the Manager Classes as "unavailable" until it returns and is refueled and deemed ready for another mission. At that time, the Manager classes classify these entities as "available".

The Ship Class is one of the most important entity classes. It stores information about the number of helos the MAGTF has, to include helos used in the air assault, as well as the dedicated logistics helos. The Ship Class also maintains the number of LCACs, and LCUs, in the simulation.

2. Mover Managers

The AAAV Platoon Mover Manager Class is given the ship's location, the location of the beachhead that the platoon is to assault, and the location of the platoon's inland objectives. This class controls all the movement of the overall platoon, and is not concerned with failures. If vehicles in the platoon fail, the Mover Manager continues the mission with the remainder of the platoon. In addition to the AAAV Platoon Mover Manager, there are multiple mover managers, each controlling the movement of the different MEU assets (i.e. Helos, LCACs, LCUs, etc.). Once a Mover Manager reaches one of the designated "waypoints" in its list of locations to travel to, it triggers an "Arrival" Event. The Arrival Event allows the Mover Managers and the Random Pause Generators interact.

3. Random Pause Generators

Once a Mover Manager reaches a waypoint the corresponding Random Pause Generator hears the event "Arrival" and schedules an event "Pause Complete" if a pause is needed. Each Mover Manager has an associated Random Pause Generator. In some cases, (for the Platoon's Mover Manager) the Time To Reach the Beach (TTB) or the Time to Start the Attack (TTS), two of the simulation's primary MOEs, are measured and recorded by the Random Pause Generators. If, upon arriving at the waypoint designated as the Beach or the LOD, the A_p is not at a (predetermined and adjustable) level, the Random Pause class will hold the platoon at that waypoint until the $A_p(t)$ changes enough times to get the A_p at the "acceptable" level. At that time the Random Pause Generator schedules the "Pause Complete" Event and record the simulation time for the TTB or TTS calculation. The reason these classes are referred to as "Random" Pause Generators is, at other times, the Random Pause Generator associated with its given Mover Manager, schedules the Pause Complete event based on a draw of time using a random number generator and specified distribution for the pause time.

3. Manager & Process Classes

The Manager and Process Classes are where most of the simulation takes place. There are many Manager Classes that perform a number of tasks and all of them, in one way or another, interact with the Process Classes to move the simulation along. The following is a general discussion of how this works.

The distributions and the parameters of the failure times of the AAAVs are controlled by the Failure Manager. When the simulation begins, this class gives each AAAV in the platoon (stored in its corresponding AAAV Class) a failure time based on an independent randomly generated number. Once an AAAV experiences a mission-affecting failure at time t, its movement is stopped and the Platoon Manager decrements the platoon's $A_p(t)$. The Failure Dispatcher Class then gets the location of the failed AAAV and assigns an appropriate Repair Process based on that location. If the vehicle is in the water, the Failure Dispatcher determines whether the AAAV is closer to the ship or the beachhead, and assigns either the Ship Repair Process or the Beach Repair Process. If the platoon already reaches the beach before the at-sea AAAV's failure time elapses, the Failure Dispatcher assigns the Land Repair Process, unless the simulation includes the use of a mobile log base.

If the simulation includes the mobile log base, the Failure Dispatcher checks the Log Base Manager to see if the LCACs have delivered the logistics assets ashore yet. Until the log base is established, all repairs must be serviced via helicopter. Each Repair Process is modeled according to Figures 1, 2 and 3, shown above except in the case where a mobile log base is established. If the mobile log base is being established, when repairs are relegated to the Repair Process Land (Log Base), this class gets the "standoff" distance from the log base to the platoon from the Platoon Manager class. It then uses this distance to compute the time it takes to deliver parts and mechanics to the downed AAAV from the Log Base. The Log Base Manager also uses a random number generator to determine whether the part that is needed for repairs is in fact present at the mobile log base (this is a simple random draw—the numbers of each part are not explicitly modeled since types of failures are not explicitly modeled). If it is not, the Repair Process Land (Log Base) asks the Ship class if there is an available helo. If there is, a helo is dispatched to fly the needed part to the log base. If a helo is not available, then the repair must wait. Finally, the Log Base Manager maintains the number of available trucks and before the Repair Process Land (Log Base) Class can assign a repair-rescue, there must be available trucks for the job.

As discussed earlier in this chapter, the Amphibious Ship class, among other things, stores the number of available helicopters. In order for the Land Repair Process and Beach Repair Process to be completed (or for a needed part to be delivered to the Log Base), the Amphibious Ship must have helicopters available. If there are no helicopters available at the time one is requested, that repair job (associated with one of the AAAV Classes) is placed in a queue to wait for resources to be made available. The Flight Manager Class records all flights that leave and return to the amphibious ship. It records the flight hours for individual helos and then that information is sent to the individual Helo Class and stored. Another task of the Flight Manager Class is to determine whether or not a helo is shot down when it enters a designated "hostile" area in its flight path. This is determined by a simple random draw from a uniform distribution: if the number drawn is less than the probability (p) of attrition, the helo is destroyed.

One of the Mover Managers for the assault helicopter squad informs the Ship class when the air assault echelon has returned. At that time, the helos used for the assault are then added to the number of helos available for logistics purposes. At *any* time when a helo completes its mission (whatever that mission may be), or also, in the case of trucks in the mobile log base, when a truck completes its mission, a check is made to see if there are any AAAVs waiting in the queue for a transportation asset to become available is made. If there are AAAVs in the queue, the job is sent back to the Failure Dispatcher Class for a determination of the Process Class to whom the job should be assigned.

The Tow Manager class, used by the Ship Repair Process and the Beach Repair Process, assigns another vehicle (AAAV) from the platoon to tow an AAAV disabled in the water. If the simulation is using LUCs for towing, it assigns one of the limited number of available LCUs. Once the functional AAAV has towed the downed AAAV, either to the beach or the ship, it is returned to the Platoon Manager class where a distance calculation is made to the current location of the platoon. This distance is then used to calculate a return time (RT), which the AAAV uses to schedule its re-joining of the platoon. Immediately after being repaired, the AAAV is, once again, subject to failure. When an LCU is used, the LCU will be sent back to a designated mid-sea station area. The Platoon Manager also takes the AAAVs that have completed the appropriate Repair Process and sends them back to the platoon in the same manner. The changes in $A_p(t)$ are also tracked and recorded by the Platoon Manager Class.

4. Data Collection and Data Collection Classes

As stated above, the model represents the platoon's availability at specific times, and the time it takes to proceed into the objective area with a pre-specified acceptable level of availability. The model has a designated line of departure (LOD). When the Mover Manager reaches the LOD, it checks the platoon's availability. If it is below a specified level, the platoon waits until enough repaired vehicles rejoin the platoon to get availability back to acceptable levels. The time is recorded when the platoon proceeds into the objective area.

In addition to the time to cross the Beach and/or LOD, the model will monitor the $A_p(t)$ of the AAAV platoon throughout the on-land operation as well as other useful metrics such as down time, delay in the repair queue, and number of available helos per mission. The Random Pause Generator Class for the AAAV Platoon informs the Platoon Manager Class when the platoon has enteres the "objective area" (OA). At that time the Platoon Manager Class explicitly measures each $A_p(t)$ for use in calculating A_m. The measurement is taken using a "Time Varying" type of statistic. Essentially it records the $A_p(t)$ at the time of each "failure" event and "return" event and records the times between the events. The Simple Data Logger class collects the initial number of AAAVs to arrive at the beach, the LOD and the Objective for every replication in the simulation for use in creating histograms of the distribution of the initial numbers of AAAVs upon arrival at those locations. The Time Collector uses an adjustable time-step length, to take measurements of A_p during the time the platoon is in the objective area. The observation of A_p is averaged over all the replications for each time-step value. The output from the Time Collector class provides a view of $A_p(t)$ for a designated t (i.e. every minute, or ten minutes, or hour, etc) during the time the platoon is in the objective area.

C. ADJUSTABLE PARAMETERS AND SIMULATION SETTINGS

The following is a list of current input parameters for the simulation:

Adjustable Parameters:

1. AAAV speed over land

2. AAAV speed over water
3. AAAV speed when towing another AAAV in the water
4. Number of AAAVs
5. Sea transit distance
6. Number of waypoints and their location (required objectives for the mission) for AAAVs
7. Number of waypoints and their location for the assault helo squad
8. Number of waypoints and their location for the LCUs
9. Location of the LOD
10. Location of the Beach Head
11. Distribution of operational pause times at each waypoint (objective) and its parameters. Possibilities are Uniform, Triangular, Weibull, etc. (All adjustable distributions have same possibilities.)
12. Threat vulnerability (probability of helos being shot down)
13. Distribution of repair times and their parameters
14. Distribution of failure times and their parameters
15. Number of dedicated logistics support helicopters
16. Number of helos in the assault echelon

17. Distribution of Logistics delay time and its parameters (time to detect/isolate a failure and relay need back to ship + time to get parts/maintenance personnel on helo).
18. Distribution of refuel time and its parameters once helo returns to ship, before it is ready for re-launch.
19. Speed of logistics helicopter
20. Number of operational pauses (i.e. if the platoon pauses to build up combat power once at the LOD only, or twice: at the beach and at the LOD)
21. Whether or not a mobile log base will be placed ashore
22. Number of trips the LCACs will have to make before the log base can be delivered
23. LCAC speed
24. Number of Trucks in the Mobile Log Base
25. Speed of Trucks
26. Distribution of refuel time and its parameters once truck returns to the log base, before it is ready for re-launch
27. Distribution of Logistics delay time and its parameters (time to detect/isolate a failure & relay need back to log base + time to get parts/maintenance personnel on truck)
28. Standoff distance between mobile log base and AAAV platoon
29. Probability that parts needed for repair will be at the mobile log base

30. Whether or not towing of downed AAAVs will be conducted by other AAAVs or LCUs

31. Speed of LCUs

32. Number of LCUs

33. Distribution of times and their parameters for the length of time it takes for one AAAV to hook up to another before it can begin towing

The simulation models the effects of these input parameters on the MOEs (listed above) for each mission. Each run of the simulation is considered to be one mission. Ultimately this simulation could be used as a tool by OT&E agencies to answer the question, "which aspects of operation, maintenance, and logistics support most sensitively affect the ability of the platoon of AAAV's to perform the mission?" According to the ORD, the acceptable level of availability, for any size unit, to successfully perform its mission, and thus be considered operationally suitable is 81%. One assumption of this simulation is that prior to a deployment, and to a greater degree, prior to an operation, the MAGTF would dedicate the bulk of its efforts to ensuring that all AAAVs within the platoon are mission-capable. Thus the model will assume that the availability of the platoon is 100% at the start of the simulation, and furthermore, that the AAAVs are as good as new. After the start of a mission, however, it is assumed that failures may begin to occur.

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V. RESULTS AND ANALYSIS

A. INITIAL SIMULATION RUNS USING A SIMPLE MODEL WITH EXTREME PARAMETER VALUES

Although the model is capable of simulating much more complicated scenarios, this section presents results of model runs that are, in many ways, oversimplified. Many of the variables that have the capability of being stochastic are set equal to constants, and many of the other settings, such as the number of support equipment (i.e. helicopters and LCU craft) are made to be arbitrarily large so as to make their supply essentially unlimited. These simplifications are made to focus attention on the extreme sensitivity of the model to failure times and the form of the assumed distribution of times to failure. Additionally, the model is simplified so that simpler model calculations can be made and compared to the results of this model.

The factors' mean time to failure (MTTF) and the distribution of the failure times have the greatest effects, by far, on the model's MOEs. This is because it is the MTTF and the shape of the distribution of failure times together that determine how often failures occur. Because of this, the focus of these initial model runs will be to show the effects of reliability growth and the effects of different failure distributions. Therefore the MTTF and the distribution of failure times will be the model's only stochastic factors. All other factors will be held constant. This can and will change in future explorations conducted in the second half of this chapter.

Note: This model is capable of making many of its factors stochastic, and thus have their times be random variables drawn from a specified distribution with specified parameters. As explained, however, for these first model runs, all factors other than the

MTTF and the Failure Distribution will be of type constant variate. Individual failure times are random. The model settings for the following output and analysis are as follows:

General Property	Value	Comments
Number AAAVs	12	
AAAV Avg Speed	25 (kts)	
AAAV Avg Tow Speed	5 (kts)	
Number LCUs	10	Allows for "unlimited" number of tow support
LCU Speed	8 (kts)	
LCU Tow Speed	4 (kts)	
Number LCACs	2	
LCAC Speed	40 (kts)	
Number LCAC trips needed prior to Log Base Delivery	1	
Total Number of Helos	31	Allows for "unlimited number of helo support
Number Assault Helos	10	Delivers Air Assault Company
Helo Avg Speed	120 (kts)	
Probability of Helo Attrition	0.0	
Number of AAAVs needed to proceed	10	Platoon stops at Beach and/or LOD until this number of functioning AAAVs is present
Stop at Beachhead	Yes	
Stop at LOD	Yes	
Method of towing AAAVs used	AAAV/LCU	Varied so that comparisons can be made

Table 1. General Properties for Initial Model Runs

Stochastic Property	Distribution	Parameters	Comments
Failure Times	Variable	Variable	Varies b/w Exponential and Mixed Exponential Distributions
Repair Times	Constant	2 hrs	

Stochastic Property	Distribution	Parameters	Comments
Prep Times for Helos	Constant	0 hrs	Time b/w rescue mission assigned to helo and helo departure
Refuel Times for Helos	Constant	0 hrs	
ALDT	Constant	0 hrs	For AAAV repairs made on ship only
Time to Commence Towing	Constant	1 hr	Time from failure to start of tow action (AAAVs only)
Pause at Attack Objective	Constant	8 hrs	Simulated length of "attack"

Table 2. Stochastic Properties for Initial Model Runs

Using the settings listed above in Tables 1 and 2, the model is run with MTTF settings from 3 to 36 (with the MTTF doubling each time). Each of these MTTF cases uses both an Exponential Distribution for the Failure Times, as well as a Mixed Exponential Distribution. The Mixed Exponential distributions for each MTTF are given a 50% chance of having an infant failure time (exact parameter settings for the Mixed Exponential distribution are shown on the tables of output data). Tables 3 and 4 below show the output of these runs for the MOEs Time to Beach (TTB) and Time to the LOD, or otherwise known as Time to Step-off (TTS). Table 3 shows the results of the model runs for the first MOE, TTB, while Table 4 shows the results for the second MOE, TTS. AAAVs were used as the towing asset for other quiescent AAAVs in the water for the below observations. As indicated in the tables, each mean and standard error observation is calculated using 200 replications with the same property settings.

Distribution of Time To Failure	**Reps**	**Time to Arrive at B (No Failures)**	**Mean Time to Arrive at B**	**Std Error of Time to Arrive at B**
		(hours)	(hours)	(hours)
Exp Mean 3	200	1.0	10.932	0.451
Exp Mean 6	200	1.0	4.223	0.230
Exp Mean 9	200	1.0	2.610	0.162
Exp Mean 18	200	1.0	1.541	0.100
Exp Mean 36	200	1.0	1.098	0.042
Mixed Exp Mean 3 p=0.5; λ_1=1, λ_2=1/5	200	1.0	13.939	0.509
Mixed Exp Mean 6 p=0.5; λ_1=1, λ_2=1/11	200	1.0	8.286	0.227
Mixed Exp Mean 9 p=0.5; λ_1=1, λ_2=1/17	200	1.0	7.653	0.210
Mixed Exp Mean 18 p=0.5; λ_1=1/30, λ_2=1/6	200	1.0	2.477	0.164
Mixed Exp Mean 36 p=0.5; λ_1=1/60, λ_2=1/12	200	1.0	1.373	0.079

Table 3. Moments of Time of 10 AAAVs (out of 12) to Arrive at the Beach (which is 25 nm away from the Ship). AAAVs were used as the towing asset.

Distribution of Time To Failure	**Reps**	**Time to Arrive at LOD (No Failures)**	**Mean Time to Arrive at LOD**	**Std Error of Time to Arrive at LOD**
		(hours)	(hours)	(hours)
Exp Mean 3	200	2.0	21.297	0.693
Exp Mean 6	200	2.0	7.712	0.264
Exp Mean 9	200	2.0	4.824	0.196
Exp Mean 18	200	2.0	2.922	0.116
Exp Mean 36	200	2.0	2.264	0.066
Mixed Exp Mean 3 p=0.5; λ_1=1, λ_2=1/5	200	2.0	24.766	0.760
Mixed Exp Mean 6 p=0.5; λ_1=1, λ_2=1/11	200	2.0	12.064	0.302
Mixed Exp Mean 9 p=0.5; λ_1=1, λ_2=1/17	200	2.0	10.348	0.239

Distribution of Time To Failure	**Reps**	**Time to Arrive at LOD (No Failures)**	**Mean Time to Arrive at LOD**	**Std Error of Time to Arrive at LOD**
Mixed Exp Mean 18 p=0.5; λ_1=1/30, λ_2=1/6	200	2.0	4.501	0.182
Mixed Exp Mean 36 p=0.5; λ_1=1/60, λ_2=1/12	200	2.0	2.751	0.103

Table 4. Moments of Time for 10 AAAVs (out of 12) to Arrive at the LOD (which is 25 nm away from the Beach and 50 nm from the Ship). AAAVs were used as the towing asset if failures occurred from the Ship to the Beach.

From the results of Tables 3 and 4 above, it is clear that the model indicates extreme sensitivity to changing the MTTF as well as to the form of the time to failure. This is especially true in the water transit phase of the amphibious operation (as the results of Table 3 show), when failures create a need to tow the quiescent AAAVs to the ship or the shore before repairs can be made. Failure times from a Mixed Exponential distribution, where a high probability of infant failure occurs, clearly create more failures in the water, and thus significantly increase the time it takes to get at least 10 AAAVs on the beach and in working condition. Figure 4, below, offers a better illustration of the effects on the TTB MOE as the MTTF and the form of the distribution are changed.

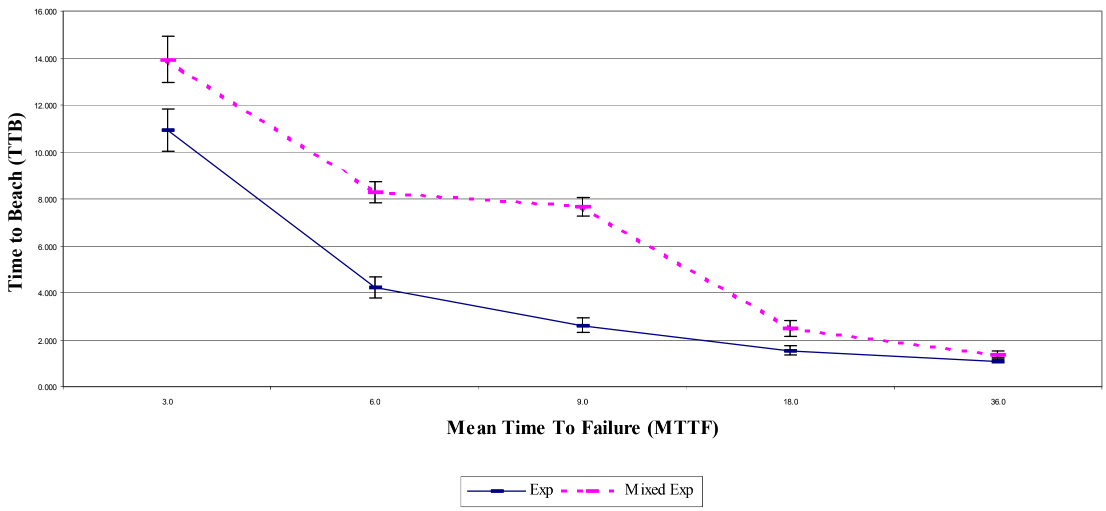

Figure 4. Comparison of Mean Times for At Least 10 of 12 AAAVs to Reach the Beach at Various MTTF When Different Forms of the Distribution of Failure Times are Used (AAAVs used as the towing asset) Parameters for the Mixed Exponential are the same as in Tables 3 and 4.

Next the towing asset is changed from AAAVs to LCUs. Now, when failures occur in the water phase of the amphibious assault, LCUs from the amphibious ships tow the quiescent AAAVs to shore. Other than changing the method of towing, all other settings are identical to those in the above data runs. Figure 5 below shows the effects on the MOE, mean TTB when the tow assets and the failure times are varied. For extremely low mean times to failure (3 hours up to 36 hours MTTF), it is observed that using LCUs, or some other auxiliary craft for towing, other than non-failed AAAVs in the platoon, decreases the times to reach the beach for the platoon. This is mainly because, if other AAAVs in the platoon have to be used for towing quiescent AAAVs there are twice as many AAAVs absent from the portion of the platoon that is still operational. Using LCUs allows as many working AAAVs as possible to get to the beach. Figure 5 shows the observed differences between mean times to the beach when failure times and the method of towing are varied. The failure times are all from the exponential distribution, however, the same general differences between tow methods are observed (at the same mean times to failure) for the Mixed Exponential distribution as well.

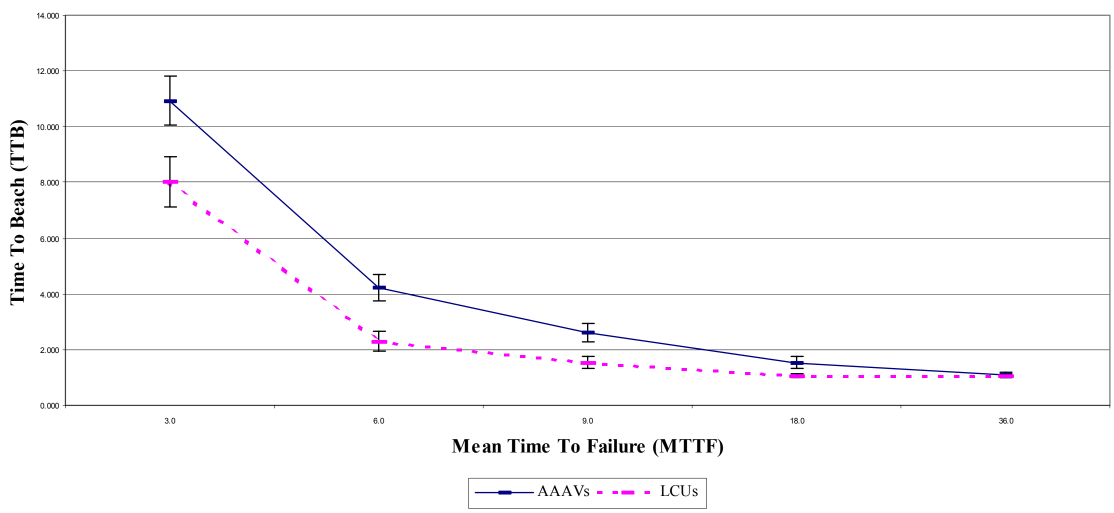

Figure 5. Comparison of Times for At Least 10 of 12 AAAVs to Reach the Beach At Various MTTF When Different Tow Methods are Used (Failure Times are from the Exponential Distribution).

Sometimes the mean and standard error are not adequate to paint the picture fully of what is happening. In order to enhance the ability to analyze simulation runs and the effects of changing various factors, the model has two other types of output. The first, shown in Figures 6 through 10, is the distribution of the numbers of working AAAVs (observed over the 200 replications) that reach a given destination (i.e. the beach or the LOD) initially. For instance, if there are two failures in the water phase of the amphibious assault and AAAVs are used as the towing asset, then the initial number to reach the beach would be 8 AAAVs. If LCUs are used as the towing asset, the initial number would be 10. Between the time the platoon leaves the beach waypoint and before it reaches the LOD waypoint, if there are, again, 2 failures, but the two failures from the first leg were not yet repaired, then the initial number to reach the LOD would be 8 (given the fact that if AAAVs are the towing asset, the towing AAAVs have rejoined the platoon). This described scenario also assumes that the number of AAAVs that must be available at the beach before the platoon moves forward to the LOD is 10. Figure 6 shows comparisons of the effects of different distributions of failure times on the initial numbers of AAAVs able to reach the beach when AAAVs are used as the towing asset. Figure 7 shows the effects of varying the towing assets on the initial number of AAAVs able to reach the beach (when failure times are from the Mixed Exponential distribution). Figure 8 shows the comparison of the effects of different distributions of failure times on the initial numbers of AAAVs able to reach the LOD, and Figure 9 shows, the same comparison as Figure 8 on the initial numbers of AAAVs able to reach the Attack Objective (AO). Figures 6-8 all require that there are 10 AAAVs operationally available at the beach and LOD prior to moving forward.

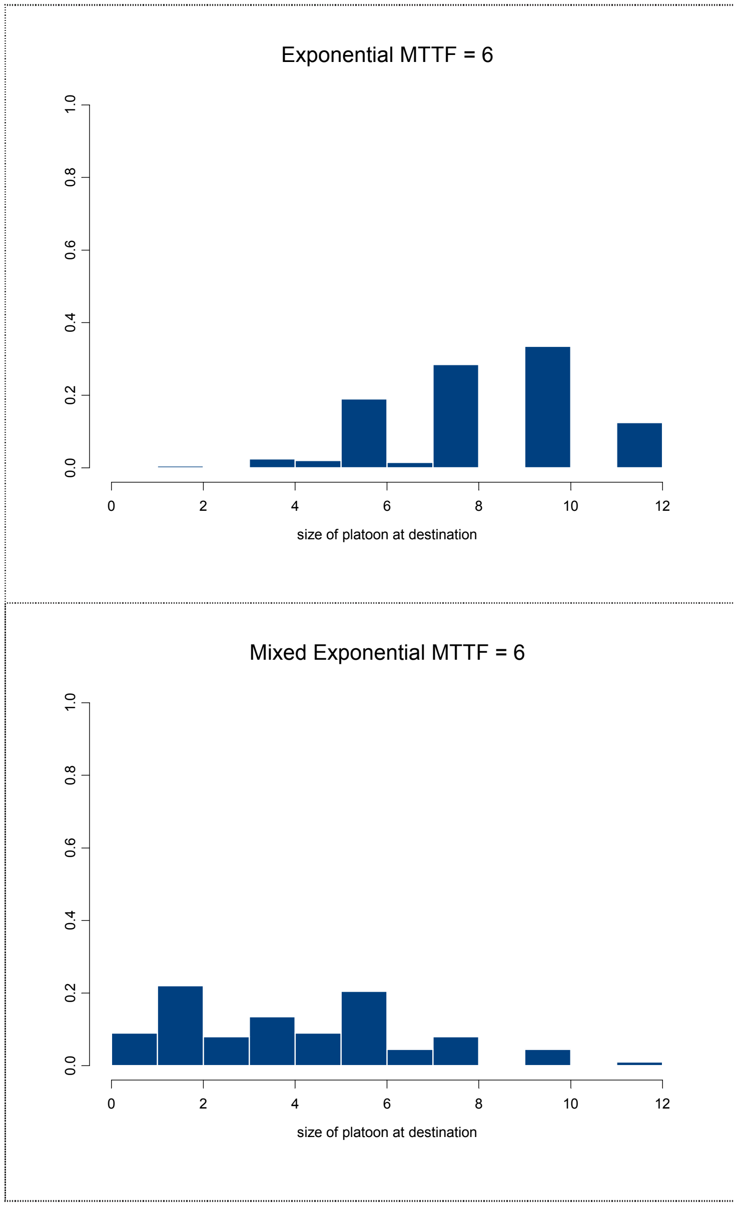

Figure 6. Comparison of Distributions of the Initial Size of the Platoon Upon Reaching the Beach When the Form of the Distribution of Failure Times is Varied (With MTTF = 6 hrs and AAAVs Used as Towing Asset). Parameters for the Mixed Exponential Distribution are: $p=0.5$; $\lambda_1=1$, $\lambda_2=1/5$.

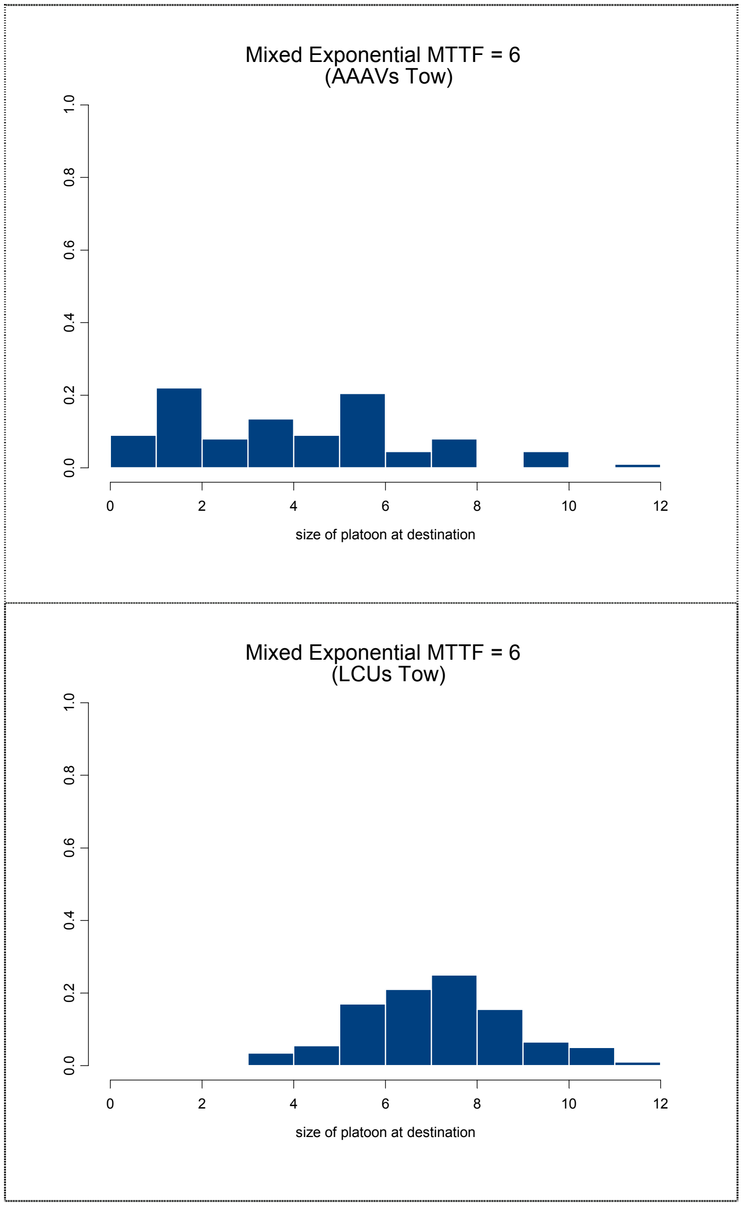

Figure 7. Comparison of Distributions of the Initial Size of the Platoon Upon Reaching the Beach When the Towing Method is Varied (With Failure Times From the Mixed Exponential Distribution with MTTF = 6 hrs). Distribution Parameters are: p=0.5; λ_1=1, λ_2=1/5.

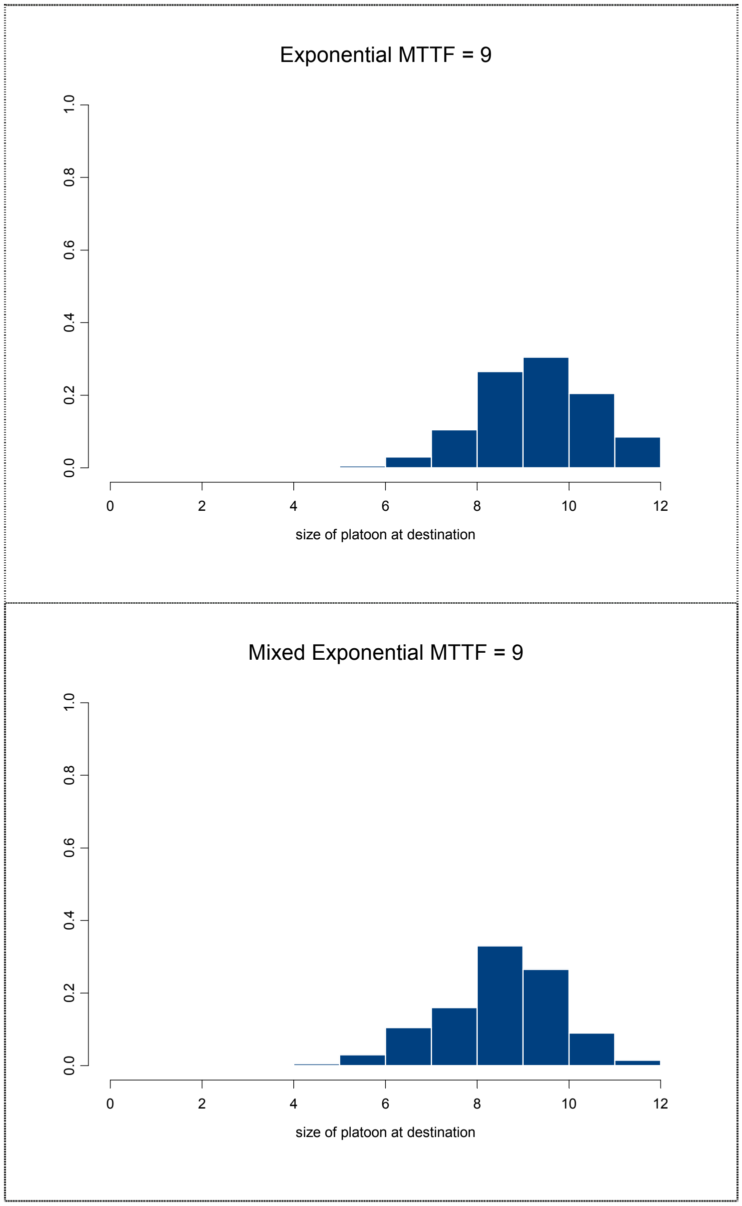

Figure 8. Comparison of Distributions of the Initial Size of the Platoon Upon Reaching the LOD When the Distribution of Failure Times is Varied (AAAVs were used as the towing asset). Parameters for the Mixed Exponential Distribution are: p=0.5; λ_1=1, λ_2=1/17.

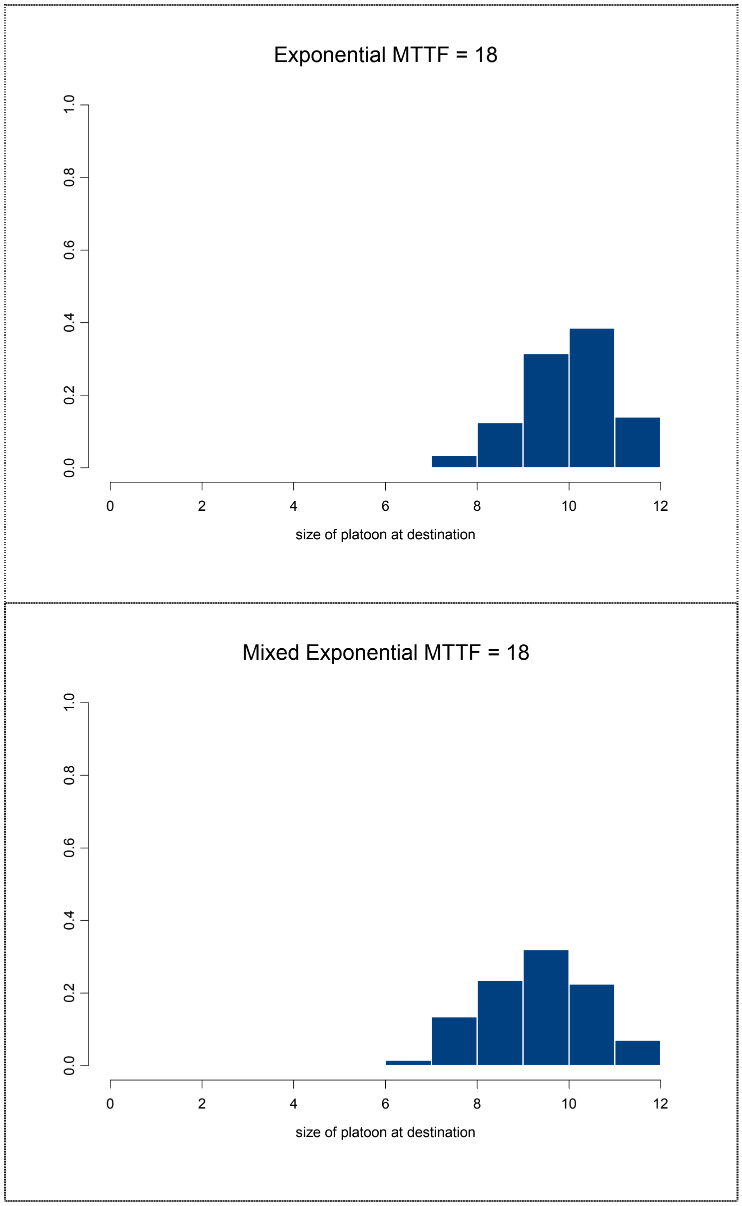

Figure 9. Comparison of Distributions of the Initial Size of the Platoon Upon Reaching the AO When the Distribution of Failure Times is Varied (AAAVs were used as the towing asset). Parameters for the Mixed Exponential Distribution are: p=0.5; $\lambda_1=1/6$, $\lambda_2=1/30$

It is clear from the above histograms (especially the ones with small MTTF) that the presence of infant failure times (modeled in the cases where the distribution of failure times are from a Mixed Exponential distribution) has a visible adverse effect on the size of the platoon upon arrival at various locations. This is also true in the comparison of tow assets used. As would be expected, using LCUs to tow quiescent AAAVs causes the distribution of the size of the platoon when it first reaches the beach to be much less spread out.

Note: The model has been tested extensively at all the levels of each factor setting. In the cases listed above (where failure times and distributions are equal) the model has been found to be within an acceptable margin of error when compared to analytical model results. The analytical models used for comparison are the subject of an NPS Technical Report by Distinguished Professor Donald Gaver et al (2001). However, in one extreme case, where failure times are from the Mixed Exponential distribution with MTTF = 3 ($p=0.5$; $\lambda_1=1$, $\lambda_2=1/5$), the simulation model exhibits seemingly anomalous behavior. Specifically, in 3 cases out of 200 replications, the model represents the initial size of the platoon upon reaching the beach as a negative number (see Figure 10). This result is merely due to the method of accounting for AAAVs that the model uses, and *does not invalidate the primary MOE*, the time to get 10 of the 12 AAAVs to the beach in an operational state, or TTB. The purpose of this model, as stated before, is to aid operational testers by suggesting sensitive aspects of operating a platoon of AAAVs. It is not reasonable to assume that, during operational testing, the AAAV will still be experiencing an observed MTTF of only three hours. The extremely low mean times to failure used in this section are only shown as a demonstration of how sensitive the MOEs are to changes in this factor (MTTF).

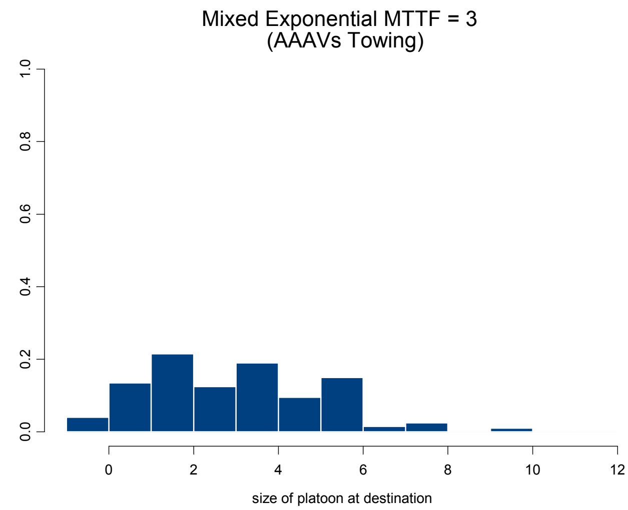

Figure 10. Distribution of the Initial Size of the Platoon Upon Reaching the Beach (extreme case where 3 observations are negative). Distribution Parameters are: p=0.5; λ_1=1, λ_2=1/5.

The second analysis enhancement this simulation model provides for examining the Times to Beach and Times to the LOD, beyond the standard statistics, is the capability to show the distribution of times for the platoon to assemble a given number of working AAAVs in the platoon at a given location. For each replication of the model, the simulation records the time to collect (in the case of these initial model runs) 10 of the 12 AAAVs at the Beach and then at the LOD. The AAAVs do not proceed from the beach to the LOD until 10 available AAAVs assemble at the beach. Just as with the plots of the distributions of the initial number of AAAVs to reach given destinations, these plots vividly illustrate the tradeoffs between different MTTF, failure distributions, and tow methods (in the case of the time to the beach (TTB)). Figure 11 shows comparisons of the effects of different distributions of failure times on the times it takes for 10 of the 12 AAAVs to reach the beach and be in working order. Figure 12 shows the effects of varying the towing assets on the times to reach the beach (when failure times are from the

Mixed Exponential distribution). Figure 13 shows the comparison of the affects of different distributions on the time for 10 of 12 AAAVs to reach the LOD.

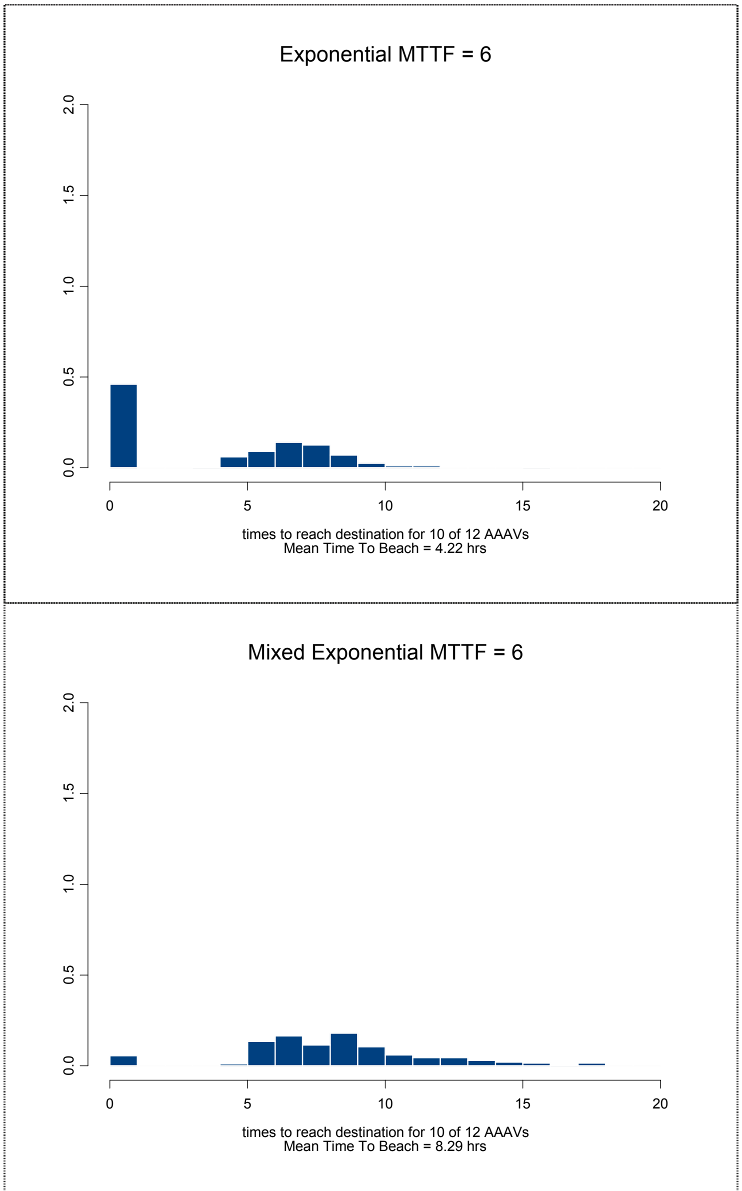

Figure 11. Comparison of Distributions of the Times to the Beach for 10 of 12 AAAVs When the Distribution of Failure Times is Varied (MTTF = 6 and AAAVs used as towing asset). Parameters for the Mixed Exponential Distribution are: $p=0.5$; $\lambda_1=1$, $\lambda_2=1/11$. Minimum time to reach beach without failure is one hour.

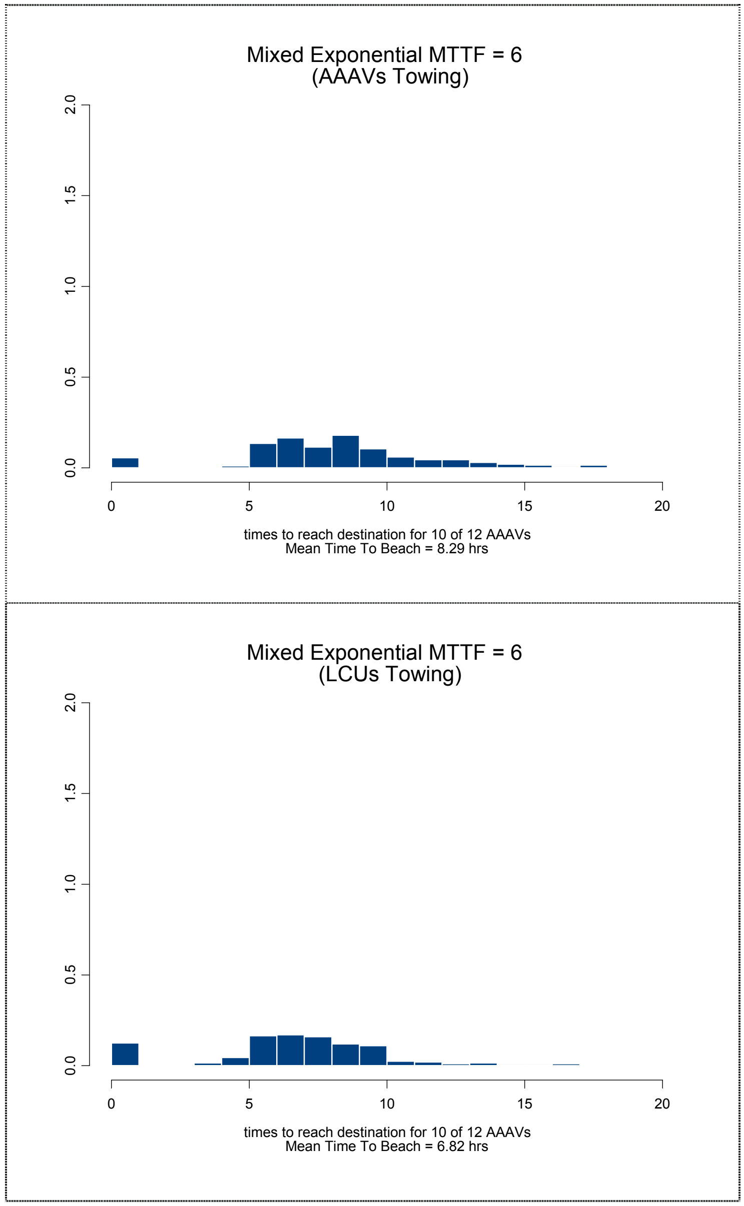

Figure 12. Comparison of Distributions of the Times to the Beach for 10 of 12 AAAVs When the Tow Method is Varied (Distribution is Mixed Exponential with MTTF = 6). Distribution Parameters are: p=0.5; $\lambda_1=1$, $\lambda_2=1/11$. Minimum time to reach beach without failure is one hour.

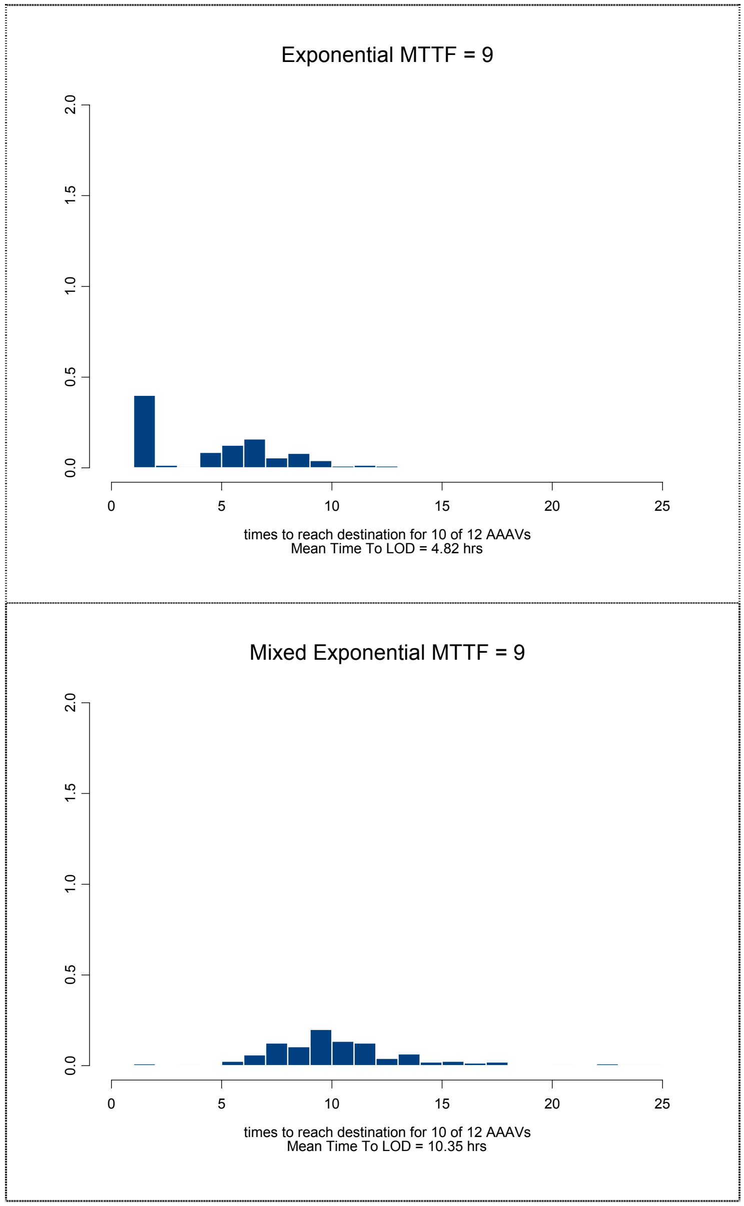

Figure 13. Comparison of the Distribution of the Times to the LOD for 10 of 12 AAAVs When the Distribution of Failure Times is Varied (MTTF = 9 and AAAVs are used as towing asset). Parameters for the Mixed Exponential Distribution are: p=0.5; λ_1=1, λ_2=1/17. Minimum time to reach beach without failure is one hour.

In addition to the MOEs TTB and TTS, other MOEs were observed during these initial runs. The other primary MOE, A_m or the time-average number of AAAVs in the platoon that are operational during the time the platoon is operating in the designated objective area, is shown below in table 5 along with other, secondary MOEs. These secondary MOEs include the Down Time Per AAAV, the Number of Available Helos per simulation, and the Flight Time Per Helo. These MOEs are observed over the same mean Failure Times and Distributions as TTB and TTS were in Tables 3 and 4. The statistics Down Time per AAAV, Number of Available Helos and Average Flight Hours per Helo are not very important for these initial model runs. The number of helos has been set to an arbitrarily large number so there should not be any shortage of helos, and, with such a large number of helos available to divide up the flight time, the total number of flight hours recorded during a simulation will be arbitrarily low. The Down Time per AAAV is also not very interesting for these initial runs because there is hardly any variability in the model (i.e. none of the times, other than failure times, are random). Add to that the fact that, with unlimited helos and LCUs, the Down Time for each observation is basically just the time for a helo to fly to the AAAV (or the time to tow the AAAV to shore or ship) plus the time to repair (which is a constant 2 hours for the initial simulation runs), which makes this statistic roughly predictable. However, these statistics become a much more valuable analysis tool when many more complications and random time generations are added to the model. Table 5's results are with model runs using AAAVs as the towing assets for quiescent AAAVs in the water.

The down time per AAAV and the number of flight hours per helo statistics are similarly measured. For down time, when an AAAV fails, the time of failure is recorded. Then when repairs have been completed, the time of repair is recorded. Subtracting the time of failure from the time of repair yields a single down time observation. The average down time per AAAV then, is simply the mean of all the observations of the type described above for one replication of the simulation. Similarly, for flight time per helo, when a helo departs, its departure time is recorded, then when it lands back at the ship, its return time is recorded. Subtracting departure time from return time yields one flight time observation. The individual helos record each flight similarly and add the times of all flights together to get a total flight time observation. At the end of each replication of the simulation, each helo records its total flight time observation (this is done at the end so as not to count flight time from helos that are destroyed). The average flight time per helo is the mean of all the observations for one replication.

Distribution of Time To Failure	**Reps**	**Avg Availability (In Obj Area)**	**Avg Down Time (per AAAV)**	**Avg Num Avail Helos**	**Avg Num Flight Hrs (per Helo)**
			(hours)		(hours)
Exp Mean 3	200	0.531 (0.004)	2.532 (0.007)	19.660 (0.032)	6.836 (0.175)
Exp Mean 6	200	0.690 (0.004)	2.658 (0.008)	21.323 (0.042)	2.460 (0.049)
Exp Mean 9	200	0.768 (0.004)	2.706 (0.011)	22.249 (0.047)	1.394 (0.038)
Exp Mean 18	200	0.862 (0.004)	2.750 (0.025)	23.403 (0.052)	0.626 (0.021)
Exp Mean 36	200	0.918 (0.003)	2.628 (0.060)	23.595 (0.247)	0.290 (0.014)
Mixed Exp Mean 3 p=0.5; λ_1=1, λ_2=1/5	200	0.549 (0.005)	2.582 (0.011)	19.782 (0.034)	7.553 (0.199)
Mixed Exp Mean 6 p=0.5; λ_1=1, λ_2=1/11	200	0.707 (0.005)	2.771 (0.015)	21.317 (0.052)	3.179 (0.071)
Mixed Exp Mean 9 p=0.5; λ_1=1, λ_2=1/17	200	0.774 (0.005)	2.827 (0.016)	21.923 (0.049)	2.438 (0.062)
Mixed Exp Mean 18 p=0.5; λ_1=1/30, λ_2=1/6	200	0.822 (0.005)	2.756 (0.016)	22.851 (0.056)	1.012 (0.031)
Mixed Exp Mean 36 p=0.5; λ_1=1/60, λ_2=1/12	200	0.877 (0.003)	2.779 (0.028)	23.520 (0.129)	0.510 (0.018)

Table 5. All other MOEs for the initial model runs. AAAVs used as towing asset. Standard error term is listed below the mean in parenthesis.

Finally, as an enhancement to the primary MOE A_m, the model is also capable of displaying, at a specified time-step interval, the $A_p(t)$ while the platoon is operating in the objective area. Each time-step interval is the average of (in the case of the initial model runs) 200 observations at that exact time. Figures 14 and 15 show the $A_p(t)$ at a time step of every 6 minutes starting at the time the platoon departs the LOD. The Objective Area is 25 miles long from the LOD to the Attack Objective (AO). At the AO the platoon pauses for 8 hours (in simulation of an attack). The vehicles in the platoon are subject to failure during the pause at the AO. Figure 14 shows the effects on $A_p(t)$ from different failure distributions (Exponential and Mixed Exponential) with a MTTF = 6. Figure 15 also shows the effects on $A_p(t)$ from different failure distributions (same distributions as in Figure 14) with a MTTF = 18 hours.

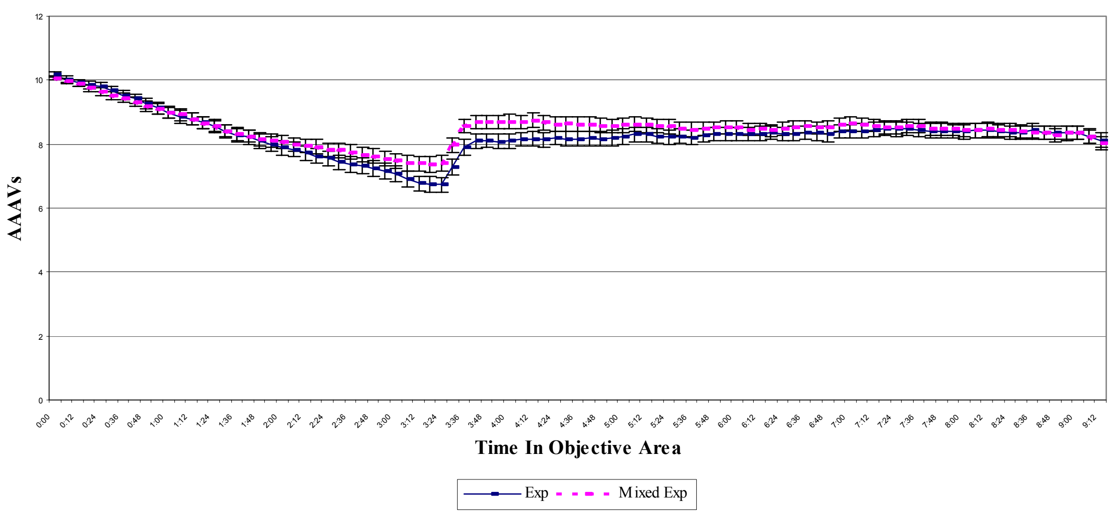

Figure 14. Mean $A_p(t)$ at a Time-Step of Six Minutes for the Length of Time the Platoon is Operating in the Designated Objective Area (MTTF = 6 hours). Data is shown with 95% confidence interval bounds.

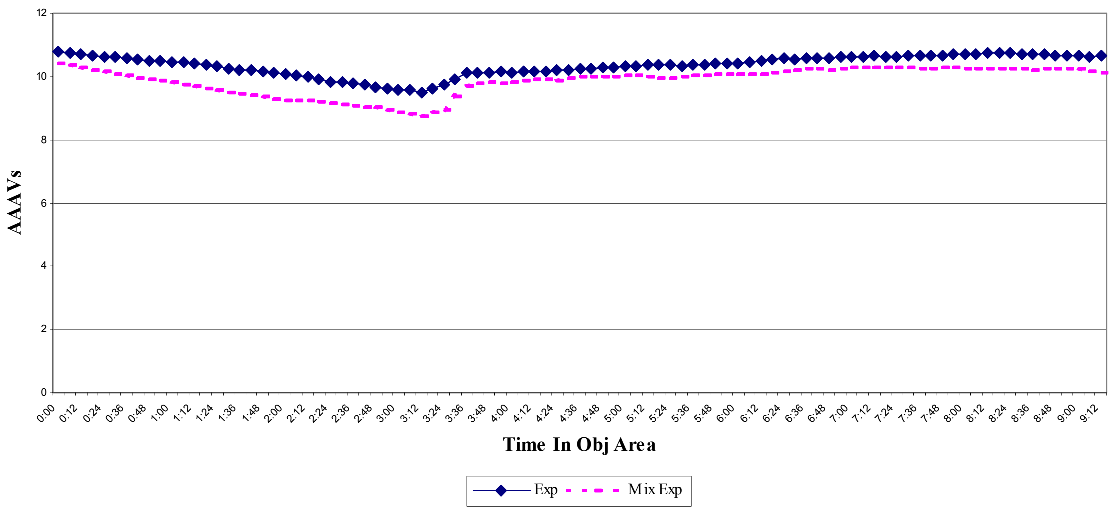

Figure 15. Mean $A_p(t)$ at a Time-Step of Six Minutes for the Length of Time the Platoon is Operating in the Designated Objective Area (MTTF = 18 hours). Data is shown without confidence interval bounds.

Figures 14 and 15 seem to show that, once the platoon has reached the objective area, in this case, at a time some hours after the initial launch, the form of the assumed distribution of failure times does not matter as much as it does early on in the simulation. Looking at the two figures together, it appears that as the MTTF increases, an assumed Exponential distribution of failure times has a slightly higher A_m however, as in Figure 14, many of the confidence interval bounds overlap, which would mean that there is no difference in A_m between the two distributions. Another thing to note is that, in both Figures 14 and 15, between the time the platoon enters the objective area until about the four hour mark, there is a dip in the $A_p(t)$. After that time, the $A_p(t)$ seems to somewhat stabilize. The likely reason for this is that, as the platoon is moving, and individual AAAVs fail along the way, they must be repaired, then travel independently back to the platoon's position, which takes time. Also, in both cases, the platoon enters the objective area with approximately 10 AAAVs, which means that most of the time there are 2 AAAVs in a downed state that have to travel back to the platoon's position independently. After some time (about three to four hours) the AAAVs that were failed at the time the platoon enter the objective area rejoining the platoon. These vehicles' failure locations were either at the LOD or at some point before it. Additionally, the AAAVs that fail en route to the AO (located somewhere between the LOD and the AO), are repaired and rejoin the platoon within that same time-span. If failures occur while the platoon is at the AO and thus, stationary (in a simulated attack), the AAAVs do not have to travel any distance to rejoin the platoon after being repaired. This explains the general state of equilibrium after about the four hour mark.

The results of Figures 14 and 15 can be compared to an analytical calculation for the long-run average time a vehicle is up, $\frac{MTTF}{MTTF+MTTR^{*}}$ (in the case of the data used to produce Figure 14, MTTF = 6 hours and MTTR* = 1.5 hours repair time + 37.5 minutes travel time from ship to AO at 120 kts) = $\frac{6}{6+(1.5+0.625)}$ multiplied by the number of vehicles in the platoon (12) yields 8.86. This number is within the confidence interval of the observed long-run availability from Figure 14.

B. SIMULATION RUNS OF A MORE COMPLICATED MODEL

1. Development of the Marine Expeditionary Unit (MEU)

Now that the basic simulation model has been built and limited cases considered, a more complicated and realistic model can be developed. This new model attempts to simulate, as closely as possible, the environment that a typical platoon of AAAVs would normally be expected to operate in. First, this requires the modeling of a Marine Expeditionary Unit (MEU). This is done by adjusting many of the settings (as shown in Tables 1 and 2 of the first section of this chapter) and adding some additional settings that control the properties of the model.

In the first model, the number of helos was given a large enough value so as to make their supply unlimited. However, a MEU can only deploy with approximately 16 helicopters. Currently the types of (support) helos on a MEU are the CH-46 (12) and the CH-54 (4). Initially 12 of these 16 total helos are required to transport the Air Assault Company of the Battalion Landing Team (BLT) to the objective. The simulation, therefore, will allocate 4 helos for logistics purposes (i.e. to provide support for failed AAAVs) until the Air Assault Company has been delivered. Once those 12 helos return and are refueled, they are added to the number of available helos for rescue missions. Additionally, helos in this model will be subject to attrition on any flight. Attrition is parameterized by a constant probability a helo is destroyed during a flight.

Also in the first model, the supply of LCU craft for towing quiescent AAAVs in the water was unlimited. The typical MEU deploys with one. Therefore the number of simulated LCU craft will also be one. In the first model the settings only allowed for either AAAVs to tow quiescent AAAVs or LCUs to do it, but not both. However, it is realistic to assume that if there is more than one failure in the water, and the only LCU available is engaged, then AAAVs would tow the additional failed vehicles. So, the settings in this model allow for either exclusive towing by the AAAVs, or combined towing by first the LCU, then the AAAVs.

As discussed in Chapter III, the situation may or may not allow for placing logistics assets ashore for support of the AAAV platoon. If the MEU commander decides to insert a logistics base ashore, however, he cannot do so until the other non-amphibious assault vehicles (LAAVs and/or Tanks) have been placed ashore. The only means for surface vehicles other than AAAVs to reach the shore is via the Landing Craft Air Cushioned (LCAC) vehicle. A MEU typically deploys with 2 LCACs that, due to weight requirements, have considerable limitations in the amount of cargo they can carry. In the first wave of the amphibious assault (along with the AAAV platoon) the LCACs launch with the battalion landing team's (BLT) other mechanized assets such as LAAV vehicles and Tanks if they are present in the MEU. Therefore, if a logistics base is to be established, it does not get to the shore until at least after the first LCAC wave is complete. If the MEU does have Tanks, the logistics base is probably not be able to be inserted ashore until after at least two LCAC trips. This model simulates one LCAC round trip before the logistics base is loaded and then taken to the shore. The load and unload times for the LCACs are implemented as random time draw from a uniform distribution, and the travel time is calculated based on the speed of the LCAC and the distance from the ship to the beach. LCACs are not subject to attrition or failure. The simulations will test the model with and without the use of a ground logistics base and look for tradeoffs between the two settings. Table 6 below shows all the general settings used for this model.

General Property	Value	Comments
Number AAAVs	12	
AAAV Avg Speed	25 (kts)	
AAAV Avg Tow Speed	5 (kts)	
Number LCUs	1	
LCU Speed	8 (kts)	

General Property	Value	Comments
LCU Tow Speed	4 (kts)	
Number LCACs	2	
LCAC Speed	40 (kts)	
Number LCAC trips needed prior to Log Base Delivery	1	
Total Number of Helos	16	
Number Assault Helos	12	Delivers Air Assault Company
Helo Avg Speed	120 (kts)	
Probability of Helo Attrition	0.05	
Number of AAAVs needed to proceed	Varies from 10 to 12	Platoon stops at Beach and/or LOD until this number of functioning AAAVs is present
Stop at Beachhead	Yes	
Stop at LOD	Yes	
Method of towing AAAVs used	AAAV only/LCU and AV combined	Varied so that comparisons can be made
Logistics Base Inserted	Yes/No	Varied so that comparisons can be made
Number of Trucks at Log Base	10	
Avg Speed of Logistics Trucks	20 (kts)	Knots used in order to keep all speed units equal
Probability that Part Needed for Repair Will Be at Log Base	0.8	If part is not available, log base must call back to ship for delivery of part via helo
Standoff Distance	15 miles	Constant distance maintained from Log Base location to position of AAAV platoon

Table 6. General Properties for Advanced Model Runs

2. Adding More Levels of Reality: Making All Settings Stochastic and Sampling Failure and Repair Times From the Weibull Distribution

The first model uses the Exponential distribution and the Mixed Exponential distribution to demonstrate the effect that the assumed form of the distribution has on the MOEs. Specifically, the Mixed Exponential distribution allows the introduction of infant failure times in the model, which is shown to have drastic effects on the platoon of AAAV's ability to maintain an acceptable level of availability, especially early on in the simulation. But because of its memoryless property, the Exponential distribution is limited in its applicability. A more flexible, but also more mathematically complicated distribution, is the Weibull distribution. The Weibull distribution, specified with a shape (κ) parameter and a scale (λ) parameter that implicitly define its mean and variance, is itself a generalization of the Exponential distribution. The Weibull distribution is widely considered to be very appropriate and useful for a wide range of applications related to system or component failures, as well as for computing times to complete a task, such as making repairs. (Leemis 1995)

The models in this section use the Weibull distribution to simulate the failure times for AAAVs as well as the times to repair the AAAVs. By varying the shape parameter (κ) the model can produce different behaviors from the random numbers generated by the distribution. When $\kappa < 1$ the distribution generates many small, but positive numbers, balanced by some that are very long in order to obtain the required mean. An example of the distribution of failure times generated from a Weibull distribution with a shape parameter less than one can be seen on Figure 16. When $\kappa = 1$, the Weibull distribution becomes equal to the Exponential distribution with mean λ. As κ becomes greater than one, the distribution of times begins to become centered about the value of the scale parameter (λ). The survivor function (probability a failure time is greater than t) of the Weibull distribution used in generating failure and repair times for this model is given by the equation, S(t) = $e^{-(\lambda t)^{\kappa}}$. Figure 17 shows the distribution of times generated from a Weibull distribution with κ equal to approximately 1.5. Finally, as κ continues to increase to a value between 3 and 4, it resembles that of a normal probability density function. Figure 18 shows an example the distribution of times generated from a Weibull distribution with κ equal to approximately 3.5.

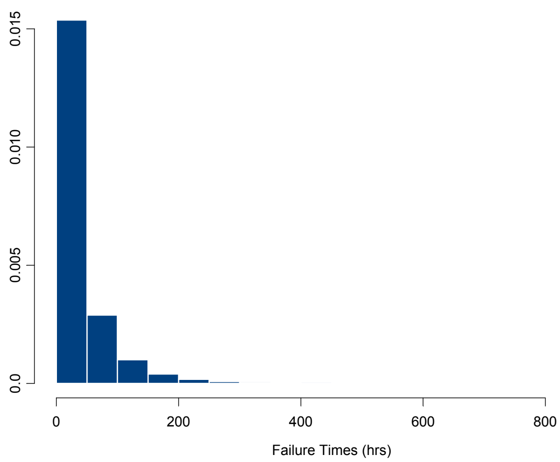

Figure 16. Distribution of Failure Times Generated from a Weibull Distribution with MTTF = 36 and Parameter Settings κ = 0.74 and λ = 30.0.

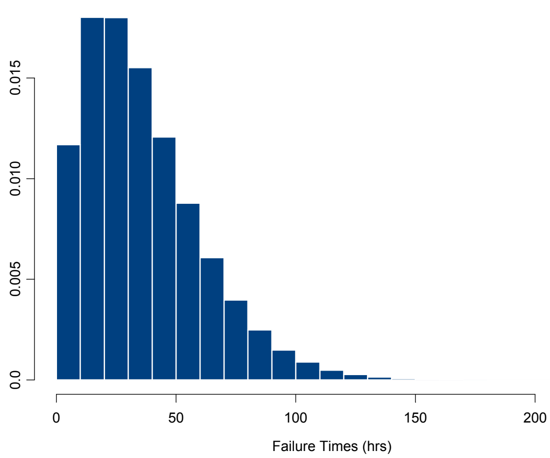

Figure 17. Distribution of Failure Times Generated from a Weibull Distribution with MTTF = 36 and Parameter Settings κ = 1.5 and λ = 40.0.

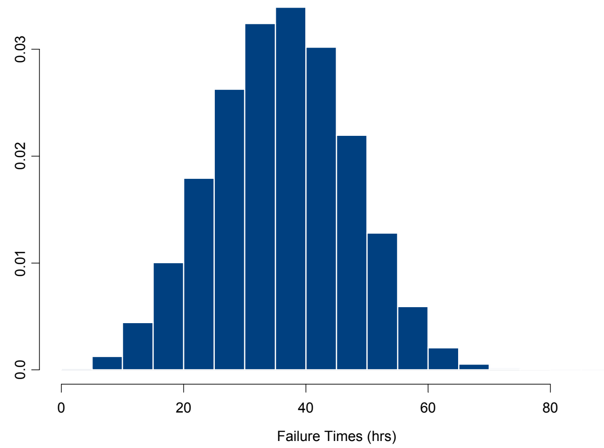

Figure 18. Distribution of Failure Times Generated from a Weibull Distribution with MTTF = 36 and Parameter Settings κ = 3.6 and λ = 40.0.

The three general forms of the Weibull distribution as shown in Figures 16-18, will be used in this portion of the thesis (using the same approximate shape parameter values) to show how varying the form of the distribution affects the MOEs. Because a shape parameter of less than one yields the highest amount of infant failure behavior, it is referred to as the "High Weibull" distribution. Any time a High Weibull distribution is used, the shape parameter is set at approximately 0.75 and the scale parameter is adjusted accordingly in order to achieve a specified MTTF. Following the same methodology, a Weibull distribution with a shape parameter of approximately 1.5 is referred to as a "Medium Weibull" and a distribution with a shape parameter of approximately 3.5 is referred to as a "Low Weibull".

The parameters used for the three types of distributions are referred to as "approximate" simply because they are not the same for every MTTF. For each MTTF used for the experiments in this section, the three types of Weibull distributions described above were obtained by estimation. Using the desired shape parameter value along with the desired MTTF value and varying the scale parameter accordingly, 1,000,000 random numbers from a Weibull distribution are generated using the S-Plus © statistical software package. The parameters that correspond to the mean of the 1,000,000 numbers are the ones used in the subsequent experiments in this section.

Because repair times, or the mean corrective maintenance time (MCMT) is a specific requirement in the ORD that must be tested, it is important to explicitly test to see if the form of the distribution of repair times has any effect on the MOEs. Therefore, the distribution of repair times is also be varied using approximately the same shape parameter values as is used for generating failure times. The distributions used to calculate a specified MCMT, therefore, will also be referred to as High, Medium and Low.

In the first model, other than the failure times, all the time-delays during the simulation are constant, or, in some cases non-existent (such as in the case of helo refuel times). However, in this model all the time-delays of the simulation are stochastic. In other words, all the time delays of the simulation are randomly generated from a specified distribution with specified parameters. All of the time delays, other than the failure times and repair times, are obtained by randomly generating values from the Uniform distribution.

The parameters used in the stochastic properties create arbitrarily large ranges of possible values. This is done in an attempt to represent the complete spectrum of possible operating conditions. However, this attempt to represent reality as closely as possible may cause a large amount of variability in the model's MOEs, especially the

MOEs that measure the time it takes the platoon to complete a task, such as the time to get to the beach (TTB). Measuring and accounting for this variability will be discussed later in this chapter. Table 7 below shows all the stochastic properties of this model and their settings.

Stochastic Property	Distribution	Parameters	Comments
Failure Times	Weibull [κ,λ]	κ ≅ 0.74 "High" κ ≅ 1.5 "Medium" κ ≅ 3.5 "Low"	Using the three values of κ, and a given MTTF, a value for λ will be determined
Repair Times	Weibull [κ,λ] with MCMT = 1.5 hours and 3 hours	κ ≅ 0.74 "High" κ ≅ 2 "Medium" κ ≅ 3.5 "Low"	Same methodology as used above
Prep Times for Helos	Uniform [a,b]	a= 0.333 hrs b = 1.0 hr	Time b/w rescue mission assigned to helo and helo departure
Refuel Times for Helos	Uniform [a,b]	a= 0.333 hrs b = 1.0 hr	
ALDT	Uniform [a,b]	a= 0.05 hrs b = 0.75 hrs	For AAAV repairs made on ship only
Time to Commence Towing	Uniform [a,b]	a= 0.5 hrs b = 1.0 hr	Time from failure to start of tow action (AAAVs only)
Pause at Attack Objective	Uniform [a,b]	a= 7.0 hrs b = 10.0 hrs	Simulated length of "attack"
Pause for Assault Helos at Obj	Constant	0.5 hours	Time to unload Air Assault Company at Objective
Pause for LCACs at Beach	Uniform [a,b]	a= 1.0 hr b = 1.5 hrs	Time to unload LCACs at the beachhead
Pause for LCACs at the Ship	Uniform [a,b]	a= 1.5 hrs b = 2.0 hrs	Time to re-load LCACs at the ship after delivering initial cargo at the beach
Refuel Times for Trucks	Uniform [a,b]	a= 0.2 hrs b = 1.0 hrs	

Stochastic Property	Distribution	Parameters	Comments
Prep Times for Trucks	Uniform [a,b]	a= 0.25 hrs b = 0.75 hrs	Time b/w rescue mission assigned to truck and truck departure

Table 7. Stochastic Properties for Advanced Model Runs

3. Method of Analysis of the Advanced Model

The primary (although not exclusive) focus of the simplistic model is on analyzing the effects of varying the MTTF and the form of the distribution of failure times on the MOEs. For the more advance model, however, *partly* because the case for the importance of the failure times and their assumed distributions has already been made, *and* because so much variability and reality has been added to the model, analyzing the effects of *multiple* variables is now the focus.

In order to study the effects of these multiple variables or *factors* on the MOEs or *response variables*, a series of screening experiments is conducted. The intent is to simultaneously study the effects of multiple factors, thus determining which are important and might warrant further study, and which can be discarded as either statistically, or practically insignificant. This is done by conducting factorial design experiments on multiple input factors that measure their effects on the MOEs This type of design requires relatively few runs per factor studied and is probably the most efficient method of analyzing several model factors. The levels of each factor are tested at ranges that attempt to represent the complete spectrum of possible operational conditions.

Note: A full factorial design is one that has all levels of a given factor combined with all the levels of each other factor in the experiment. Although none of the factorial design experiments have replications, each "run" (simulation with specific factor level settings) of the experiment is actually the average of 200 replications of that particular run. This should produce test observations (means of each of the 200 replications) that are normally distributed due to the Central Limit Theorem, which should, in turn result in normally distributed sets of residual standard error terms. The Central Limit Theorem states that even when the population distribution is non-normal (as they most-certainly are in this case), when the populations are averaged, the distribution of the collection of population means is normally distributed. (Devore 1995) However, the variances of the population averages may not be the same. In particular it is reasonable to expect that as the value of the response (in the case of the mean time to reach a destination) increases, so does the variance of the response.

Because these factorial design experiments involve the comparison of multiple population means based on sample statistics from the simulations, one of the techniques used for analysis in this section is Analysis of Variance (ANOVA). ANOVA works by partitioning the variance of the dependent variable from an experiment into parts to test whether or not the factors that were introduced into the design actually affect its value. The efficiency of ANOVA is derived by utilizing all the observations across all combinations of test factors to estimate the *experimental error* or random error inherent in the process. ANOVA uses the F-test to compare the estimated variability attributable to a test factor to the estimated error and, subsequently, tests for a significant effect. However, the F-test is based on the model that requires that the variances of the population means for all the factors be equal. Even though this assumption may be violated, ANOVA is still used for partial and preliminary data exploration. The justification for doing so is that even with some assumptions violated, ANOVA can still be used as a crude, but initial tool to show which variables are very important, or not very important, or which ones lie somewhere in between. Variables for which ANOVA tests show are not very important can be discarded and those that are deemed otherwise can be tested using other analysis methods.

Each experiment has designated, primary factors, that are explicitly tested, however, as mentioned above, there will be multiple, uncontrolled and randomly generated stochastic time-delays present in every run of the simulation. Because each "observation" of the factorial experiments will actually be the average of 200 runs of the simulation with the same factor levels, this could hide the fact that there is a large amount of variability *between* runs. Actually, this behavior should be expected since the model does have so much inherent variability.

Just using the population (factor level) means to describe the effects that important factors and their possible levels may have on measured MOEs is, on its own, also too crude of a measurement. Because of this, the variability between runs of a simulation with the same factor level settings is explicitly measured. To further highlight the between-run variability, some populations of runs with selected factor level settings are analyzed in-depth using techniques introduced in the first section of this chapter.

4. Analysis of Factor Effects on MOE Time To Beach (TTB)

An experiment is conducted to measure the time for the entire AAAV platoon (12 AAAVs) to reach the beach from a ship 25 nm offshore. Four primary factors are tested for their effects on the response variable (TTB): mean failure times, failure time distribution, repair time distribution, and tow method. The first three factors each have three levels, and the last factor has two levels. A full factorial design is used requiring 54 runs of the model in order to compare each factor level against every other factor level. Each run consists of 200 replications. Figures 19-22 below show the results of this experiment.

Factor	Type	Levels	Values
Repair Distn	fixed	3	Wei(low) Wei(med) Wei(hi)
Fail Dis	fixed	3	Wei(low) Wei(med) Wei(hi)
MTTF (hours)	fixed	3	18 36 72
Tow Method	fixed	2	AV AV/LCU

Analysis of Variance for Time To Beach (TTB) using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Repair Distn	2	0.304	0.304	0.152	6.48	0.005
Fail Distn	2	**213.874**	213.874	106.937	4567.45	0.000
MTTF	2	**32.850**	32.850	16.425	701.54	0.000
Tow Method	1	0.158	0.158	0.158	6.76	0.015
Repair D*Fail Dis	4	0.546	0.546	0.137	5.83	0.002
Repair D*MTTF	4	0.123	0.123	0.031	1.31	0.289
Repair D*Tow Meth	2	0.009	0.009	0.004	0.19	0.832
Fail Dis*MTTF	4	**43.813**	43.813	10.953	467.83	0.000
Fail Dis*Tow Meth	2	0.215	0.215	0.107	4.58	0.019
MTTF*Tow Meth	2	0.054	0.054	0.027	1.16	0.328
Error	28	0.656	0.656	0.023		
Total	53	292.602				

Figure 19. Analysis of Variance on the Response Variable Time for 12 AAAVs To Reach the Beach (TTB).

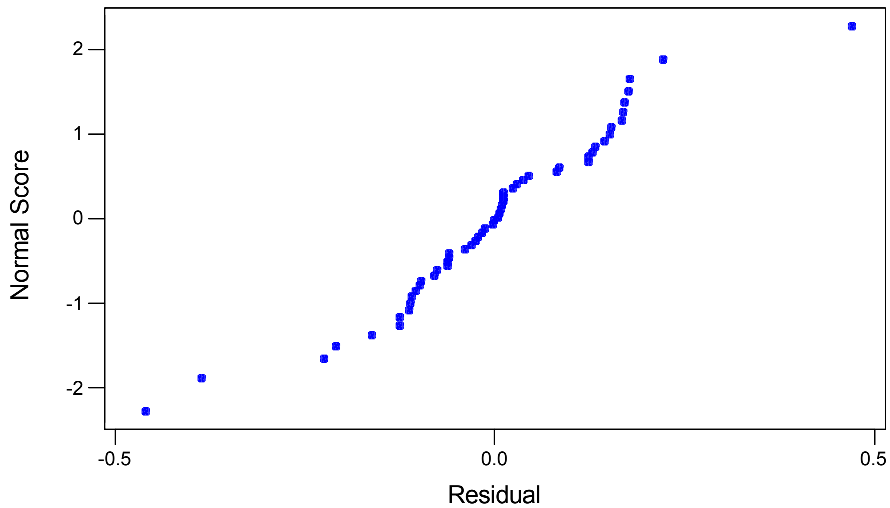

Figure 20. Normal Probability Plot of Residuals Where the Response Variable is the Time for 12 AAAVs to Reach the Beach (TTB).

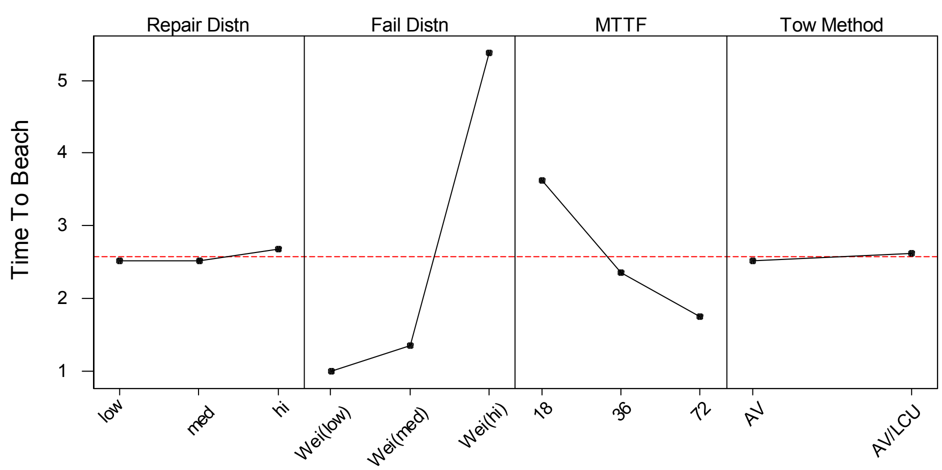

Figure 21. Main Effects Plot Where the Means are the Times for 12 AAAVs to Reach the Beach (TTB).

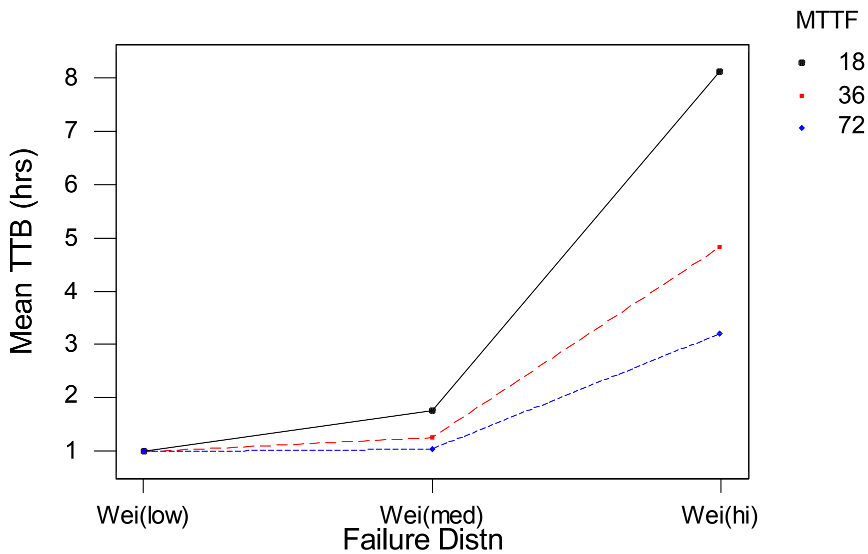

Figure 22. Plot of the Interaction Between the Factors MTTF and Failure Distribution Where the Response Variable is the Times for 12 AAAVs to Reach the Beach (TTB).

Figure 20 shows a standard normal plot of the residual terms. Since the plot is roughly linear, the residual terms appear to be roughly summarized by a normal distribution. The assumption that the observations have normal distributions with the same variance is required in order to use the F-test to determine significance. However, as stated, even if the variances are not equal, the F test can be used for exploratory data analysis.

From the Analysis of Variance in Figure 19, it is overwhelmingly clear that the factors that most strongly affect the mean time for the platoon to reach the beach are the MTTF and the form of the assumed distribution of failure times. Out of a total sum of squares value of 292.602, the failure distribution's sum of squares value is 213.874, or 72.4% of the model's variability. Second in terms of the model's sources of variability, is the first-order interaction between the Failure Distribution and the MTTF. Figure 22 above illustrates why this is the cause of 15% of the model's variability. Regardless of the MTTF (even at its lowest level = 18 hours), if the distribution of failure times is from a Weibull distribution with a shape parameter of approximately 3.5, failures never occur during the water-transit stage of the simulation, thus leading to a mean TTB of 1 hour with zero variability between runs (see Figure 23 below). One hour is the minimum time to reach the beach. If the distribution of failure times is Weibull with a shape parameter of approximately 1.5, it still has no effect on the mean TTB if the level of the MTTF factor is 72 hours. For MTTF factor levels 36 and 18, however, a shape parameter of 1.5 causes a slight increase in the mean TTB, although the mean value of the TTB is still under 2 hours for both levels. The average between-run variability of all simulations with a shape parameter approximately equal to 1.5 (measured in standard deviations) is 1.36 hours. But when the failure distribution shape parameter is approximately equal to 0.74, the mean TTB is drastically affected. In addition, the between-run variability of the model, when the failure distribution factor is at this level, is very large. The average between-run variability at this level (in standard deviations) is 5.44 hours. In contrast to Figure 23, Figures 24 and 25 show how a typical simulation, with the failure distribution having a shape parameter approximately equal to 0.74, creates a large distribution of times to the beach for the platoon.

Finally from the ANOVA table in Figure 19, the third largest source of variability in the model is from the MTTF, which contributes 11.2%. These three terms together combine for 98.5% of the model's variability. Even with the wide range of variability, in most cases, given to the other factors, their effect on the mean time to reach the beach for the model is extremely minimal. The error term from the ANOVA table, which shows the model's unexplained source of variance is only 0.2%. Again, this says *nothing* about the variability of the model between runs when factor levels are constant.

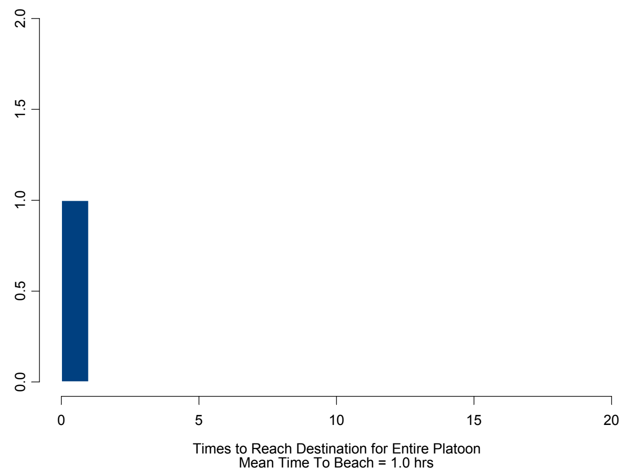

Figure 23. Distribution of Times For 12 AAAVs to Reach the Beach When Failure Times are from a Weibull Distribution (κ = 3.55 and λ = 20) with MTTF = 18 hours.

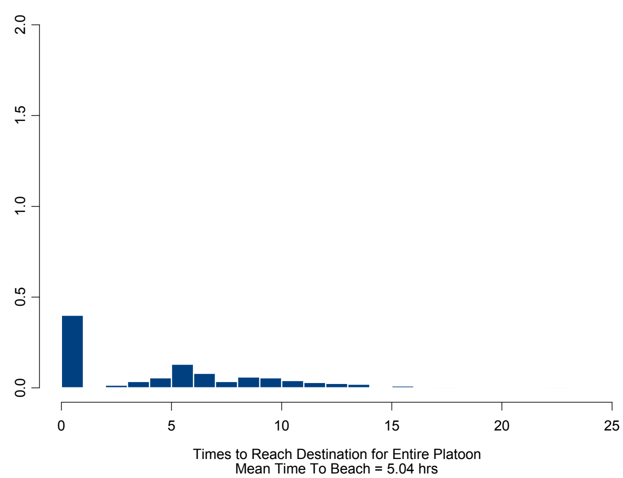

Figure 24. Distribution of Times For 12 AAAVs to Reach the Beach When Failure Times are from a Weibull Distribution (κ = 0.742 and λ = 30) with MTTF = 36 hours.

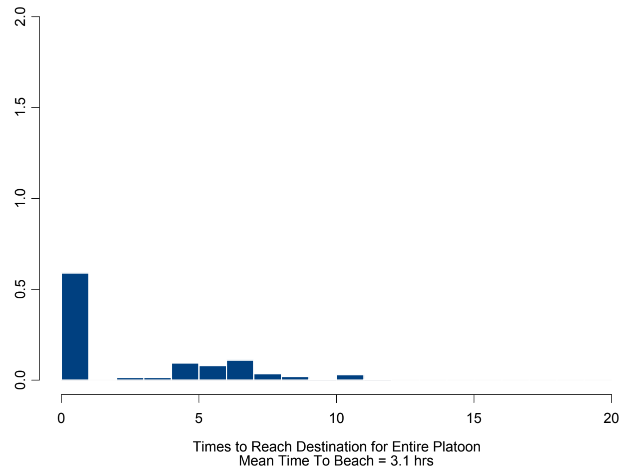

Figure 25. Distribution of Times For 12 AAAVs to Reach the Beach When Failure Times are from a Weibull Distribution (κ = 0.74 and λ = 60) with MTTF = 72 hours.

The histograms above in Figures 23-25 show that a mean time to get to the beach calculation is not always a good summary of the data on its own. Although mean time calculations are influenced by outliers, the between-run variability must be looked at in order to gain a full appreciation of the possible range of values, such as in the case of Figures 24 and 25.

Because it is shown that the variances of this model are somewhat dependent on the response (mean time to the beach), a further analysis of the ANOVA model is conducted. Once again, the assumption is that, because a large number of observations are used to form the population (factor level) means, the Central Limit Theorem (CLT) ensures that the distribution of means can be summarized by a normal distribution. This assumption is verified by a normal plot of the residuals that seems roughly linear. However, as seen from the observations of individual runs, as well as the means of multiple runs, the variance increases as the mean time to reach the beach increases. This type of behavior can mean that there is a condition in the data known as *heteroscedasticity*. This is usually characterized by residuals, in a residuals versus fitted Y-value plot, that exhibit increasing or decreasing scatter versus a fitted response variable. Another noticeable feature of the data being analyzed, particularly in the case of the MOEs mean TTB and mean TTS, is that the individual time observations tend to be heavily concentrated at the far left of the x-axis, with long, thin tails to the right. This, despite the large sample CLT effects, might mean that errors are not normally distributed. The presence of heteroscedasticity or nonnormal errors, as is conceded earlier, could undermine the rationale for the F-test and, in-turn, cast doubt on the validity of the observed P-values.

To explicitly test for heteroscedasticity and non-nomality, a plot of the residuals versus the fitted Y-values (responses) is made. If heteroscedasticity exists, then a horn or funnel shape in the data should be noticed as the size of the residuals tend to increase as the size of the observations increase. Figure 26 below does, in-fact, show that some heteroscedasticity exists, and that there is a pattern of increasing residual values as the response value increases.

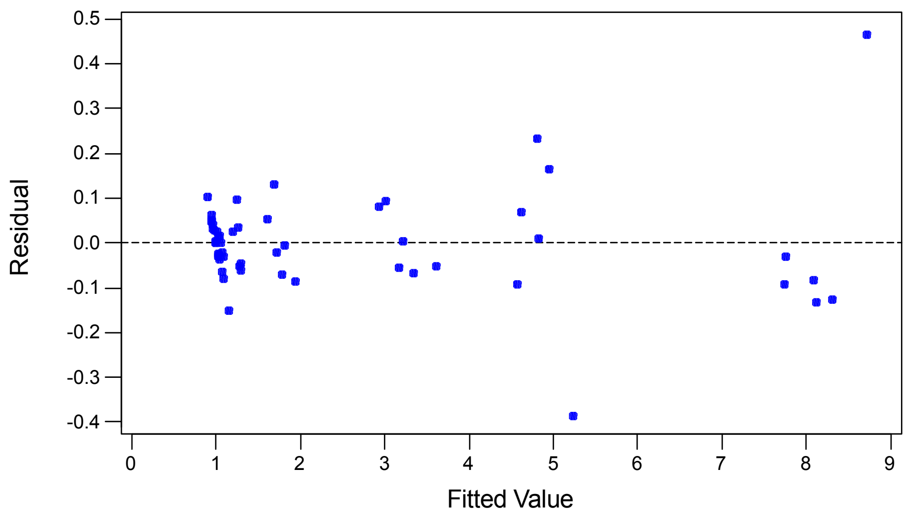

Figure 26. Plot of Residuals Versus Fitted Y-Values Where the Response Variable is Mean TTS. Plot shows some heteroscedasticity exists.

To try and alleviate this problem, the log of each population mean observation is taken. Taking logs tends to make the means and variances of the times less associated. This transformation technique is widely used to when problems of nonnormality and heteroscedasticity exist in data. After the data is transformed, another ANOVA model is constructed. Figure 27-28 below show results using the transformed data.

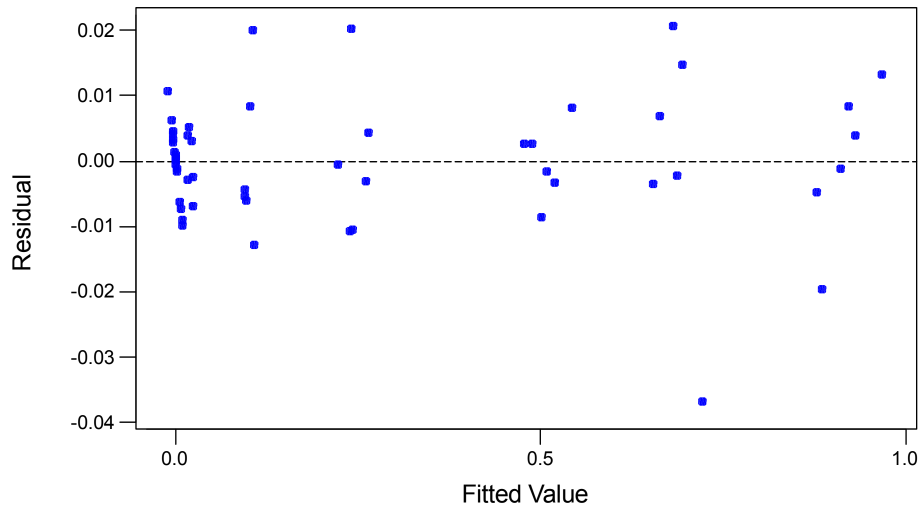

Figure 27. Plot of Residuals Versus Fitted Y-Values Where the Response Variable is log(Mean TTS).

Factor	Type	Levels	Values
Repair Distn	fixed	3	Wei(low) Wei(med) Wei(hi)
Fail Dis	fixed	3	Wei(low) Wei(med) Wei(hi)
MTTF (hours)	fixed	3	18 36 72
Tow Method	fixed	2	AV AV/LCU

Analysis of Variance for log(mean TTB)

Source	DF	SS	MS	F	P
Repair D	2	0.00278	0.00139	7.96	0.002
Fail Dis	2	5.06538	2.53269	1.4E+04	0.000
MTTF	2	0.40735	0.20367	1164.41	0.000
Tow Meth	1	0.00245	0.00245	14.00	0.001
Repair D*Fail Dis	4	0.00422	0.00105	6.03	0.001
Repair D*MTTF	4	0.00102	0.00025	1.45	0.243
Repair D*Tow Meth	2	0.00006	0.00003	0.16	0.853
Fail Dis*MTTF	4	0.25516	0.06379	364.69	0.000
Fail Dis*Tow Meth	2	0.00182	0.00091	5.21	0.012
MTTF*Tow Meth	2	0.00039	0.00020	1.12	0.342
Error	28	0.00490	0.00017		
Total	53	5.74552			

Figure 28. Analysis of Variance on the Response Variable is log of Mean Time for 12 AAAVs To Reach the Beach (TTB).

Figure 27 above, shows that the heteroscedasticity that exited in the non-transformed data, seems to have been eliminated by taking the log of each of the population means, although there is the presence of one rather large outlier. Now the assumption of equal variance is more valid, which should, in-turn remove some of the doubt about the validity of the F-test. Comparing Figure 28, the analysis of variance of the transformed data, to Figure 19, the ANOVA with the normal, non-transformed data shows that the F-statistics and P-values do not noticeably change. The factors and first-order interactions that are significant and important when a key assumption is violated, are still significant after the data is transformed, and the assumptions are met. This is not the only data-transformation technique however, therefore others will be tested on later models to see if they have an effect on F-statistics and P-values.

Although many of the factors and interaction terms are statistically significant (i.e. p-values of less that .05) only the two factors and the interaction between them (discussed above and highlighted in bold print in Figure 19) are *practically* significant. Figure 21 examined in conjunction with Figure 19 illustrates this well. For instance, the form of the distribution of repair times is found to be statistically significant at a level of 99.5% in Figure 19, however, Figure 21 shows that its real affect on the mean TTB can be measured in a small amount of minutes and thus is practically insignificant. This fact goes back to the earlier discussion about the reasons for using the ANOVA model. In some cases (here it overvalues the repair time distribution factor) it is too crude a tool to be used alone.

Finally, Figure 29 below is another good example why significance testing is good, but can be misleading if viewed independently of any other type of statistic.

Although all the primary factors, and two first-order interactions are found to be statistically significant, Figure 29 clearly shows that there is no real difference in the mean time to reach the beach between any of the levels for the tow method or repair distribution factors. This fact can easily be extended to the first-order interactions involving ether of these factors. This is due to the fact that the confidence intervals of the different levels of the tow asset and repair dstribution factors overlap. The confidence intervals of the mean time to reach the beach for the factors MTTF and Failure Distribution do not overlap, however, so the same cannot be said about them. The inconsequential effect that varying the tow method has on the mean TTB response variable should not be surprising. One auxiliary vehicle compared to none is not much of a change in factor levels. However, the benefit of several auxiliary vehicles is clearly shown with the simpler model in the first section of this chapter.

```
                          Individual 95% CI
Fail Distn      Mean   -------+---------+---------+---------+----
Wei(low)        1.00    (--*--)
Wei(med)        1.36      (--*--)
Wei(hi)         5.39                               (--*--)
                       -------+---------+---------+---------+----
                           1.50      3.00      4.50      6.00

                          Individual 95% CI
MTTF            Mean   --+---------+---------+---------+---------
18              3.63                            (------*-----)
36              2.36            (------*-----)
72              1.75   (------*------)
                       --+---------+---------+---------+---------
                      1.40      2.10      2.80      3.50

                          Individual 95% CI
Tow Method      Mean   ---------+---------+---------+---------+--
AV              2.53    (------------------*-----------------)
AV/LCU          2.64      (------------------*-----------------)
                       ---------+---------+---------+---------+--
                             2.00      2.50      3.00      3.50

                          Individual 95% CI
Repair Distn    Mean   -------+---------+---------+---------+----
low             2.53   (------------------*------------------)
med             2.53   (------------------*------------------)
hi              2.69      (------------------*------------------)
                       -------+---------+---------+---------+----
                           1.80      2.40      3.00      3.60
```

Figure 29. Means and Confidence Intervals for the Primary Factors Where the Response Variable is mean TTB.

5. Analysis of Factor Effects on MOE Time To LOD (TTS)

An experiment is conducted to measure the time for the entire AAAV platoon (12 AAAVs) to reach the Line of Departure (LOD) which is 25 nm from the beachhead. This experiment is run simultaneously with the previous experiment; that is, after the platoon waits at the beach for all 12 AAAVs to arrive and become operational (and have their time to do so measured) they proceed onto the LOD and undergo the same procedure there. As a consequence, the platoon always leaves the beach with 12 working AAAVs. An additional consequence to this is that long times to get 12 AAAVs to the Beach (TTB) have a direct effect on this response variable because the time to the LOD includes the TTB. The same four primary factors as before are tested for their effects on the response variable (TTS): mean failure times, failure time distribution, repair time distribution, and tow method. The first three factors each have three levels, and the last factor has two levels. A full factorial design is used requiring 54 runs of the model in order to compare each factor level against every other factor level. Each run consists of 200 replications. Figure 30 below shows the results of this experiment.

The results of this experiment show that, once again the form of the distribution of failure times, the MTTF and their interaction effect combine to create more than 99% of the model's variability. This is essentially the same result as in the previous experiment, and therefore is not discussed further.

Factor	Type	Levels	Values
Repair Distn	fixed	3	Wei(low) Wei(med) Wei(hi)
Fail Distn	fixed	3	Wei(low) Wei(med) Wei(hi)
MTTF (hrs)	fixed	3	18 36 72
Tow Method	fixed	2	AV AV/LCU

Analysis of Variance for Time To LOD, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Repair D	2	0.363	0.363	0.181	5.71	0.008
Fail Dis	2	**478.621**	478.621	239.311	7539.18	0.000
MTTF	2	**94.082**	94.082	47.041	1481.96	0.000
Tow Meth	1	0.064	0.064	0.064	2.02	0.167
Repair D*Fail Dis	4	0.780	0.780	0.195	6.15	0.001
Repair D*MTTF	4	0.115	0.115	0.029	0.90	0.475
Repair D*Tow Meth	2	0.050	0.050	0.025	0.79	0.466
Fail Dis*MTTF	4	**112.204**	112.204	28.051	883.71	0.000
Fail Dis*Tow Meth	2	0.080	0.080	0.040	1.26	0.300
MTTF*Tow Meth	2	0.013	0.013	0.007	0.21	0.815
Error	28	0.889	0.889	0.032		
Total	53	687.260				

Figure 30. Analysis of Variance on the Response Variable Time for 12 AAAVs To Reach the LOD, or Time to Step-Off (TTS).

6. Analysis of Factor Effects on MOE Mission Availability (A_m)

An experiment is conducted to measure the average number of AAAVs available in an operational condition during the time the platoon is in the designated objective area, otherwise known as mission availability (A_m). Five primary factors are tested for their effects on the response variable A_m: failure times, failure distribution form, repair distribution form, operational distance, and logistics support method. As before, the factors failure distribution form, and repair distribution form have three levels, high medium and low. This experiment, however, only looks at two levels for the MTTF, 36 and 72 hours. MTTF = 18 hours is not examined because this is an unrealistic value, especially for what should be expected during operational testing. Two levels for the distance factor are used, 50 and 100 nm. These distances include the total length of travel from the ship to the final objective. Finally the logistics support method is varied between inserting a ground logistics base with trucks, and conducting all logistics support from the ship via helos. However, even when the simulation uses a ground logistics base, it is only inserted after the LCACs have made one round trip with their original cargo. That is, the log base appears after the LCACs travel to the beach, draw a randomly generated unload time, travel back to the ship, draw a randomly generated load time (load time parameters are larger than unload parameters), travel back to the beach, and finally draw a randomly generated unload time. A full factorial design is used requiring 72 runs of the model in order to compare each factor level against every other factor level. Each run consists of 200 replications. Figures 31-33 below show the results of this experiment.

Factor	Type	Levels	Values
Repair Distn	fixed	3	Wei(low) Wei(med) Wei(hi)
Fail Distn	fixed	3	Wei(low) Wei(med) Wei(hi)
MTTF (hours)	fixed	2	36 72
Distance (miles)	fixed	2	50 100
Log Base	fixed	2	Yes No

Analysis of Variance for Availabi, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Repair D	2	0.0000107	0.0000107	0.0000053	0.62	0.544
Fail Distn	2	**0.1304645**	0.1304645	0.0652322	7531.13	0.000
MTTF	1	0.0090429	0.0090429	0.0090429	1044.02	0.000
Distance	1	0.0025924	0.0025924	0.0025924	299.29	0.000
Log Base	1	0.0008785	0.0008785	0.0008785	101.42	0.000
Repair D*Fail Dis	4	0.0000078	0.0000078	0.0000020	0.23	0.922
Repair D*MTTF	2	0.0000055	0.0000055	0.0000028	0.32	0.728
Repair D*Distance	2	0.0000041	0.0000041	0.0000021	0.24	0.788
Repair D*Log Base	2	0.0000105	0.0000105	0.0000053	0.61	0.549
Fail Dis*MTTF	2	0.0040778	0.0040778	0.0020389	235.39	0.000
Fail Dis*Distance	2	0.0013839	0.0013839	0.0006919	79.88	0.000
Fail Dis*Log Base	2	0.0010354	0.0010354	0.0005177	59.77	0.000
MTTF*Distance	1	0.0001269	0.0001269	0.0001269	14.65	0.000
MTTF*Log Base	1	0.0001186	0.0001186	0.0001186	13.69	0.001
Distance*Log Base	1	0.0000823	0.0000823	0.0000823	9.50	0.004
Error	45	0.0003898	0.0003898	0.0000087		
Total	71	0.1502316				

Figure 31. Analysis of Variance on the Response Variable A_m.

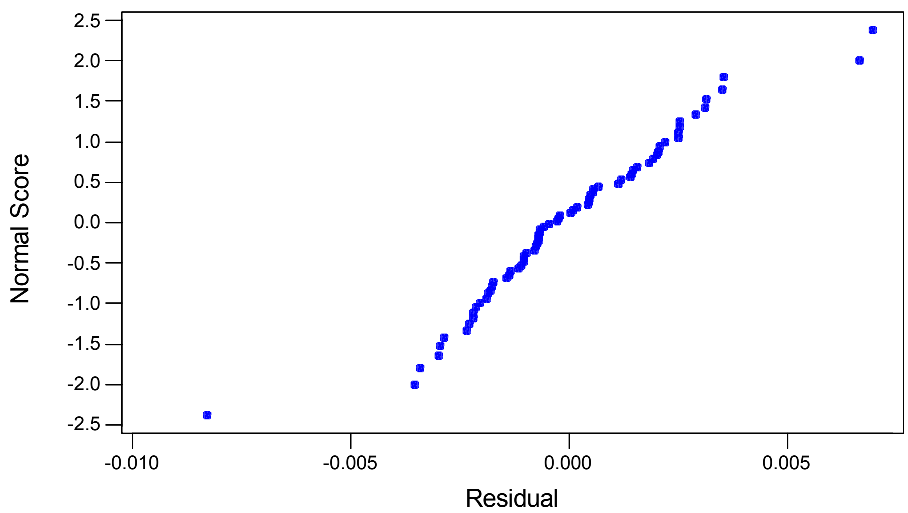

Figure 32. Normal Probability Plot of Residuals Where the Response Variable is A_m.

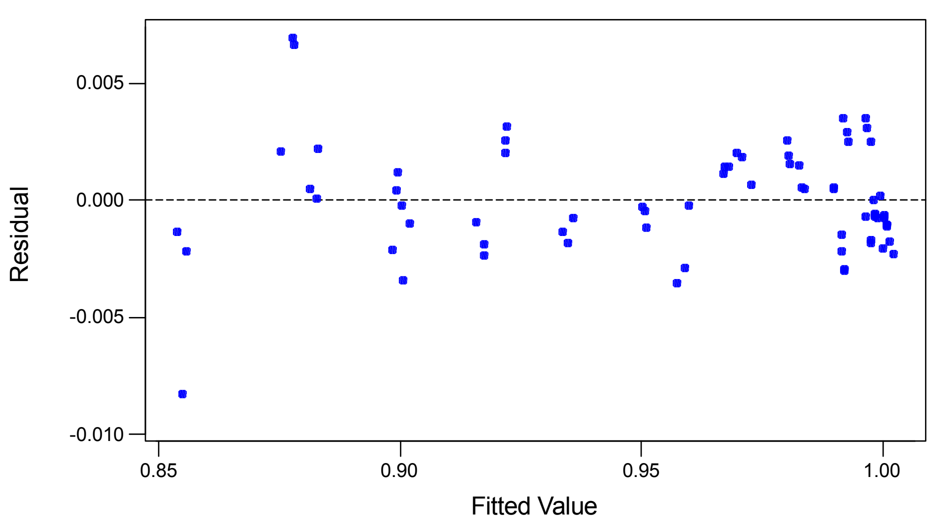

Figure 33. Plot of Residuals Versus Fitted Y-Values Where the Response Variable is A_m.

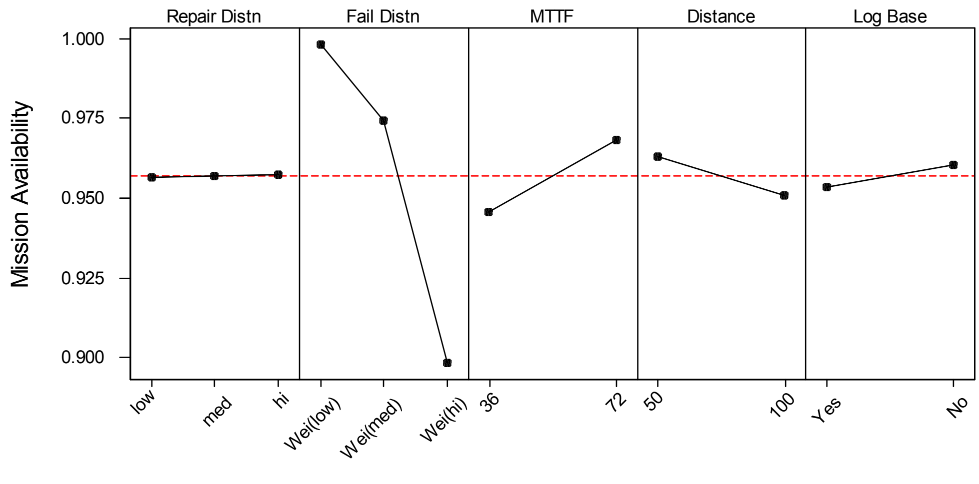

Figure 34. Main Effects Plot Where the Means are for the Time Average Number of AAAVs in the Platoon That are Operational During the Time the Platoon is in the Objective Area.

The normal plot of the residual standard error terms in Figure 32 suggests that the residuals are roughly summarized by a normal distribution. Figure 33, the residuals versus the fitted Y-values plot, shows that, except for the presence of three outliers, the data seems to be generally patternless and thus, *homoscedastistic*. These two figures together show that for this response variable, all the necessary assumptions for using ANOVA seem to be met even without a data-transformation. The Analysis of Variance in Figure 31 shows that, again, the primary factor causing variability in the model is the form of the distribution of failure times. This factor has a sum of squares value of 0.1304 or 86.8% of the model's variability. This is not a surprise, since all the models prior to this have also had similar results. The factor MTTF, however, only accounts for 6% of this model's variability. Other than that, there are many other factors and interaction terms that account for approximately 1% or less of overall model variability.

Figure 34 is perhaps the most revealing illustration of this model's results. While the ANOVA table in Figure 31 again shows that many of the factors and interactions are statistically significant, none of the factors except for the failure distribution form (and then only marginally) are at all practically significant. Of these results, one of the most surprising is the fact that varying the operational distance of the platoon by 50 miles only accounts for a change in the mean A_m of 0.002 or 0.2%. In other words this is a change in the mean of the time average number of available AAAVs (out of 12) from 11.436 to 11.412. This is hardly a substantial difference. Figure 34 (above) along with Figure 35 (below) show similar results for all the factors tested.

But perhaps the lack of practical significance for most of the factors is not so surprising after-all. For example, the distance factor is varied by 50 miles, but if there is a logistics base inserted, this does not matter, since the trucks maintain a constant standoff distance from the platoon. In the case where there is no logistics base, the helos travel at a speed of 120 kts. At that rate of speed, the difference between the distance factor levels, 50 miles, is only 25 minutes. Additionally, with a standoff distance of 15 miles, trucks in the logistics base (with a speed of 20 kts) have a travel time of 45 minutes, while helos, even from 100 miles away, have a travel time of only just under 50 minutes.

The between-run variability of all factor levels was also very low and thus not very significant. An example of this can be found in figure 36 (below). This figure shows the time-step measured $A_p(t)$ while the platoon is in the objective area. The measurements are taken with the factor level for the failure distribution set with a shape parameter of 0.74 and the factor level for MTTF set at 36 hours. Each point and subsequent confidence band are the summary of 200 observations at that exact time-period.

Once again, the results of the observed long-run availability (from Figure 36) can be compared to an analytical calculation for the long-run average time a vehicle is up, $\frac{MTTF}{MTTF + MTTR^*}$ (where $MTTR^*$ = MCMT + minimum possible prep time + travel time) $= \frac{36}{36 + (1.5 + 0.25 + 0.8333)}$ = 0.93 multiplied by the number of vehicles in the platoon (12) yields 11.16. This is clearly not the same as the observed long-run availability as seen in Figure 36. The model (at the factor levels used to produce Figure 36) seems to reach a steady state of slightly less than 10 vehicles. As is the case in the first section of this chapter, the analytical calculation for the long-run availability is more optimistic than the values observed here. The comparison against this section's model is not as good as it is against the simper model, however. This is understandable since there are many other stochastic events that can adversely affect availability in this model.

```
                              Individual 95% CI
Fail Distn        Mean    ---+---------+---------+---------+--------
Wei(low)        0.9983                                      (-*)
Wei(med)        0.9742                              (-*)
Wei(hi)         0.8984     (*-)
                          ---+---------+---------+---------+--------
                        0.9000    0.9300    0.9600    0.9900

                              Individual 95% CI
MTTF              Mean    ----+---------+---------+---------+-------
36              0.9457     (----*----)
72              0.9682                                 (----*----)
                          ----+---------+---------+---------+-------
                         0.9440    0.9520    0.9600    0.9680

                              Individual 95% CI
Distance          Mean    -+---------+---------+---------+---------+
 50             0.9630              (-----------*------------)
100             0.9510     (-----------*------------)
                          -+---------+---------+---------+---------+
                      0.9360    0.9480    0.9600    0.9720    0.9840

                              Individual 95% CI
Log Base          Mean    --+---------+---------+---------+---------
Yes             0.9535    (--------------*---------------)
No              0.9604           (--------------*---------------)
                          --+---------+---------+---------+---------
                       0.9400    0.9500    0.9600    0.9700

                              Individual 95% CI
Repair Distn      Mean    ---+---------+---------+---------+--------
low             0.9564    (-----------------*-----------------)
med             0.9570     (-----------------*-----------------)
hi              0.9574     (-----------------*-----------------)
                          ---+---------+---------+---------+--------
                        0.9400    0.9500    0.9600    0.9700
```

Figure 35. Means and Confidence Intervals for the Primary Factors Where the Response Variable is A_m.

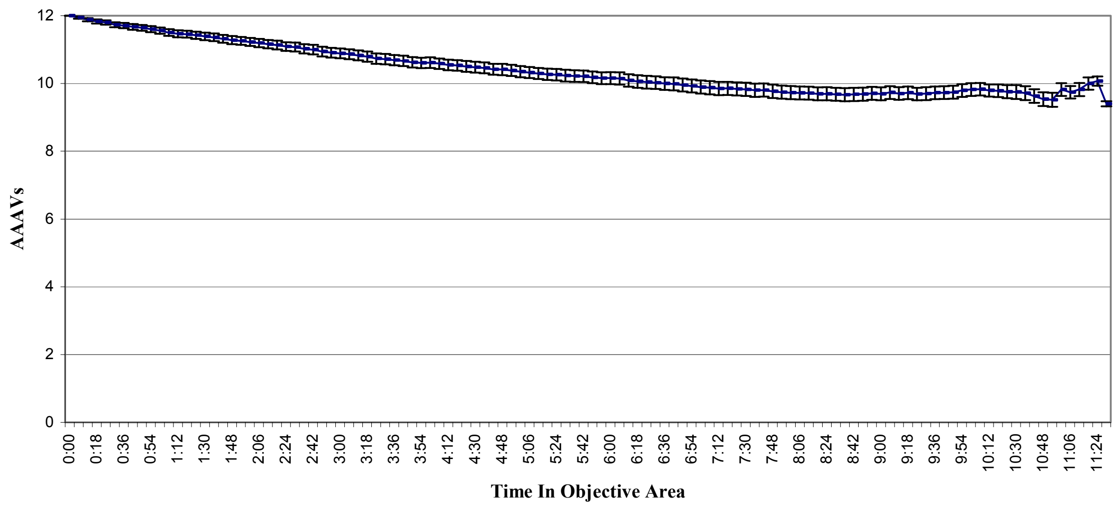

Figure 36. Mean $A_p(t)$ at a Time-Step of Six Minutes for the Length of Time the Platoon is Operating in the Designated Objective Area. Failure Times are from a Weibull Distribution ($\kappa = 0.74$ and $\lambda = 30$) with MTTF = 36 hours. The Total Operational Distance From Ship to Attack Objective (AO) is 100 nm.

7. Further Analysis of Different Factor's Effects on MOE Time to LOD (TTS).

In all three models tested above, with settings at levels that attempt to reflect the true assets of a MEU, the failure distribution form and the MTTF are the only two practically significant factors when measuring factor effects on population means. This is a result that should not be glossed over. It is undeniable proof that merely calculating a MTTF during testing and assuming that the failures are exponentially distributed is not adequate. A MTTF could represent many short times to failure coupled with some very long times to create a distribution of failure times like some of those simulated in this thesis.

However, many of the more complicated simulation model's results seem to be too optimistic, in terms of all the MOEs. One of the reasons for these over-optimistic results could be the number of helos available during the simulations. The number of helos is kept constant because the model simulates the fact that early in the operational mission, most of the helos are not available due to the fact that they are transporting the Air Assault Company. The remainder of the helos on the MEU (those not in the air assault wave) are made available for supporting downed AAAVs. When the air assault helos return, they are added to the total number of helos available to the AAAV platoon. This could represent an unrealistic amount of the MEU's vertical lift assets dedicated to supporting the AAAV platoon's maintenance effort.

The BLT on the MEU has three rifle companies that have to be inserted. The current doctrine is that one of the companies be inserted via small zodiac boats. However, these simulations are modeling the insertion of the BLT many miles inland beyond the beachhead. In this scenario, small boats might not be of any use (unless the boat company's mission was to secure the beachhead and surrounding area, possibly to allow for the insertion of logistics assets via LCAC). If the entire BLT is needed at the attack objective, which, in these models is at least 25 nm inland from the beachhead, then the MEU's helo assets will probably need to insert two companies. The first wave would likely go in a combined initial assault with the company being delivered by the AAAV platoon (as has been modeled in this thesis), then the helos would return to the ships to pick up and deliver the second company, which would be used in a tactical reserve status.

If this is the case, then there should be an even longer period of time during which the number of helos available to the AAAV platoon for logistics support is very limited. The following experiments use a model that implements this feature.

An experiment is conducted to measure the time for the entire AAAV platoon (12 AAAVs) to reach the LOD, which is 25 nm on land from the beachhead. The beachhead is 25 nm from the amphibious ships offshore. Unlike the last experiment where the response variable is mean TTS, this time the platoon does not pause at the beachhead to wait for a particular number of AAAVs to become operational. Therefore the mission of the AAAV platoon is to proceed from the ship to the beach and beyond to the LOD *without stopping* along the way.

The five primary factors tested for their effects on the response variable (mean TTS) are: failure times (MTTF), failure time distribution form, mean corrective maintenance time (MCMT), logistics support method, and the total number of helos available to the AAAV platoon. All factors have only two levels each, which facilitates the use of a 2^n experimental design, or in this case, a 2^5 design. The total amount of runs required to compare each factor level with every other level is 32. Each run consists of 200 replications.

As mentioned earlier, the model is changed to reflect the need to transport two rifle companies instead of just one. This characteristic is present in both the levels of the factor, number of available helos. In order to fully test the importance of the role of helos in support of the AAAV, the levels of this factor are changed from allowing all the remaining helos not transporting the Air Assault Companies to be available for support, to only two of the remaining four being available. In addition, in the second level of this factor, even after all the Air Assault Companies are delivered, only two additional helos are assigned to be available to support the AAAV platoon. Therefore the in the factor's first level there are, at first, 4 helos available until two companies (requiring two round-trips of the remaining helos) are delivered. After the assault helos return, then an additional 12 are made available to the AAAV platoon. In the factor's second level, there are 2 helos available initially, then when the assault helos return, only 2 more are added to the total number of helos available for the AAAV platoon. The time until additional helos are added to the total number of helos available for logistics support is the time to travel from the ship to the objective, a constant 30 minute unload time, a return-trip travel time, followed by a randomly drawn refuel/reload time. This cycle completes one round trip. Two round trips are made in this model before additional helos are made available.

This constrained factor level can be considered to be reasonable since helos are always in demand for many reasons other than logistics support of the AAAV platoon. Helos must always be set aside for medical evacuations and logistics resupply operations, and they need to always be ready to tactically maneuver the ground forces. In addition, it is not always realistic to assume that of the 16 total helicopters on the MEU, all are fully operational.

An additional factor that has not been studied prior to this experiment is the mean corrective maintenance time (MCMT), or the average time required to repair a downed AAAV. Because in the three previous experiments, the form of the distribution of repair times is not found to be significant, it is not tested in this one. A single distributional form, the Weibull distribution with $\kappa = 2.0$ is used and the MCMT is changed from 1.5 hours (an ORD threshold requirement for the MCMT for 2nd Echelon, or unit level, repairs) to 3.0 hours. Three hours is used to reflect the fact that not all failures are ones that only require 2nd echelon work. A deployed MEU is capable of conducting up to 3rd echelon repairs, but there is no ORD requirement for the average length of these repairs.

Finally, because a Weibull Failure Distribution with a shape parameter of 3.5 hardly produces any failures, regardless of the scale parameter used, it is discarded as a factor level. Figures 37-40 below show the results of this experiment.

Factor	Type	Levels	Values
Helos	fixed	2	2/2 4/12
Log Base	fixed	2	No Yes
MTTF (hrs)	fixed	2	36 72
Fail Distn	fixed	2	Wei(med) Wei(hi)
MCMT (hrs)	fixed	2	3 1

Analysis of Variance for Time To, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Helos	1	6.177	6.177	6.177	3.27	0.089
Log Base	1	13.497	13.497	13.497	7.15	0.017
MTTF	1	**96.170**	96.170	96.170	50.98	0.000
Fail Dis	1	**448.104**	448.104	448.104	237.54	0.000
MCMT	1	**66.151**	66.151	66.151	35.07	0.000
Helos*Log Base	1	1.741	1.741	1.741	0.92	0.351
Helos*MTTF	1	3.964	3.964	3.964	2.10	0.166
Helos*Fail Dis	1	5.848	5.848	5.848	3.10	0.097
Helos*MCMT	1	0.389	0.389	0.389	0.21	0.656
Log Base*MTTF	1	4.097	4.097	4.097	2.17	0.160
Log Base*Fail Dis	1	11.682	11.682	11.682	6.19	0.024
Log Base*MCMT	1	2.282	2.282	2.282	1.21	0.288
MTTF*Fail Dis	1	63.612	63.612	63.612	33.72	0.000
MTTF*MCMT	1	13.294	13.294	13.294	7.05	0.017
Fail Dis*MCMT	1	52.259	52.259	52.259	27.70	0.000
Error	16	30.183	30.183	1.886		
Total	31	819.450				

Figure 37. Analysis of Variance on the Response Variable Time for 12 AAAVs (out of 12) to Reach the LOD (TTS).

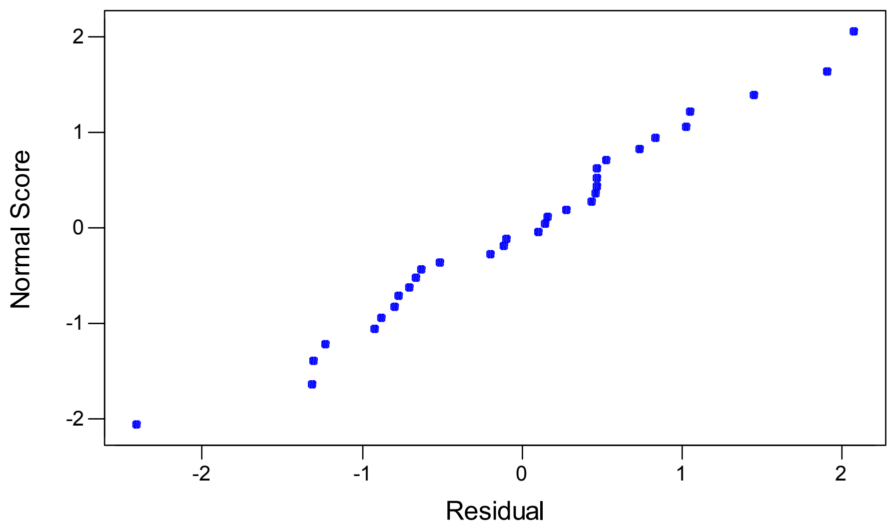

Figure 38. Normal Probability Plot of Residuals Where the Response Variable is TTS.

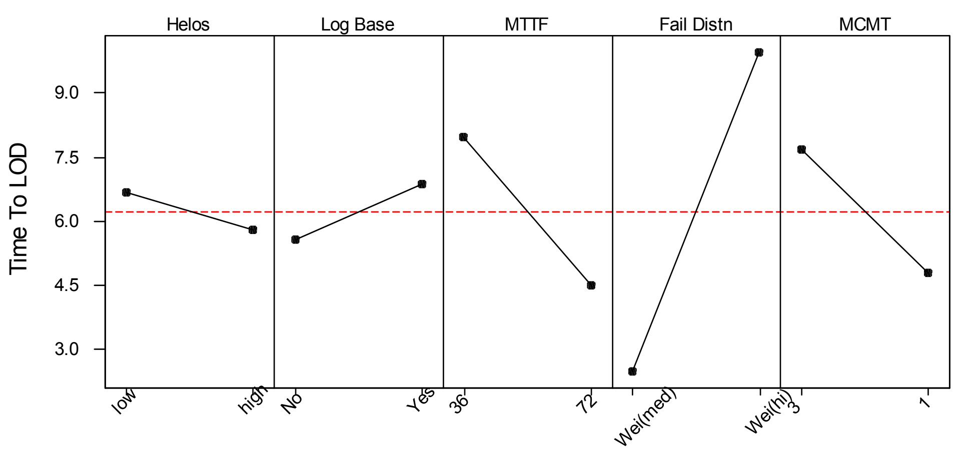

Figure 39. Main Effects Plot Where the Means are Times Required to Get 12 AAAVs to the LOD (TTS).

```
                        Individual 95% CI
Fail Distn      Mean    -------+---------+---------+---------+----
Wei(med)        2.49    (----*-----)
Wei(hi)         9.97                              (----*----)
                        -------+---------+---------+---------+----
                            3.00      6.00      9.00     12.00

                        Individual 95% CI
Helos           Mean    ----------+---------+---------+---------+-
restricted      6.67           (----------------*-----------------)
unrestricted    5.79     (-----------------*----------------)
                        ----------+---------+---------+---------+-
                               4.50      6.00      7.50      9.00

                        Individual 95% CI
Log Base        Mean    --+---------+---------+---------+---------
No              5.58    (----------------*----------------)
Yes             6.88            (----------------*----------------)
                        --+---------+---------+---------+---------
                       3.20      4.80      6.40      8.00

                        Individual 95% CI
MTTF            Mean    ----------+---------+---------+---------+-
36               8.0                      (-----------*-----------)
72               4.5    (-----------*------------)
                        ----------+---------+---------+---------+-
                                4.0       6.0       8.0      10.0

                        Individual 95% CI
MCMT            Mean    ---------+---------+---------+---------+--
3                7.7                   (-----------*-----------)
1                4.8     (-----------*-----------)
                        ---------+---------+---------+---------+--
                               4.0       6.0       8.0      10.0
```

Figure 40. Means and Confidence Intervals for the Primary Factors Where the Response Variable is TTS.

Before the data from the ANOVA model above in Figure 37 is analyzed a plot of the residuals versus the fitted values for this test is made to see if the same problems of heteroscedasticity seen before, exist in the current data. Figure 41 below shows that there does not appear to be heteroscedasticity, however the residuals do appear to have a curvilinear relation, and possibly a nonnormal distribution since the residuals are unevenly distributed above and below the zero-line in the y-axis. Further analysis of these residuals is done this time in Figure 42, which shows a histogram of the residual terms of this model. This plot shows some skewness to the right, but otherwise a distribution that can be generally summarized as normal, which is somewhat contradictory of the results of Figure 41.

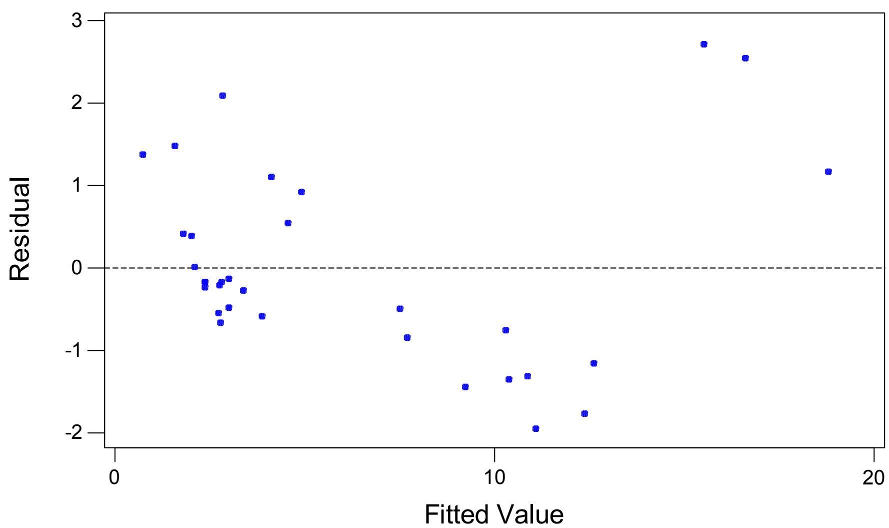

Figure 41. Plot of Residuals Versus Fitted Y-Values Where the Response Variable is Mean TTS. Plot shows possible nonnormal distribution or curvilinear relation between residuals.

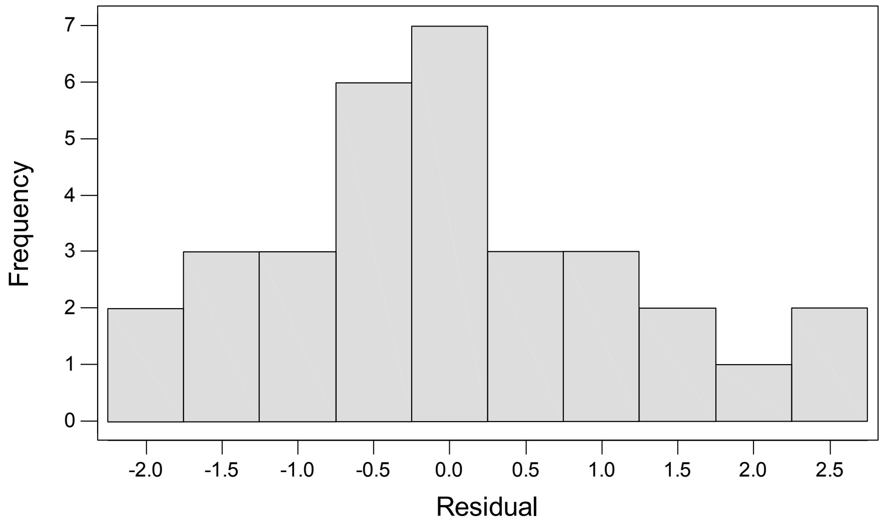

Figure 42. Histogram of the Residuals Where the Response Variable is the Mean TTS.

Once again, to try and alleviate the problem highlighted in the residuals versus fitted Y-value plot (Figure 41), the experiment above is conducted again, this time taking the log of the time to the LOD for each replication, then, averaging those replications to form a factor level mean. This is another transformation technique that is widely used to when problems of nonnormality and heteroscedasticity exist in data. The results of this analysis is shown below in Figures 43-45.

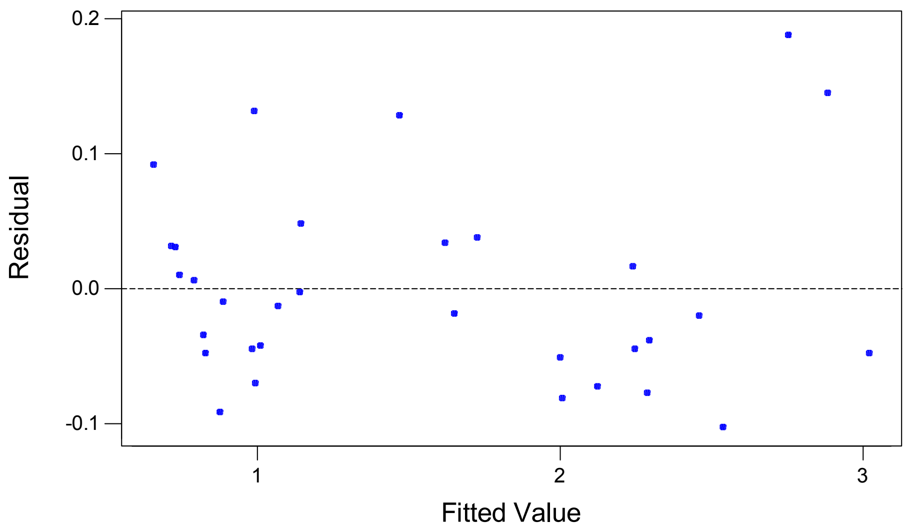

Figure 43. Plot of Residuals Versus Fitted Y-Values Where the Response Variable is the Mean log(TTS). Plot shows that residuals are generally homoscedastistic.

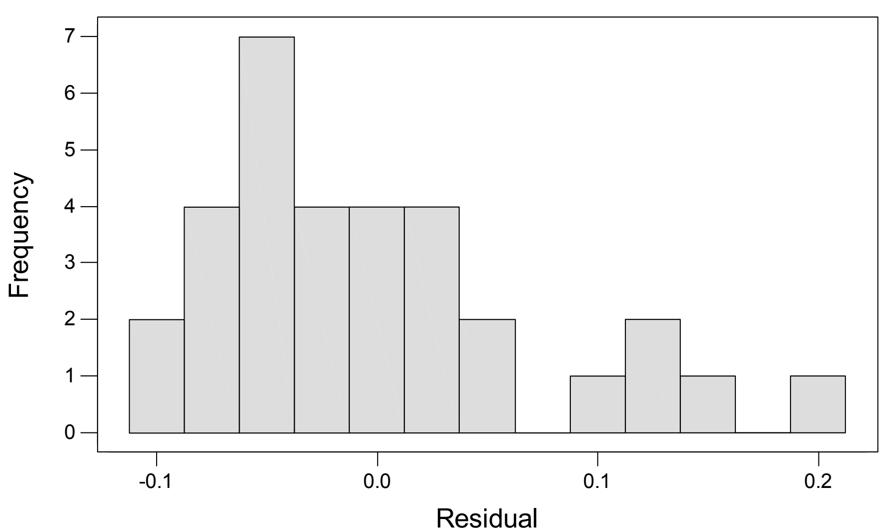

Figure 44. Histogram of the Residuals Where the Response Variable is the Mean log(TTS).

Factor	Type	Levels	Values
Helos	fixed	2	2/2 4/12
Log Base	fixed	2	No Yes
MTTF (hrs)	fixed	2	36 72
Fail Distn	fixed	2	Wei(med) Wei(hi)
MCMT (hrs)	fixed	2	3 1

Analysis of Variance for log(TTS), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Helos	1	0.0472	0.0472	0.0472	4.91	0.041
Log Base	1	0.1324	0.1324	0.1324	13.76	0.002
MTTF	1	1.5916	1.5916	1.5916	165.42	0.000
Fail Dis	1	13.6993	13.6993	13.6993	1423.85	0.000
MCMT	1	0.8853	0.8853	0.8853	92.02	0.000
Helos*Log Base	1	0.0116	0.0116	0.0116	1.20	0.288
Helos*MTTF	1	0.0156	0.0156	0.0156	1.62	0.220
Helos*Fail Dis	1	0.0365	0.0365	0.0365	3.80	0.068
Helos*MCMT	1	0.0013	0.0013	0.0013	0.13	0.719
Log Base*MTTF	1	0.0219	0.0219	0.0219	2.27	0.150
Log Base*Fail Dis	1	0.0755	0.0755	0.0755	7.84	0.012
Log Base*MCMT	1	0.0066	0.0066	0.0066	0.68	0.420
MTTF*Fail Dis	1	0.2883	0.2883	0.2883	29.97	0.000
Fail Dis*MCMT	1	0.3692	0.3692	0.3692	38.37	0.000
Error	17	0.1636	0.1636	0.0096		
Total	31	17.3458				

Figure 45. Analysis of Variance When the Log of Each Observation of TTS Is Taken.

Figure 43 is the plot of the residuals versus the fitted y-values (mean log(TTB)). This plot seems to show that the transformation has eliminated the non-linear shape of the residuals, and made them more featureless and thus, homoscedastistic. However, in the plot of the histogram of the residuals (Figure 44), the distribution seems even less normal than before (compared to Figure 42). Finally, and most importantly, Figure 45 shows the analysis of variance for the log-transformation model. The comparison to the ANOVA for the non-transformed model is, again, very similar. The same factors that the first model finds to be significant are still significant in the transformed model, and those that the first model finds insignificant are still insignificant in the second model. The one indication that the log-transformed model might be better in this case is the fact that in the first model, the error term accounts for 3.7% of the model's variability, while in the transformed model, the error term only accounts for 0.94% of the variability.

Regardless of which model is best, the fact is that the ANOVA and its F-test, although used extensively in this section as an analysis tool, is not by any means, used independently or exclusively. The nature of this simulation model is that there are many variable factors that might have an effect on its MOEs. ANOVA is simply an *initial*, *exploratory* tool to test for this significance. Although some of the assumptions that the ANOVA requires may not be completely met in every case, it has been shown that the results do not change when all the assumptions are met. In the end, the message is still that this test can *help* to explain which factors are important and which may not be as important.

Using the ANOVA of the transformed data in Figure 45, it can be seen that all the primary factors tested are statistically significant, at least at a 95% confidence level. As usual, the form of the distribution of failure times accounts for the lion's share of the variability in the model. The percentage of variability due to this factor is 79%, which is roughly the same percentage of the explained variance compared to previous experiments. In the non-transformed ANOVA this factor only accounts for 54.7%, which is a decline in explained variance compared to previous models. One explanation for this, however, is that in previous experiments (using non-transformed data) the failure distribution factor has had three levels and the MCMT remained constant. The addition of changes in the MCMT introduces considerable variability, while the loss of the distribution factor third level decreases (slightly) the factor's total influence. The MTTF factor accounts for 9.2% of the model's variability and the MCMT Factor accounts for 5.1%. Even after creating a large range between the levels of the factor, number of available helos, it only accounts for 0.27% of the model's variability. As mentioned earlier the model's unexplained variance, or the error term, accounts for only 0.94% of the model's variability.

As emphasized, however, the analysis of variance should not be the only analysis technique used. Figures 39 and 40 show that *all* the primary factors have a significant practical effect on the mean time to get 12 AAAVs to the LOD. This is illustrated by the fact that the helo availability factor affects the platoon's ability to get to the LOD by an average of 52.8 minutes. Additionally, the difference in the mean time to reach the LOD between the MCMT Factor's two levels is 2 hours and 54 minutes on average. This, in particular, is an important fact to consider. Up to now the message of the results of the models have been that the MTTF and the form of the distribution of failure times is extremely important. That fact certainly has not changed. However, these results point to the fact that testers should also be greatly concerned with the MCMT of *all* types of repairs. In other words, a MCMT of 2nd and 3rd echelon type repairs combined should be measured, not just one for 2nd echelon repairs. If a large proportion of failures are of type 3rd echelon, or if the proportion is small, but the MCMT for 3rd echelon repairs is large, this could have a *substantial adverse affect* on the platoon's ability to deliver an adequate-sized force at a designated time.

Once again, the measured between-run variability of this model is generally very large. The average between-run variability for the entire experiment (measured in standard deviations) is 5.48 hours. Figures 46-49 show examples of the various distributions of the individual times to the LOD when the factor levels for the number of available helos, MTTF, MCMT and the distribution of failure times are varied. The minimum time to reach the LOD with no failures is 2 hours.

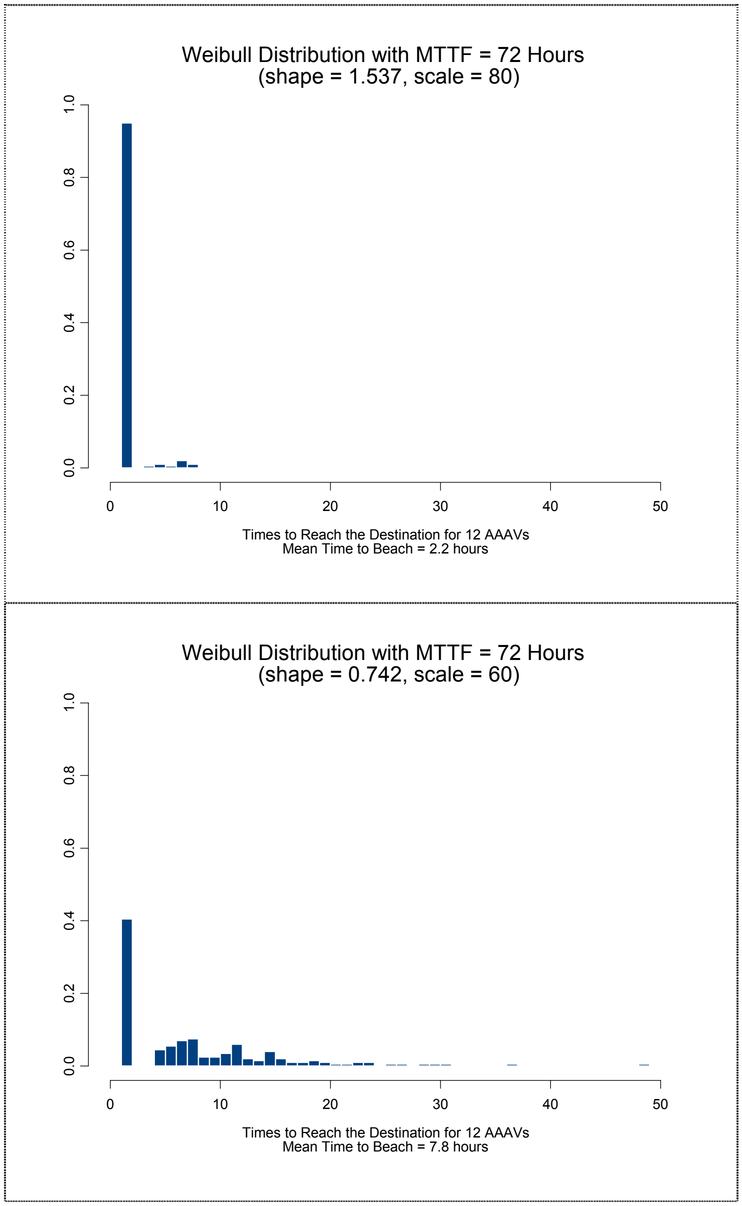

Figure 46. Comparison of the Distribution of Times to the LOD when the Shape Parameter is Varied to Change the Form of the Distribution of Failure Times. All Other Factor Levels are the Same: No Log Base Used, and MCMT = 3 hrs.

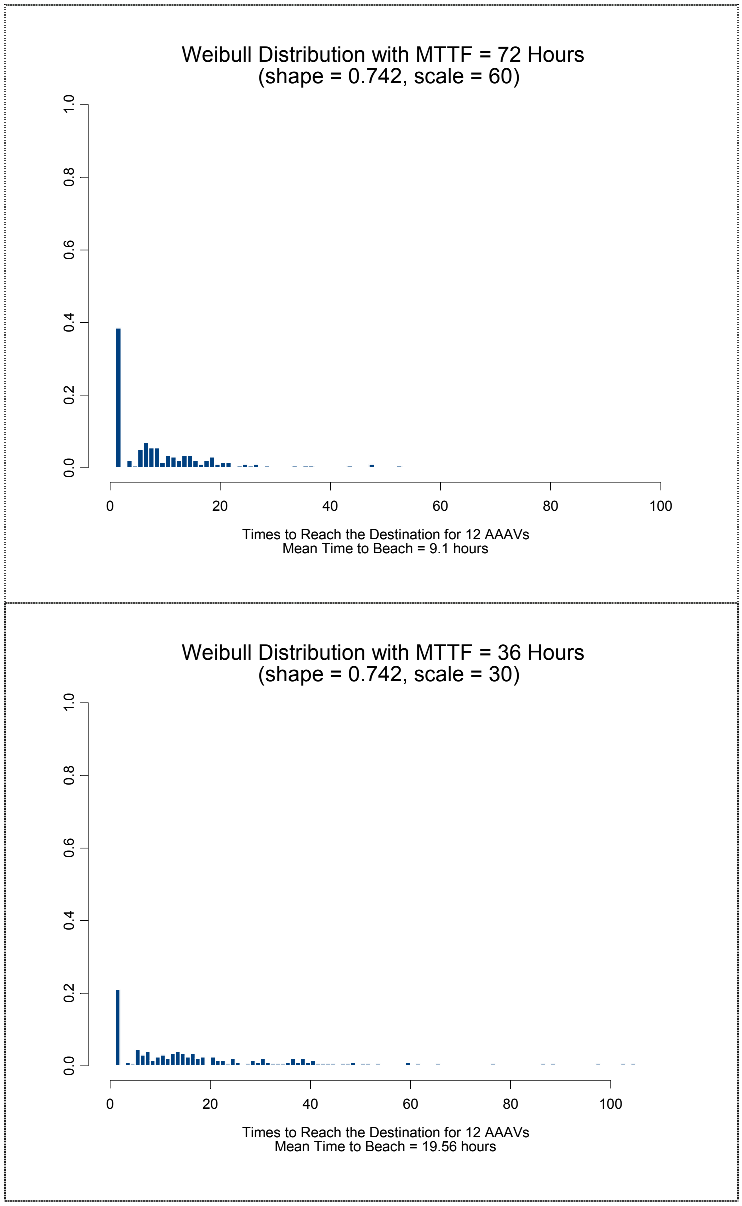

Figure 47. Comparison of the Distribution of Times to the LOD when the Scale Parameter is Varied to Change the MTTF. All Other Factor Levels are the Same: No Log Base Used, and MCMT = 3 hrs.

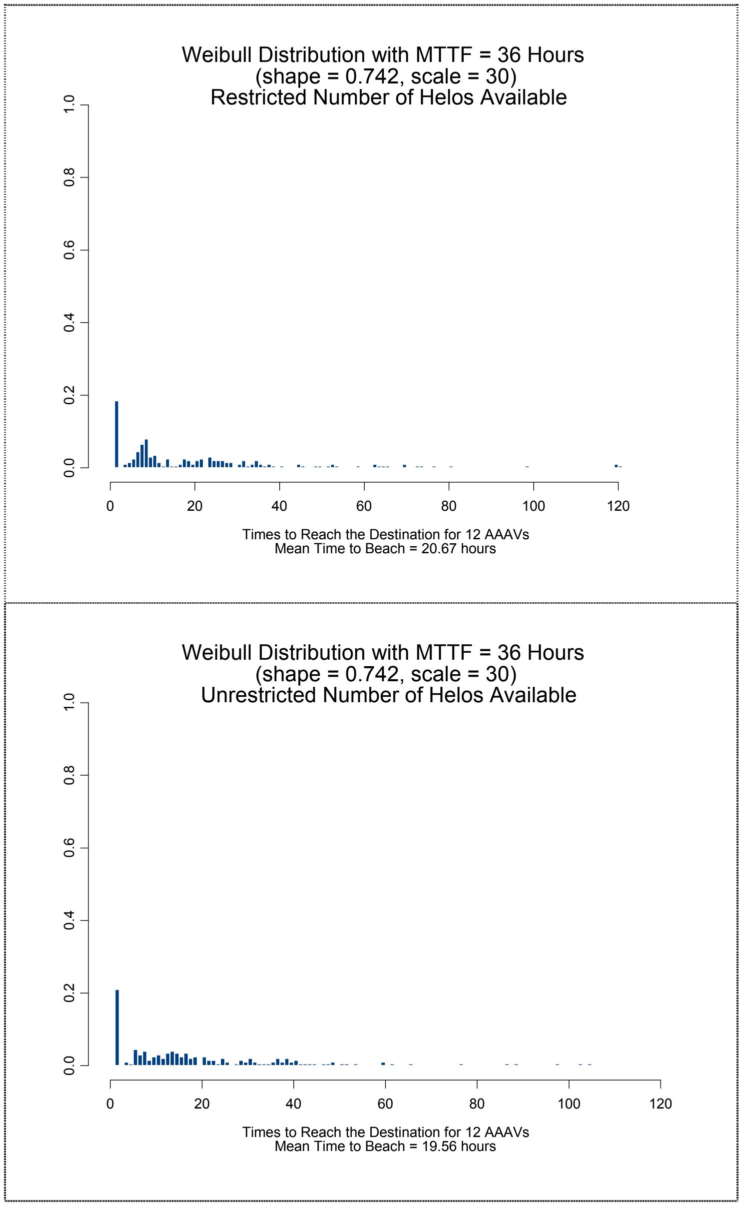

Figure 48. Comparison of the Distribution of Times to the LOD When the Number of Available Helos Varies from Large to Small. All Other Factor Levels are the Same: MTTF = 36 hours, No Log Base Used, and MCMT = 3 hrs.

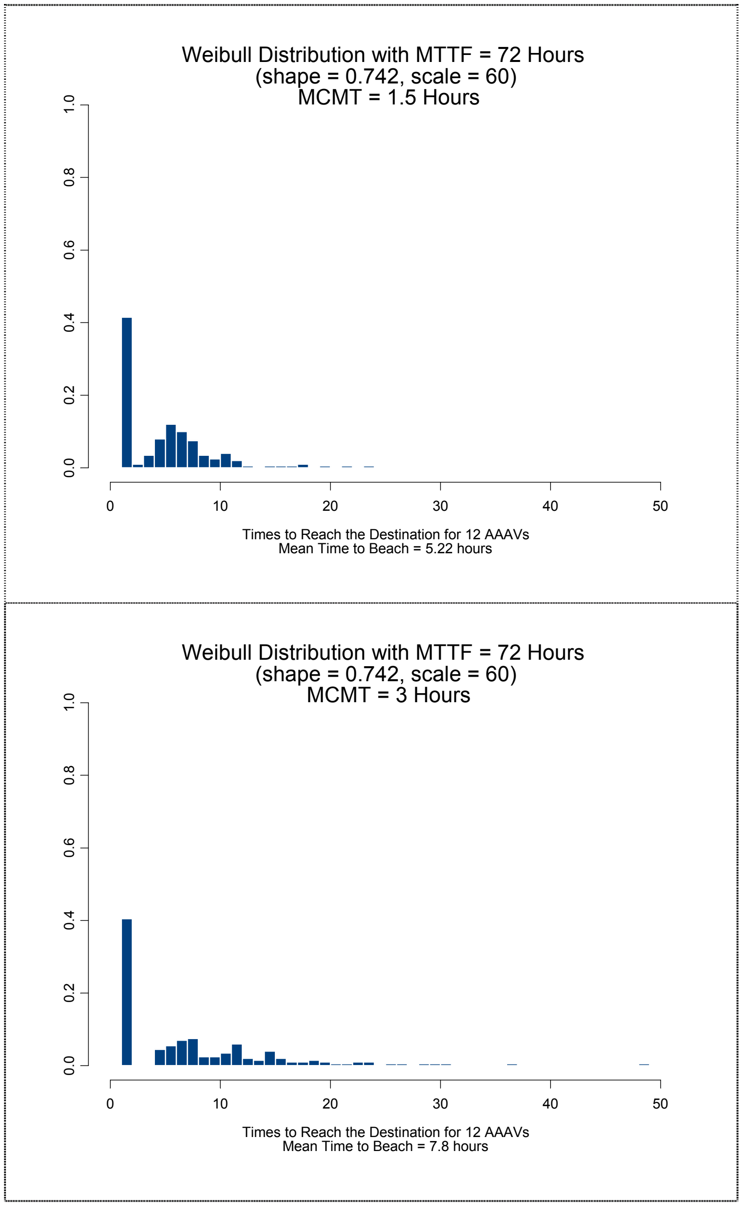

Figure 49. Comparison of the Distribution of the Times to the LOD When MCMT is Varied From 1.5 Hours to 3.0 Hours. All Other Factor Levels are the Same: MTTF = 72 hours, No Log Base Used, and MCMT = 3 hrs.

The last but most important observation to be made from this experiment, highlighted in Figure 40, is that the mean time to the LOD for a MTTF of 72 hours is 4 hours and 30 minutes with a large confidence interval for the mean response that spans from the minimum time, 2 hours to greater than 7 hours. This is perhaps the strongest proof yet that the assumed form of the distribution of failure times is of the utmost importance. Even at a MTTF of 72 hours, which is within the ORD threshold limit for this requirement, *the variability of the ability to move a platoon 50 nm over a combination of water and land in a timely manner is huge* based on the result of this model.

8. Further Analysis of Different Factor's Effects on MOE Mission Availability (A_m).

Simultaneous to the experiment conducted above, another experiment is conducted on the MOE, Mission Availability (A_m). The experiments are conducted simultaneously because, after the experiment above measures the time to get 12 AAAVs to the LOD, the same simulation runs measure the platoon's subsequent A_m in the objective area. Therefore the same five primary factors tested for their effects on the response variable (mean TTS) are also tested for their effects on A_m. They are: failure times (MTTF), failure time distribution form, mean corrective maintenance time (MCMT), logistics support method, and the total number of helos available to the AAAV platoon. All factors have only two levels each, which facilitates the use of a 2^n experimental design, or in this case, a 2^5 design. The total number of runs required to compare each factor level with every other level is 32. Each run consists of 200 replications. Figures 50-51 below show the results of this model.

Once again all the factor main effects are statistically significant to a high level as seen in Figure 50. However, just as in the previous experiment where A_m is the response variable, none of the factors are practically significant as can be seen from Figure 51. The form of the distribution of failure times has the greatest physical effect on the response variable, but even it only accounts for a difference of 0.69 AAAVs between its two levels. The average between-run variability for the entire experiment (measured in standard deviations) was 0.042 or 0.504 AAAVs. Figures 52-54 compare different factor levels for individual runs when all other factors are the same.

Factor	Type	Levels	Values
Helos	fixed	2	2/2 4/12
Log Base	fixed	2	No Yes
MTTF (hrs)	fixed	2	36 72
Fail Distn	fixed	2	Wei(med) Wei(hi)
MCMT (hrs)	fixed	2	3 1

Analysis of Variance for Mission Availability, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Helos	1	0.0000297	0.0000297	0.0000297	5.11	0.038
Log Base	1	0.0014696	0.0014696	0.0014696	252.85	0.000
MTTF	1	**0.0095888**	0.0095888	0.0095888	1649.70	0.000
Fail Distn	1	**0.0264162**	0.0264162	0.0264162	4544.77	0.000
MCMT	1	0.0009042	0.0009042	0.0009042	155.56	0.000
Helos*Log Base	1	0.0000149	0.0000149	0.0000149	2.56	0.129
Helos*MTTF	1	0.0000044	0.0000044	0.0000044	0.76	0.397
Helos*Fail Dis	1	0.0000276	0.0000276	0.0000276	4.75	0.045
Helos*MCMT	1	0.0000010	0.0000010	0.0000010	0.16	0.691
Log Base*MTTF	1	0.0001509	0.0001509	0.0001509	25.96	0.000
Log Base*Fail Dis	1	0.0008348	0.0008348	0.0008348	143.63	0.000
Log Base*MCMT	1	0.0000694	0.0000694	0.0000694	11.94	0.003
MTTF*Fail Dis	1	0.0003404	0.0003404	0.0003404	58.57	0.000
MTTF*MCMT	1	0.0000775	0.0000775	0.0000775	13.34	0.002
Fail Dis*MCMT	1	0.0001356	0.0001356	0.0001356	23.33	0.000
Error	16	0.0000930	0.0000930	0.0000058		
Total	31	0.0401579				

Figure 50. Analysis of Variance on the Response Variable A_m.

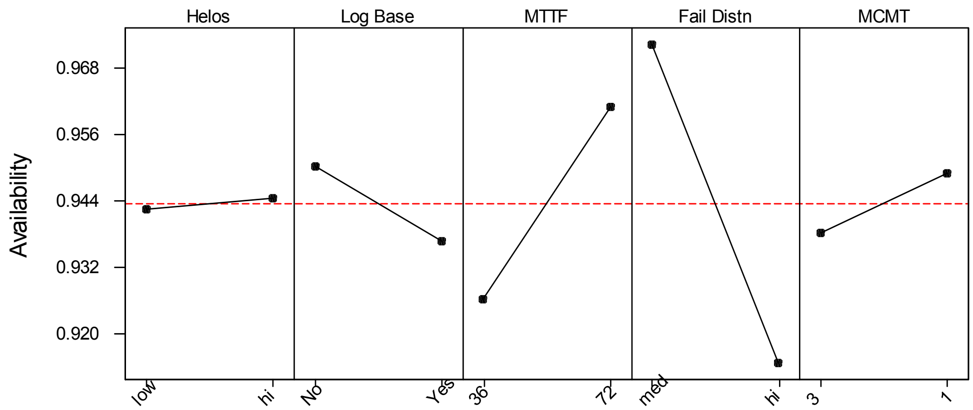

Figure 51. Main Effects Plot Where the Means are the Number of AAAVs in the Platoon That are Operational During the Time the Platoon is in the Objective Area.

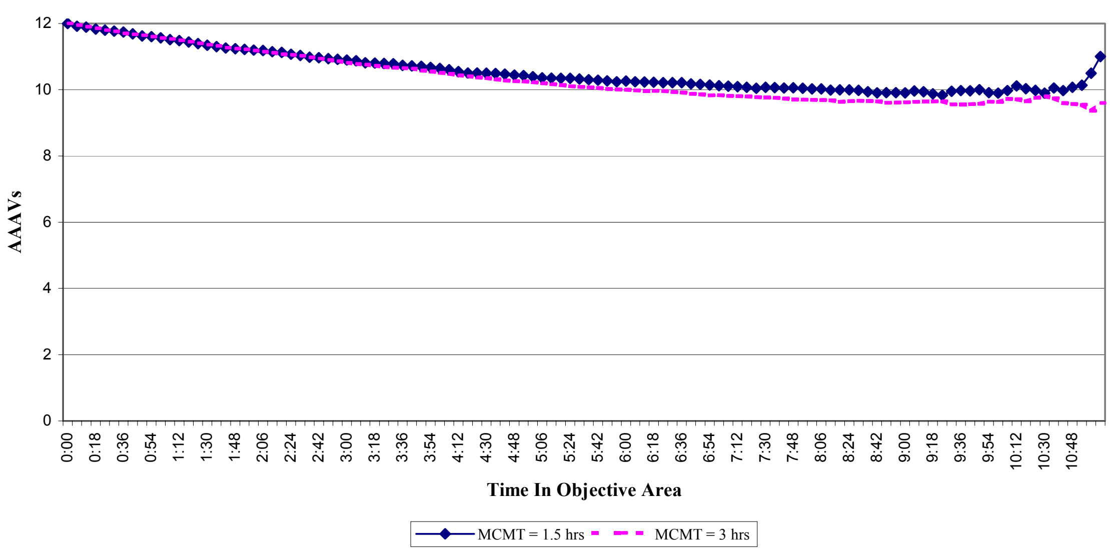

Figure 52. Comparison of The Effects of MCMT On Mean $A_p(t)$ at a Time-Step of Six Minutes for the Length of Time the Platoon is Operating in the Designated Objective Area (MTTF = 36 hours).

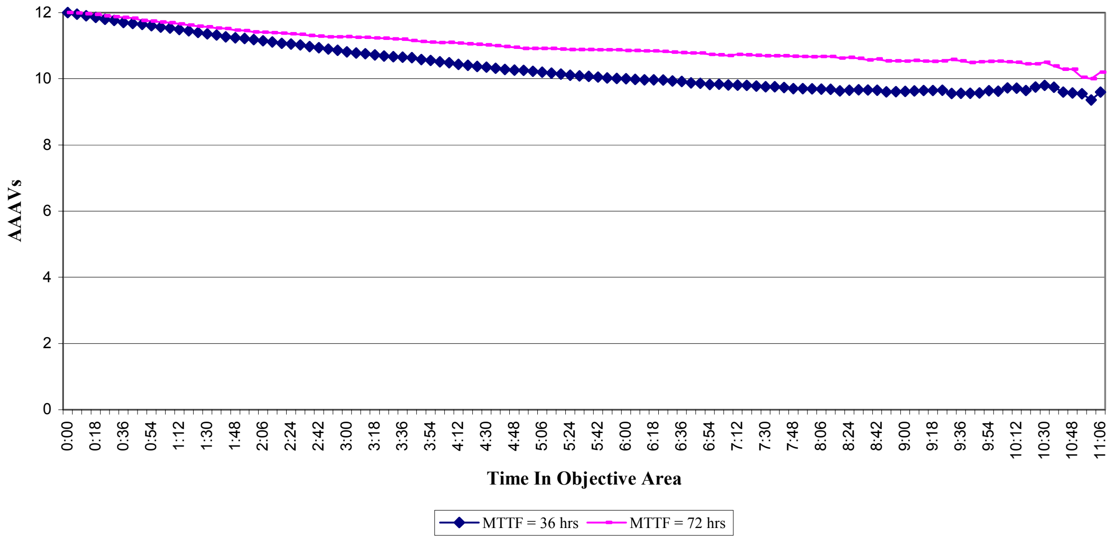

Figure 53. Comparison of The Effects of MTTF On Mean $A_p(t)$ at a Time-Step of Six Minutes for the Length of Time the Platoon is Operating in the Designated Objective Area (shape parameter $\kappa = 0.742$, MCMT = 3 hours).

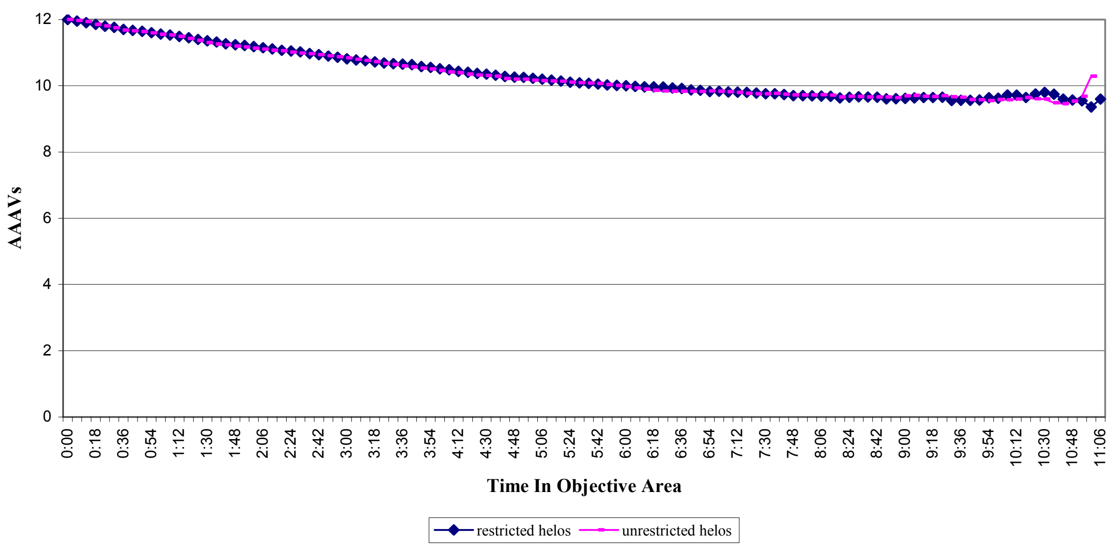

Figure 54. Comparison of The Effects of Number of Helos On Mean $A_p(t)$ at a Time-Step of Six Minutes for the Length of Time the Platoon is Operating in the Designated Objective Area (MTTF = 36 hours with shape parameter $\kappa = 0.742$, MCMT = 3 hours).

Although the effects of different factors on the mean time average availability is not very substantial, using population means may not be telling the whole story, even more so than when the response variable is the mean TTB or TTS. In Figures 52-54 above, it is clear that, no matter what the factors or their levels, the platoon enters the objective area with 100% availability (because the platoon waits at the LOD until it has all AAAVs operationally available before proceeding) but immediately after entering the objective area the $A_p(t)$ begins to drop, and then continues to drop until it reaches a steady-state after somewhere between 6 and 8 hours of operation in the objective area. As shown before in comparisons to long-term availability analytical equations, the observed long-term availability for these models is generally lower. One of the reasons for the arbitrarily high values of A_m in this section is likely due to the fact that all the experiments have measured the A_m starting with an $A_p(t)$ of 12 vehicles or 100%.

Comparing the results of the time-step graphs in this section to those in the first section of this chapter shows that the model creates an A_m steady-state after some length of time. In both the simpler model and the models of this section, moving from the LOD to the attack objective creates a substantial decrease in $A_p(t)$. After those vehicles that fail while the platoon is en route are able to catch-up and the platoon is stationary at the attack objective, it begins to reach the steady-state. And once again, when the statistical means are used without any other measure, as is the case in this experiment, their values are too optimistic. Looking at the time-stepped plots of A_m for observations where factor levels are constant, however, shows that even with a MTTF of 72 hours (albeit with a distribution of failure times that has a high number of infant failure times) the platoon cannot maintain its initial level of availability with which it enters the objective area.

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VI. CONCLUSIONS AND RECOMMENDATIONS

The models used in this thesis clearly show that, by far the most important factor for testers to consider in operational test and evaluation of the AAAV is the form of the assumed distribution of failure times. Requirements that guide operational testing only specify, threshold and objective values for the mean time to failure (MTTF). However, the results show that even with a high MTTF, if the distribution of those failure times allows a high or even moderate number of short, infant failure times, the results on a platoon of AAAV's ability to perform its stated missions can be drastically detrimental. From a ship 25 nm offshore, with a MTTF of 72 hours for each vehicle, it is shown to take the entire platoon anywhere from 1 hour (the minimum time required to get to the beach) to 2.5 hours when the distribution of the times to failure was varied. And from the ship to the beach, then onto the LOD (50 miles from the ship) a MTTF of 72 hours was shown to have a variation in the average times for the platoon anywhere from 2 hours (the minimum time required to get to the LOD) to more than seven hours. In addition, when the MTTF was 72 hours with random failure times drawn from a Weibull distribution with a shape parameter of 0.75 and scale parameter of 60.0 (i.e. a high amount of infant failures) there were individual observations of the time for the platoon to reach the LOD with 12 working vehicles of up to 50 hours.

Another conclusion is that, failures that occur when the AAAV is in its water-transit mode can create many problems. If there is no asset available for towing quiescent AAAVs to the shore or ship, then this job must be undertaken by other AAAVs of the unit. If other AAAVs must tow AAAVs that have failed in the water, the detrimental effect on the platoon's ability to deliver effective combat power within a certain amount of time is increased by a factor of two. The results of the simple model created in section 1 of Chapter V clearly demonstrate the advantages of having some other auxiliary craft available for towing failed AAAVs in the water.

Finally, it was found that the MCMT can have a substantial effect on the MOEs time to reach the beach (TTB) and time to reach the LOD (TTS). Although the ORD specifically lists a requirement for the MCMT of 2^{nd} echelon repairs, it does not say anything about higher level (3^{rd} echelon) repairs. The model finds that an increase in MCMT from 1.5 hours to 3.0 hours has an average effect of 2 hours and 45 minutes on the mean time to reach the LOD. Three hours is not an unreasonable average of 2^{nd} and 3^{rd} echelon MCMT combined, so the message is that both times, as well as the proportion of failures that require each type of repair should be carefully measured.

Although there are many scenarios run and factors tested in this thesis, not all the possible factors and combinations are tested, nor are all the possible scenarios run. This thesis is developed as a tool to help testers explore for sensitive aspects that they might not otherwise discover in actual testing, therefore the model should be exercised many more times and in many more ways. Specifically, actual operational scenarios proposed for testing the AAAV should be run prior to the actual tests in order to highlight the sensitive aspects on which testers should focus.

While the models in this thesis can hopefully add valuable insight into what aspects of operational testing are important and highly sensitive, there is much more that can be done. Although many attempts were made to add reality to the model, much of this simulation is still oversimplified. One of the biggest recommendations for improvements to the simulation would be to explicitly model the AAAV into subsystems. If some subsystems fail, it would not necessarily catastrophically affect the AAAV's ability to perform its mission. Unfortunately, all failures in this model are treated equally. By modeling each AAAV by its subsystems, many more important insights could be gained, one of which might be finding what limited parts and the number of those parts with which the MEU needs to deploy.

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