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Development of a Methodology for Evaluating and Anticipating Improvised Explosive Device Threat Activity Using a Fault Tree Based Process

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Accepted by:
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ABSTRACT

This document is a redacted version of the original dissertation titled "Development of a Methodology for Evaluating and Anticipating Improvised Explosive Device Threat Activity Using a Fault Tree Based Process." To allow for publication, information was removed which was considered sensitive in nature or which could be used by those who employ the Improvised Explosive Device, to negate any advantage gained by this research. The complete un-redacted dissertation is available (with proper vetting) to those whishing to further develop the concepts outlined in this document. Those interested in obtaining access to the complete document should contact the Joint IED Defeat Organization (JIEDDO).

To date there is little published evidence to believe that a sufficient IED threat prediction capability has been developed. Most of the countermeasures seen on the battlefield today are reactive in nature designed to neutralize the effects of a device before it causes injury to military and civilian personnel. These countermeasures have meet with varying levels of success. An efficient threat prediction capability will significantly increase the ability of military forces to eliminate the threat associated with the IED. The lack of an accurate threat prediction capability is a possible result of not having identified all of the variables or the variable relationships associated with IED placement.

This research analyzes the variables associated with an IED incident and develops an IED threat prediction process using the Fault Tree model. This dissertation also explores the use of visualization software to determine their suitability in C-IED operations. Furthermore, the application of a Fault Tree based process as a decision support tool for use by decision makers involved in C-IED operations is analyzed.

This research is conducted in three phases with the first phase dedicated to the development of a Fault Tree diagram representing an IED incident. During this phase a complete Fault Tree is constructed identifying, sequencing, and establishing relationships between all variable associated with a successful IED attack against a military vehicle operating on a road.

The second phase outlines the development of a complete process intended to serve as an operational guide for those attempting to employ the concepts addressed. To ensure a more precise understanding of the required procedures, a theoretical case study was used to articulate and demonstrate the requisite activities.

Through this research, events were identified as required for an effective attack to take place. Through the integration of the Fault Tree, probability information and visualization assets a threat prediction capability is demonstrated.

The ability to predict IED activity will provide military personnel a distinct advantage in defeating the IED threat and directly contribute to the increased safety of military and civilian personnel living and operating in an IED environment.

DEDICATION

This work is dedicated to Captain Mathew August, Captain Timothy McGovern, First Lieutenant Josh Hurley, Staff Sergeant Stephen Seale, Sergeant Carleton Clark, and Corporal Jos Zamora of the United States Army. These comrades, brothers, friends and heroes made the ultimate sacrifice in defense of our nation. There is hope that this research will help deny the enemies of our nation the ability to effectively employ the Improvised Explosive Device.

ACKNOWLEDGEMENTS

I would first like to thank Dr. Mashrur Chowdhury for his tremendous support as my committee chair. Dr. Chowdhury is an outstanding advisor and educator whose willingness to support a non traditional student and this unique research endeavor is testament to his professionalism. I am extremely grateful for his willingness to participate in the numerous late night phone calls and weekend meetings required to see this project through to completion. Furthermore, I would like to express my sincere appreciation and gratitude to the other members of my committee; Dr. Lansford C. Bell, Dr. Jennifer H. Ogle and Dr. Charles O. Skipper. Their assistance, outstanding guidance, and superb mentorship was critical to the completion of this project and is very much appreciated.

I would like to thank those who assisted in finding an acceptable solution to the issues associated with publishing a sensitive document of this nature. Clemson, JIEDDO, the Security Reviewers, and the other advisors with whom I work, were critical in developing a way to contribute to the body of knowledge while protecting the military benefit associated with this research.

I owe a debt of gratitude to those members of our military who I know, and with whom I have served. I have had the honor of serving in many outstanding units and with many amazing individuals. Those experiences and influences have been instrumental in my professional growth and have provided a solid understanding of military operations. This understanding is the foundation upon which this research was built.

Much is owed to my family and friends. I am blessed with a tremendous and solid support structure that has always been there for me without fail. Most significant are my Mother and Father, two amazing individuals who have always provided unconditional love and unbelievable opportunity. Through their example they have instilled within me a confidence and a desire to seek out challenges as well as a drive to see them through to completion. For there influence I am eternally grateful.

Most importantly I must say thank you to my wife Audrey. She is a tremendous example of constant and unwavering love, support, kindness, and patience. Without her support none of this would have been possible.

TABLE OF CONTENTS

Table of Contents (Continued)

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

Introduction

This document is a redacted version of the original dissertation titled "Development of a Methodology for Evaluating and Anticipating Improvised Explosive Device Threat Activity Using a Fault Tree Based Process." To allow for publication, information was removed which was considered sensitive in nature or which could be used by those who employ the Improvised Explosive Device, to negate any advantage gained by this research. The complete un-redacted dissertation is available (with proper vetting) to those whishing to further develop the concepts outlined in this document. Those interested in obtaining a copy of the complete document should contact the Joint IED Defeat Organization (JIEDDO).

The Improvised Explosive Device (IED) continues to be one of the largest casualty producing weapons used against coalition forces participating in combat operations in the Afghanistan and Iraq Theater of Operations. As of 22 September 2007 there have been over 81,000 recorded IED incidents in Iraq causing the death of 1,952 American servicemen and women and the injury of 19,248 more (Atkins, 2007). These deaths are a direct result of the enemy's employment of the IED. IEDs capitalize on the Coalition Forces reliance on, and use of, established highways, freeways, and other vehicular transportation corridors. Terrorist and insurgent groups have employed the IED with marked success and have been able to disrupt both non-military and military operations with this effective weapon system. This dissertation focuses on limiting the enemy's ability to engage targets by developing a method to anticipate enemy activity and predict where an IED will be placed.

The Department of Defense is actively and aggressively searching for ways to defeat the IED. The United States Government is spending billions of dollars searching for ways to defeat the insurgent's weapon of choice (Levine, 2006). The military created the Joint IED Task Force and gave them, along with other organizations, the mission of developing new ways to defeat the IED (Levine, 2006). The military's research and development assets, industry, and academia are all actively engaged in developing ways to mitigate the effects of this often simple and destructive weapon system.

Many of the new developments and countermeasures seen on today's battlefield are reactive in nature, designed to increase chances of survival when in proximity of an IED. Many of these measures emphasis traditional force protection and survivability principles focusing on allowing a soldier to survive the blast of an IED or preventing an existing IED from detonating. Some of the improvements being fielded include equipping vehicles with stronger armor as well as developing disposal vehicles which are designed to locate suspicious objects and survive the blast should a device detonate. Electronic jamming equipment is also in use designed to jam the detonating signal as vehicles approach or cause premature detonation before a vehicle enters a kill zone (Vanden Brook, 2007). These measures have all met with varying levels of success.

As is the case with armed conflict against a thinking enemy there is a constant evolution of technology and tactics between opposing forces. Each side adapts and evolves with the aim of gaining and maintaining an advantage over the opponent. This evolution is evident in the Iraqi theater of operation. An illustration of this concept is when the American Military develops stronger armor designed to survive a blast of an IED, insurgent forces build more powerful IEDs designed to defeat the improved armor. When the military develops a way to jam a specific detonating signal the insurgent forces develop effective ways to detonate the device while avoiding the jammed frequency.

To prevent casualties and minimize the risks associated with this constant action-reaction relationship and to help limit the ability of an enemy force to effectively employ the IED, the international coalition of forces operating in Iraq require a method to minimize the enemy's ability to evolve. Specifically with the IED, this evolution can be reduced by limiting the enemy's ability to engage targets with the IED. This can be accomplished by developing a threat prediction capability.

To date there has been no published evidence to suggest that any method, model or tool has been developed to accurately and reliably anticipate threat activity or identify locations of Improvised Explosive Devices. This is a possible result of not having identified all of the variables associated with IED placement.

A failure based model like the Fault Tree can effectively be used to identify all variables present during an incident and clarify their relationship to IED activity. Information derived from the Fault Tree can then be integrated into visualization software and used to identify areas which meet specified criteria. Anticipating location and threat activity can be accomplished through the use of the Fault Tree and provide the understanding of relationships between IED related variables. To date, there is no evidence to suggest that this approach has been thoroughly explored.

This research project will identify and analyze specific variable relationships related to an IED incident with the aim of effectively combining the principles of Fault Tree modeling, Geographic Information Systems (GIS), simulation, and military doctrine to present an effective process which can be used to understand and anticipate threat activity. The primary intent is to develop a Fault Tree based process for anticipating IED activity and locations. A secondary objective is to analyze the effectiveness of various visualizations assets in Counter-IED (C-IED) related activities. The ability to predict IED activity will provide military personnel a distinct advantage in defeating the IED threat. Anticipation of enemy ambush locations will encourage the preemptive neutralization of the device, denial of the location, and the elimination of personnel attempting to place an IED. A prediction capability will allow Coalition Forces the ability to deny the enemy their intended effects of the IED.

Statement of Problem

Coalition Soldiers, Sailors, Airman, and Marines have experienced significant casualties as a result of the Improvised Explosive Device. IEDs have caused 68% of the 31,101 combat deaths and injuries sustained by the United States military in Iraq (Atkins, 2007). This does not include the many more thousand Iraq citizens whose lives have also been devastated by the IED. From January 2007 to July of 2007 coalition forces estimated that over 11,000 Iraqi civilians have been killed or wounded by the IED (Atkins, 2007). The physical, psychological, political and financial effectiveness of this weapon requires a reliable and effective method of mitigating the IEDs effect. To date there is little published evidence to suggest that a reliable method of predicting and determining IED locations has been developed.

The IED is often a simple device which is relatively cheap to construct, easy to emplace, difficult to detect, and which can be employed with significant effectiveness against many of the vehicles in the military inventory. By studying the recent evolution of insurgency warfare it is easy to assume the IED will continue to be the weapon of choice for the insurgent, guerilla, terrorist, or any other organization searching for a way to offset the superior technological advantage of the American military. The Director of National Intelligence, John Negroponte, testified before the United States Senate in January of 2007 stating that the use of conventional explosives continues to be the most probable terrorist attack scenario (Negroponte, 2007).

The most recent events between the American Military and Iraqi militants combined with the recently well publicized 2006 conflict between the Hezbollah party of the Lebanese Government and the Israel Army have given current and potential enemies insight as to how to counter larger and more lethal conventional forces. Two experts of guerrilla warfare, US Army Lieutenant General James Lovelace and Brigadier General Joseph Votel, believe that “with relatively small amount of resources-access to common electronic components and military ordinance and electronic and demolition skills-insurgent terrorists can build devices that literally have the capability to destroy prominent conventional warfare systems like the Abrams Tank and Bradley Fighting Vehicle” (Lovelace, et al., 2004, pg.1). There is little doubt that future opponents have taken notice of the effectiveness of this weapon and the world will continue to see the employment of IEDs well beyond the limits of America's War on Terror.

As armies develop new ways to counter the effects of the IED, the enemy develops new ways to ensure its effectiveness. As demonstrated in the war in Iraq, when armor and vehicles are made stronger and tougher, IEDs become bigger, more powerful and are employed in ways which capitalize on observed vulnerabilities. There are at least two documented cases were IEDs were successful in disabling the vehicle and killing the occupants of a M1 Abrams Tank and M2 Bradley fighting vehicle, two of the most heavily armored vehicles on today's battlefield (Wilson, 2005), (United States Department of Defense, 2006). "Defense planners should view IEDs like medical professionals view the influenza virus, another "primitive", adaptable, and lethal enemy. As soon as vaccines have defeated a certain flu strain, the virus evolves" (Levine, 2006). There is a visible evolution with the terrorist groups in Iraq and the Coalition. When the U.S. develops a countermeasure, insurgents improve and adapt their IED to overcome the advantage gained.

One way to decrease the number of soldiers who are injured by the IED is to develop a way to identify probable IED locations before sending soldiers into harms way. If a prediction tool can be developed which can identify and predict enemy IED locations from a secure environment first response military personnel will have the advantage of knowing where a possible device is located before entering the area. Furthermore, stand-off disposal techniques can be employed which would allow for the neutralization of the device from a safe distance. An accurate threat prediction capability has the potential to significantly reduce the number of personnel exposed to the IED threat.

The ability to know where the enemy is going to attack is of extreme importance to military commanders. The accurate prediction of the actions of an opposing force will help enable its destruction. The ability to anticipate will provide the opportunity for a force to focus resources and be pre-emptive in denying enemy terrain and neutralizing personnel performing hostile actions.

Purpose of the Study

This research is intended to develop a framework which can eventually lead to the anticipation of IED locations. If an individual or organization is going to truly understand the employment of the IED, that organization must study an environment where IEDs are routinely employed and examine every facet of their use. This in-depth analysis will create a foundation and baseline which can then be further enhanced and applied to different geographical areas, militant forces, and technical variations of the IED.   This research project will analyze current military operations being conducted in support of OPERATION IRAQI FREEDOM with the hope of developing a framework and methodology for identifying and analyzing variables associated with the IED environment. Once the identification of variables is achieved a process will be developed and a method presented which can be used to analyze IED attack information with the intent of identifying locations where IED activity will take place.

It is important to understand that this research project is theoretical and general in nature and will not be able to predict exactly where on a road in Iraq enemy forces might place an IED. It is the intent of this research project to develop a general process which can be used to assist decision makers in understanding and anticipating IED activity. The situation in Iraq will be used to understand threat tactics and will contribute to the development of an experimental data set which will be used to illustrate a process.

This research project encompasses three separate tasks. These tasks include an identification of IED related variables and variable relationships, interfacing threat data with the Fault Tree model and visualization assets, as well as development of a process which can be used by decision makers involved with C-IED operations to understand threat activity and identify threat locations.

Any student or practitioner of the profession of arms understands the necessity of a complete understanding of all facets of the military operating environment. This analysis must be in-depth and thorough. Any study of the IED without a complete understanding of the environment and conditions of its employment would be short-sighted and incomplete. One can not attempt to analyze the employment of a weapon system unless there is a complete understanding of the who, what, when, where, how, and why of its employment. The culmination of this analysis is the development of a basic Fault Tree Model correctly describing the variables and variable interaction in the IED environment. This is the first objective of this research initiative.

Once the Fault Tree is complete a process will be developed which can be used to anticipate threat activity. The process developed is intended as guidance to decision makers involved with C-IED operations. The process is intended to describe how to implement the principles of the Fault Tree into an effective decision support tool. The process includes the integration of threat data into the Fault Tree, employment of visualization assets to help illustrate location information, and explanation of how these concepts can be used to anticipate and predict threat activity and IED locations.

The IED is often referred to as a "roadside bomb" since the majority of attacks take place against military convoys which use established transportation corridors. Accordingly this dissertation focuses on convoy operations and the variables related to the employment of IED on vehicular transportation corridors. Developing a methodology for analyzing IED information will allow military personnel the ability to develop models capable of identifying areas which meet specific IED criteria. The integration of the Fault Tree model with threat data and visualization software will provide the military with a method of more clearly understanding the IED environment.

Methodology of Study

This research project is conducted in two phases. These two phases are Phase 1: Fault Tree Development and Phase 2: Implementation Guidance. The methodology and intent of each phase is listed in detail below.

Phase 1: Fault Tree Development: An axiom of warfare is that a complete understanding of the operating and threat environments is critical to military success. This understanding must encompass every aspect of the operating environment. The environment includes, but is not limited to, the training, tactics, equipment, logistics, locations used by friendly and enemy forces, and their relationship to an IED incident. The conditions in which the enemy chooses to fight should be understood in detail. This detailed analysis provides a foundation from which all future activities are based and is essential as the environmental influences are what dictate friendly and enemy behavior.

A Fault Tree Model will be used to identify and understand the variables which are present during an IED attack. The U.S. Nuclear Regulatory Commission uses the Fault Tree analysis as a systematic method for acquiring information about a system failure (Fault Tree Handbook, 1981). Fault Tree analysis has been used in transportation studies in the past to identify causal factors of highway crashes (Chowdhury, 1995). Specifically, a Fault Tree failure model will be developed which will identify the variables present for a failure to take place. In this case a failure is defined as an IED attack against a military vehicle on a road network. From this failure model information pertaining to the specifics of each attack can be analyzed, integrated, and compared to threat and exposure data in order to anticipate threat activity.

The specifics of real-world IED attack information are classified and not available for use in this study. As such a theoretical data set will be created to illustrate the analysis process. The data set was created by identifying IED attack locations on a road network in the city of Richmond Hill, Georgia. Richmond Hill was selected because it is the residence of the author and as such provides the opportunity to illustrate data collection requirements and techniques. The incident locations selected will be dissected with relevant data extracted for integration with the Fault Tree model.

<u>Phase 2: Implementation Guidance:</u> Once the Fault Tree is complete and the exposure information and threat data identified, a process will be developed to provide a clear understanding of how to employ the Fault Tree as a decision support and threat

prediction tool to be used by those decision makers involved in C-IED operations. Visualization assets will be employed as a method of translating threat data and Fault Tree information into visually identifiable areas on the ground. Two visualization software packages will be used in this study. The visualization packages are the transportation simulation software package Paramics and the GIS package ArcInfo. The visualization models are intended to provide clarity to the process and allow for easier interpretation of location information.

Hypotheses

This research project developed three separate hypotheses relative to the use of the Fault Tree Failure Model, the locations of Improvised Explosive Devices, and the use of visualization assets in threat prediction. These hypotheses were created to help guide research activities. These hypotheses are subjective in nature and cannot be proven or disproved by a theoretical data set. Ultimate validation of the concepts presented can only be accomplished through the integration of real IED data into the proposed process. Without access to real-world data the hypothesis presented are validated by the presentation and acceptance of logical information specific to the principles of the IED threat, military operations, Fault Tree modeling, simulation and GIS programming. This research project is presented for further development by those organizations with access to real world IED data. The hypothesis described are intended as basic fundamentals which can assist in the execution of future research intended to defeat the threat of IED data.

The first hypothesis (the specific details of this hypothesis have been removed to allow for publication) is associated with establishment of identifiable relationship exists between specific events associated with a successful IED incident against a military vehicle on a road. Through the establishment of these variables and relationships information can be obtained which will allow for the identification of IED locations. H1o represents the first null hypothesis where H1a represents the first alternative hypothesis. IEDV represents IED variables and IEDL represents decision IED locations.

$$H1o: IEDV = IEDL$$

$$H1a: IEDV \neq IEDL$$

The second hypothesis is that a Fault Tree based model can be used as a decision support tool in C-IED operations and in the prediction of IED activity. Specifically, employment of a Fault Tree based process can serve as an effective decision support tool with multiple applications including anticipation and identification of IED activity and locations. The null hypothesis for this question can be stated as a Fault Tree model equals a beneficial IED decision support tool. The alternative hypothesis can be written as a Fault Tree model does not equal a beneficial IED decision support tool. For this hypothesis H1o represents the first null hypothesis where H1a represents the first alternative hypothesis. FTM represents the Fault Tree Model and DST represents decision support tool.

$$H1o: FTM = DST$$

$$H1a: FTM \neq DST$$

The third hypothesis is presented to determine the effectiveness of various visualization assets in the identification of IED locations and evaluate their utility in C-IED operations. It is also intended to help guide research activities. It is believed that a visualization tool can be integrated with the Fault Tree in an effective manner to provide clear and understandable information relative to threat locations. Specifically when required, visualization platforms can be us in conjunction with the Fault Tree to translate information into a visually recognizable location. The null hypothesis for this question can be stated as visualization assets can be integrated with a Fault Tree to visualize anticipated IED locations. The alternative hypothesis can be written as visualization assets can not be integrated with Fault Tree to visualize anticipated IED locations. For this hypothesis H1o represents the first null hypothesis where H1a represents the first alternative hypothesis. VFT represents the integration of visualization platforms and Fault Tree and AIEDL represents anticipated IED locations.

$$H1o: VFT = AIEDL$$

$$H1a: VFT \neq AIEDL$$

Assumptions and Limitations

Care has been taken to ensure that the threat analysis is complete and provides a complete understanding of the operating environment. Due to the unique difficulty associated with collecting data in a combat zone and the information security issues associated with releasing sensitive military information several assumptions will be made during the conduct of this research project. These assumptions are based largely on careful analysis of unclassified literature pertaining to combat operations and tactical theory as well as established principles of engineering. When required the author made assumptions to guide the execution of this research. The assumptions are listed below.

- Assumption 1: The unclassified, open source information available is sufficient to adequately understand the threat and environments associated with the use of the improvised explosive device. From this information and a general understanding of military operations, a sensible failure diagram can be established. Only information released to the public will be used in this study.
- Assumption 2: The methods described in this dissertation can be applied to the overall study of the IED as they pertain to attacks on military vehicles on established road networks.

The limitations associated with this research initiative are explained in detail below.

- Limitation 1: This research project will not utilize any official, classified, or sensitive information. All information and analysis conducted in this report will be obtained from published, unclassified, open source documents.
- Limitation 2: A theoretical data set (Richmond Hill, Ga) was created for use in this research. The selected incident locations were based on analysis and understanding of present day threat tactics, techniques, and procedures. Validation for purposes of this dissertation will be derived from a logic based analysis and understanding of Fault Tree modeling and

the IED environment. Ultimate validation of these concepts can only be achieved through integration of real-world location information and IED data.

- Limitation 3: This dissertation is focused on IEDs placed on roads to attack military vehicles. This methodology is not designed to predict other explosive based attacks such as car bombs and suicide bombers.
- Limitation 4: There will be causal factors identified that exceed the capabilities of the visualization assets which would provide a stronger prediction capability. It is the hope of the author that the information pertained in this dissertation may eventually be incorporated and integrated into more robust simulation models.

Anticipated Benefits

The overall hope of the author and the primary purpose of this project is that the information obtained and the process described in this dissertation can be used to help save the lives of the members of the American military who are forced to do battle with the IED. It is believed that this research project will provide a new framework for analysis, a fresh perspective, and relative information, which can be further developed by individuals and organizations working to solve the threat associated with the IED. This research is presented as a new approach to solving the IED threat. Preliminary research of the topic indicates that no individuals or organization has attempted to correlate and integrate IED locations utilizing the Fault Tree model and visualization assets focused on the principles established in this dissertation. The endstate of this project is that new information is developed which can positively contribute to the ongoing effort to protect members of the military against the threats associated with the IED.

CHAPTER 2: LITERATURE REVIEW

Fault Tree

Introduction

The Fault Tree failure model is the primary method used in this dissertation for identifying and analyzing variables associated with an IED attack. The Fault Tree provides a systematic approach for acquiring information about a system and presents information in a logical, structured, and easily understood format, which can be manipulated to meet specific research requirements. The graphical manner in which information is presented encourages ease of interpretation and clarity of understanding. The Fault Tree is a proven method of identifying and analyzing events and has been used in numerous studies to identify and evaluate causes of failure. The Fault Tree has been used extensively in transportation research to identify variables associated with, and causes of, vehicular accidents in a transportation system. This application closely parallels the objectives of this IED study.

The following paragraphs discuss the history of the Fault Tree, the principles of Fault Tree analysis, past applications of the Fault Tree model, and a discussion of why the Fault Tree is best suited for identifying variables present during an IED attack.

History of the Fault Tree

The Fault Tree failure model was developed in 1961 by H.A. Watson of Bell Laboratories. Bell Laboratories was assisting the Boeing Company and United States Air Force with the development and analysis of the launch control system of the Minuteman Missile system. The Boeing Company, an international aerospace company, was the main contractor responsible for the development of the entire Minuteman Missile program (Engel, 2003). Boeing quickly recognized the value of the Fault Tree as an analysis tool and began to apply the Fault Tree to the entire Minuteman program. After witnessing the effectiveness of the Fault Tree on the Minuteman, Boeing was quick to recognize the numerous benefits which could be achieved by applying the Fault Tree to the aircraft division of the Boeing organization. Boeing began using Fault Tree analysis in the design and product development of their commercial aircraft. In 1965 Boeing, in cooperation with the University of Washington, sponsored a joint System Safety Conference in which several papers were presented on the Fault Tree (Ericson, 1999). This conference led to worldwide interest in the Fault Tree and recognition of its effectiveness as a prime method for identification and evaluation of variables associated with failures of complex systems.

In 1966 Boeing developed a computer simulation program which was able to analyze complex Fault Trees. The integration of computer technology to assist with the analysis process was an important step in Fault Tree development. Computer assistance allowed for a less time consuming and more error free evaluation of complex Fault Trees (Ericson, 1999). Today there are numerous computer programs on the market which are able to quickly interpret Fault Tree information.

In 1971 the nuclear power industry adopted the Fault Tree for use in the design and development of nuclear power plants. The nuclear industry has made the Fault Tree a part of their institutional culture resulting in significant contributions to the progression and enhancement of Fault Tree analysis. The United States Nuclear Regulatory

Commission has developed the Fault Tree Handbook which is an excellent reference for Fault Tree employment. In a paper on the history of the Fault Tree, Clifton A. Ericson, a system safety and Fault Tree expert, states that Nuclear Power Industry has contributed more to the development of Fault Tree theory and software codes than any other single user group (Ericson, 1999).

Over the past 46 years the Fault Tree has been used extensively in industry. Here are a list of major industries and technologies which utilize the Fault Tree (Ericson, 1999).

1. Aircraft – commercial, fighters, bombers, tankers, Unmanned Aerial Vehicles (UAV), Airborne Warning Alert Control Systems (AWACS), helicopters
2. Power Systems – nuclear, solar, electric
3. Transit Systems – trains, Morgantown Personal Rapid Transit (MPRT)
4. Space – Apollo, space shuttle, satellites, launch vehicles, space station
5. Robotic Systems
6. Auto Systems
7. Missile Systems – Minuteman, SRAM, ALCM, Tomahawk
8. Oil Platforms
9. Torpedoes
10. Hydrofoils

In his 1999 paper Mr. Ericson cataloged over 775 technical articles and books on the subject of Fault Trees. The prolific and continuing development of the Fault Tree lends credibility to the assertion that the Fault Tree is an effective tool for safety analysis, failure modeling, risk assessment, accident investigation, cause analysis, and system reliability.

Principles of Fault Tree Analysis

The information contained in this section comes primarily from the U.S. Nuclear Regulatory Commission (NRC) Fault Tree Handbook, a document which is used by the NRC and others as the principle reference in Fault Tree analysis.

The Fault Tree is a "systematic method for acquiring information about a system" (Fault Tree Handbook, 1981, pg. I-1). The Fault Tree is most effectively used to analyze a system failure. System failures are more clearly defined and often easier to identify than system successes. A clear understanding of what comprises a system is critical to effective application of a Fault Tree analysis. The Fault Tree Handbook devotes five pages in the beginning of the text to the definition and clear understanding of a "system". On page I-4 of the Fault Tree Handbook a "system" is defined as a "deterministic entity comprising an interacting collection of discrete elements".

The key terms are "deterministic" and "interacting collection of discrete elements". Deterministic means the system is identifiable. Interacting collection of discrete elements suggests that the system is a collection of smaller entities or subsystems that interact. It is the collective interaction of the parts which comprises the system.

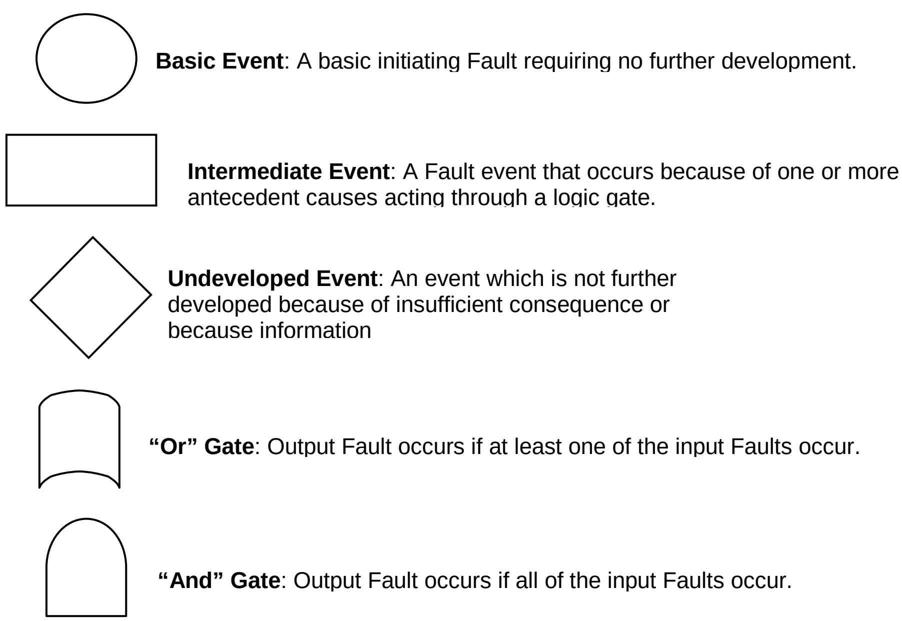
There are two separate analytical approaches which can be applied to Fault Tree analysis, the Inductive Approach and the Deductive Approach. The Inductive Approach is used to understand the effect of one subsystem or component on the overall system. An investigator applying an Inductive Approach manipulates one specific variable to understand how this variable affects the overall system. The Inductive Approach can be viewed as working forward in a failure analysis. For example, to determine what happens to a vehicle when a tire loses air pressure during highway operation, an investigator can deflate the tire and evaluate the behavior of the vehicle. The investigator is analyzing the effect of losing air pressure on a tire (subsystem) and the overall operation of the vehicle (system).

Conversely, a Deductive Approach works in reverse to determine the cause of a failure. Accident investigators generally use a Deductive Approach. If a vehicle has crashed on a highway the investigator can work backwards analyzing the individual subsystems to see which or how the actions of the subsystem caused or contributed to the overall failure. Investigators routinely use the Deductive Approach to determine how an airplane crashed, a train departed the track, and a boat sank. This type analysis is also often executed as a pre-emptive measure by a system manufacturer to identify how different subsystems can cause system failure. “In summary, inductive methods are applied to determine what system states (usually failed states) are possible; deductive methods are applied to determine how a given system state (usually failed state) can occur” (Fault Tree Handbook, 1981, pg. I-8).

The difference between a fault and a failure is also an important concept. A car engine can be used as an example. The “system” is defined as the engine and everything associated with its operation. Failure is defined as any condition which causes the engine to stop running. If a malfunctioning fuel pump provides less fuel than is required for optimum performance the engine may continue to run, although its performance is degraded. The engine is operating at a less than optimal rate. The fuel pump did not fail but is not performing correctly. The substandard operation of the fuel pump is referred to as a fault. The fuel pump is not considered in a state of failure because it did not cause the engine to stop running. The Fuel Pump is in a state of fault because it is not operating correctly.

An advantage of the Fault Tree is the clear graphical depiction of information. The “tree like” structure which results from depicting the interaction of the components is where the Fault Tree earned its name. A brief description of the basic symbols of a Fault Tree diagram are listed below in Figure 2.1 and are taken from page IV-3 of the Fault Tree Handbook.

Figure 2.1 Basic Elements of Fault Tree (Fault Tree Handbook, 1981)

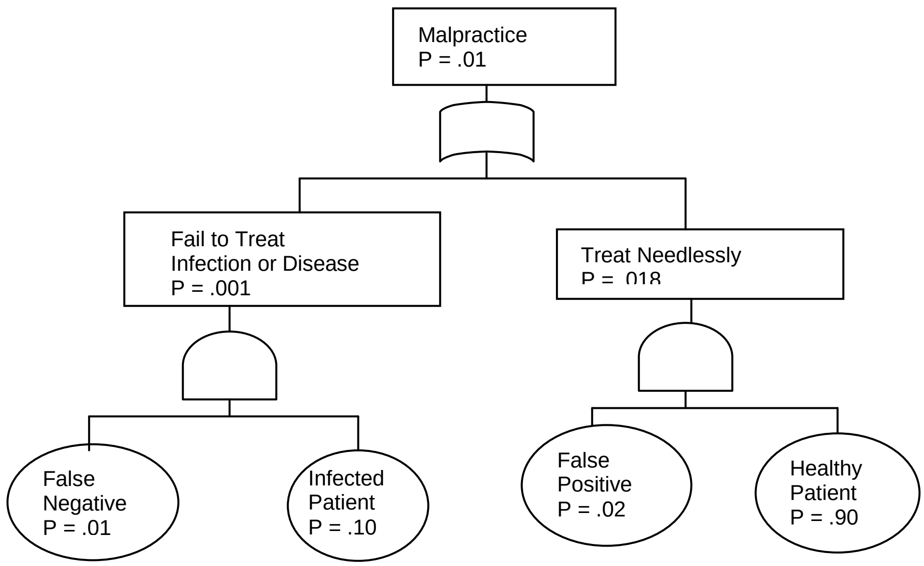


Once the Fault Tree has been constructed it can be evaluated and analyzed by either a Qualitative or Quantitative method. A Qualitative analysis uses the principles of Boolean Algebra (often referred to as the Algebra of Events) to determine a path to overall failure and describes the interaction and contribution of elements in system failure. A Qualitative analysis will define a systematic path which can lead to system failure and will provide a description of the interaction of Fault Tree elements. The combination of events that will lead to overall system failure is referred to as a Minimal Cut Set. The Minimal Cut Set is defined as “the smallest combination of component failures which, if they occur will cause the top event to occur” (Fault Tree Handbook, 1981, pg. VII-15).

The Quantitative approach provides the user with the ability to apply probability information to the Fault Tree in order to gain a better understanding of the likelihood of system failure. This empirical analysis is built from the bottom up identifying the probability of individual component failure and through the application of the minimal cut set can provide tangible information on the probability of system failure. The Quantitative and Qualitative methods can be used individually or in combination, based on the requirements of the study.

Figure 2.2 represents an example of a simple Fault Tree containing both qualitative and quantitative information to help understand Fault Tree diagrams. In this example the system is defined as a doctor, a patient, an infection or disease, and a test to identify the infection or disease. Failure is labeled “Malpractice” and is where the doctor subjects the patient to an incorrect treatment. The Probability (P) of each event is located in the bottom of the icon.

Figure 2.2: Sample Fault Tree (Chowdhury, 2006)



The Fault Tree is constructed with a top down approach with the failure event (malpractice) placed as the top level event. After careful analysis of how malpractice can occur it is determined that either of two events could cause the failure. The two events which can cause failure are failing to treat an infection or disease or treating a patient when they are not infected with a infection or disease. Since either event can cause failure an "Or" gate is used to separate the top level event from the intermediate event. Below each intermediate event there is an "And" gate implying that both of third level, basic events, must both occur for each of the intermediate events to occur. The third level events are enclosed in a circle indicating a basic event. The basic events terminate their specific branch of the tree since by definition no further development is required. The basic events under the *Fail to Treat Infection or Disease* are *False Negative* and *Infected Patient*. A false negative means that the test indicates no infection or disease is present when the patient is indeed infected or carrying the disease. The basic events below the second intermediate event are *False Positive* and *Healthy Person*. A false positive means the test indicates that the patient has the infection or disease when in reality the patient has neither. Applying the principles of Boolean Algebra and the laws of probability of the basic events up to the top level event, the probability of failure is 1.9%.

Real World Examples of Fault Tree Application

The Fault Tree has a multitude of applications and has been used extensively in numerous segments of industry by differing types of professionals responsible different for various aspects of system performance. The following list contains examples of why an individual would select the Fault Tree as a research tool (Ericson, 1999).

1. Accident/incident analysis
2. Visual diagrams of cause-consequence events
3. Common cause analysis
4. Numerical requirement verification
5. Identification of safety critical components
6. Product certification
7. Product risk assessment
8. Design change evaluation

Two transportation research initiatives are detailed in the following paragraphs which employed the Fault Tree. Although there are hundreds of examples how the Fault Tree has been used in transportation research these two employ the Fault Tree in a manner which relates to how the Fault Tree is applied in this dissertation. The two research projects are titled "A Causal Analysis of Large Vehicle Accidents through Fault Tree Analysis" and "Improvements of Highway Safety I: Identification of Causal Factors through Fault Tree Modeling"

Study 1: A Causal Analysis of Large Vehicle Accidents Through Fault Tree Analysis utilizes the Fault Tree to examine the relationships between a driver, a vehicle, and the environment, during a large vehicle accident. The intent of the study was to identify and determine, in a qualitative and quantitative manner, the level of contribution of variables present in a large vehicle accident. By identifying the crash characteristics and variables associated with the crashes, the authors are be able to make viable recommendations which could help prevent future accidents (Joshua, 1992).

The authors provide background on the selected methodology by providing a brief overview of five established accident theories. These accident theories are: "The Single Event Theory, The Chain of Events Theory, The Determinant Variable Theory, The Branched Event Theory, and The Multilinear Events Sequence Theory" (Joshua, et al., 1992, pg.174).

An explanation of each of these theories and the advantages and limitations of each is discussed in adequate detail with the Determinant Variable Theory, The Branched Events Theory, and The Multilinear Events Sequence Theory, appearing to most influence the investigation of large vehicle crashes and the utilization of the Fault Tree model.

The Determinate Variable Theory is based on the statistical and fact based analysis of accident data which presents the belief that “accident proneness” can be determined by examining all available accident data (Brenner, 1978). Additionally, there are common factors in all accidents. The Fault Tree is well suited for use in identifying the branched events discussed in The Branched Event Theory. This theory is based on the belief that an accident is likely to occur if a path which allows an event to happen is present.

The Multilinear Events Sequence Theory is a complex theory which tends to suggest that accidents are part of a continuum of activities with an associated process approach to understanding accidents. The Multilinear Events Sequence defines events and states that events during an accident happen in parallel and in series and suggest the use of a flow chart to describe the accident. This charting of the accident will help identify, and place in order, the events which happened and allow for better understanding of how they occurred and why they occurred (Brenner, 1975).

In attempting to identify causes of large vehicle accidents the researchers used the Fault Tree to identify how accidents occur, the relationship between failures, and how much protection is provided by the design of the vehicle (Joshua, 1992).

From the work of past accident research it was initially established that the major factors which contribute to an accident can be related to the driver, the vehicle, or the environment. As such, these three variables were each treated as subsystems and evaluated. Each evaluation was then discussed in context to the overall objective which is a large vehicle crash. The driver, vehicle, and environment stems were developed down to basic events and were then evaluated in both a qualitative and quantitative manner. The qualitative data was based on a logical analysis and from Virginia Department of Transportation accident data from 1984-1986. The quantitative data came from the accident data from1984-1986 which contained information on 2760 large vehicle accidents.

Minimal cut sets were developed for each subsystem. The minimal cut set for Driver Related Failure was broken down to 10 combinations of events which could result in a crash. The minimum cut set with the highest probability is when a driver of normal aptitude made an error in judgment and is unable to successfully execute an evasive action. The minimum cut set for Vehicle Related Failure determined that failure of a vehicle component is the cause of 73% of all vehicle related failures. Lastly, the Environmental Related Failure determined that the minimal cut set has 14 combinations that can relate to an environmental related crash (Joshua, et al., 1992).

Once the causes of large vehicle accidents were identified potential solutions were identified and discussed. These countermeasures were broken down and titled Preventative measures for Driver Related, Vehicle Related, and Environmental Related Failures. The recommendations ranged from improving vehicle and road compatibility with the specific characteristics of the driver population, driver education and enforcement, improved vehicle reliability, enhanced ergonomic design, and better highway design to improved driver training for inclement weather.

The advantage of the Fault Tree method over other accident investigation methods is that the relationships between basic failures and the most harmful failure are clearly established. “The Fault Tree method of analysis provides extremely useful insight into the problem of vehicular accidents” (Joshua, et al.,1992, pg.186). The Fault Tree analysis method also enables the researcher to identify most effective countermeasure which can be employed to help prevent accident occurrence.

Study 2: Improvement of Highway Safety I: Identification of Causal Factors through Fault Tree Modeling. This research initiative is part one of a two part study which provides a framework for analyzing factors which directly relate to automobile safety and which will help contribute to better design practices in multiple areas including automotive and roadway design. It is the primary objective of phase 1 (Improvement of Highway Safety I) to provide a clear methodology and tool for understanding and describing the interaction of human factors, vehicle factors, environmental factors and understanding how each of these variables contribute to accident occurrence (Kuzminski, et al., 1995).

The Fault Tree model was used to provide a framework for quantitatively and qualitatively identifying variables which can lead to accident occurrence. The chief qualitative advantage of using the Fault Tree is that it “describes fault occurrences and the interactions which lead to an undesired situation as well as providing a structured approach to studying failure” (Kuzminski, et al.,1995, pg.294).

The system boundaries for this model are defined as the driver-vehicle-roadway. As with the previous study which identified causal factors associated with large vehicle accidents, the three primary subsystems for this study were the driver, the vehicle, and the environment.

The study goes into excellent detail defining each of the levels of subsystems. The research states that the function of the driver is to provide steering, braking, and speed inputs to the vehicle so it may operate in a steady state condition which is appropriate to the operating environment. The analysis borrows from a previous study by James C. Fell and further separates the driver subsystem into four additional subsystems. These four driver subsystems are perception, comprehension, decision, and action.

The purpose of the vehicle is to move personnel and equipment in a safe manner which is in compliance with the speed and directional inputs of the driver. The vehicle is expected to operate in an appropriate harmonious state with the environment based on conditions. The vehicle subsystem is further divided into five additional subsystems. These additional subsystems are directional, speed governance, environment-driver interface control, passenger compartment control and vehicle artificial information provision system (Kuzminski, et al.,1995).

Once the system and subsystems are adequately defined a Fault Tree is constructed. As earlier discussed a critical step is to define the failure, this is the top event of the Fault Tree.   “Vehicle Violation of Space Occupied by Another Object” is the top level event. This is the definition used for an accident. Through careful dissection of the different ways an accident can occur the researchers developed a hierarchy of contributing events (Kuzminski, et al.,1995). From this Fault Tree the researchers were able to develop a detailed qualitative and quantitative understanding of the variables associated with accident occurrence and suggested numerous driver, vehicle, and environmental recommendations to improving safety.

Fault Tree Application in IED Analysis

The studies listed above are two of many transportation research projects which have used the Fault Tree as a method for identifying causes of accident. The Fault Tree is a flexible, versatile, and effective, model which has be used for 46 years in hundreds studies and a variety of industries by professionals attempting to understand various aspects of system operation.

The Fault Tree is equally effective in both qualitative and quantitative applications and can be manipulated to meet specific research objectives. It is apparent that the Fault Tree is an effective tool for providing a clear understanding what variables are present during an event, how those variables interact and how variables contribute to a specific event. These characteristics make the Fault Tree ideal for researching variables associated with IED attacks.

Classification and Regression Tree Analysis

There are other types of tree structured models which can be useful in the analysis and decision making process. The Classification Tree and the Regression Tree are examples of two tree structure models which are routinely used in multiple fields of engineering. Like the Fault Tree, these two models are effective in specific situations and provide a technique for modeling the probability of an event and analyzing explanatory and predictor variables (Loh, 2006). This section will provide a basic overview of the Classification Tree and Regression Tree Analysis models, emphasizing practical application rather than statistical theory. Additionally a comparison of these two methods and the Fault Tree will be discussed as well as the possible application of Classification and Regression Tree Analysis to IED research.

Classification and Regression Tree Analyses are also used to support the understanding of relationships between variables and identify patterns contained in a large data base and are methods which provide a statistical decision support tool capable of describing the relationship between variables within a data set. Classification and Regression Trees use tree-building algorithms to determine a set of logical if-then conditions between variables that permit accurate prediction of classification of cases (Lewicki, et al., 2007).

There are four common components found in a classification and decision problem in which Classification Tree and Regression Tree analyses are used. These four components are the categorical outcome or dependent variable, the predictor or independent variable, the learning data set, and test or future data set (Lewis, 2000). The dependent variable is a characteristic or outcome which the decision maker hopes to predict. This prediction is based on the analysis of the related predictor or independent variables associated with the classification or decision. The learning data set is a collection of information which includes values from both the dependent and independent variables and is representative of the situation to be classified. Lastly, the test or future data set is the data which is analyzed for actual prediction, classification, or decision purposes (Lewis, 2000).

The Classification Tree and Regression Tree are based on statistical relationship theories and when constructed present a logical and easy to understand representation of variable relationships. A tree is graphically depicted as a collection of nodes and branches. The top node is referred to as the top node and termination node is called a leaf. The process of partitioning the nodes begins at the root and proceeds in a recursive manner (Qin, et al., 2005). This process eventually creates a well defined tree with its leaves representing different groups of dependent variables corresponding to associated and related predictor variables (Qin, et al., 2005). This is a very simplified description of how a tree is constructed and intentionally does describe the statistical theory associated with identifying the relationships between variables. Figure 2.3 and Figure 2.4 are Classification and Regression Trees and illustrate how they are used as decision support tools.

Figure 2.3 is a very simple Classification Tree. As the name implies it is often used when the classification of an element is the desired endstate. In this example the decision maker creates a Classification Tree based on petal width, to assist in identifying the type of flower present. This Classification Tree is based on the analysis of the pedal width to determine the type of plant present. If the petal width is less than 0.800 the flower is identified as a Setosa. If the petal width is greater than 0.800 the decision maker must continue down the tree and decide if the size of the petal is greater or less than 1.750. If the petal width is less than 1.750 the flower is a Virginic. If the Petal is greater 1.750 then the flower is a Versicol.

Figure 2.3: Classification Tree for Identification of Flowers (StatSoft, 2007)

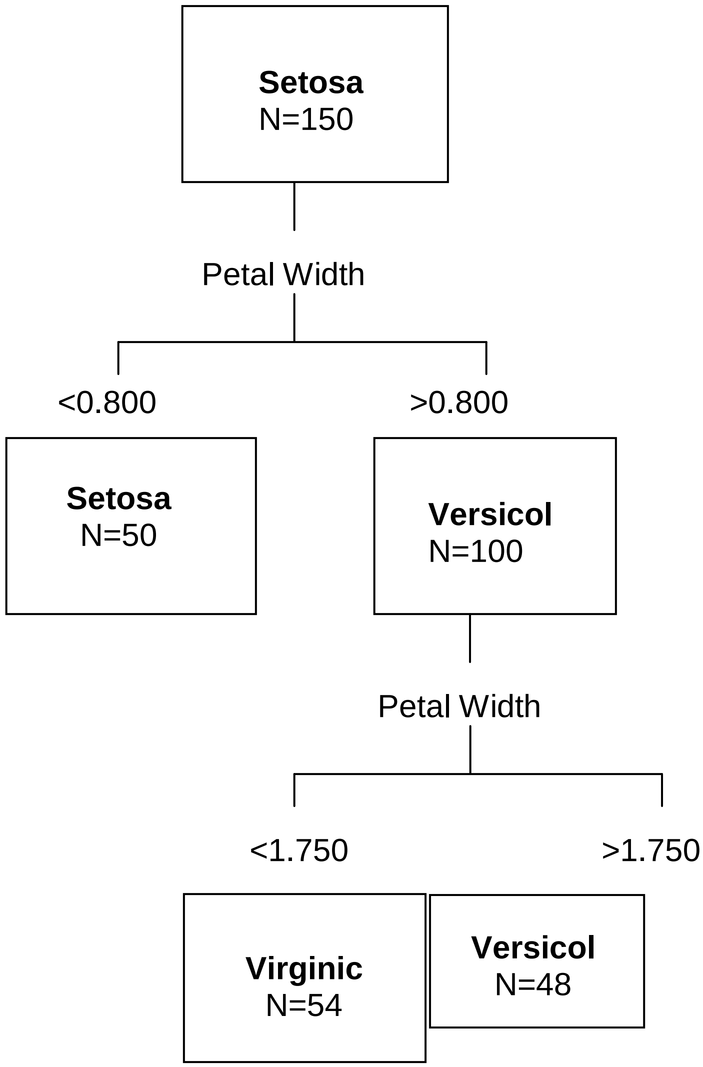
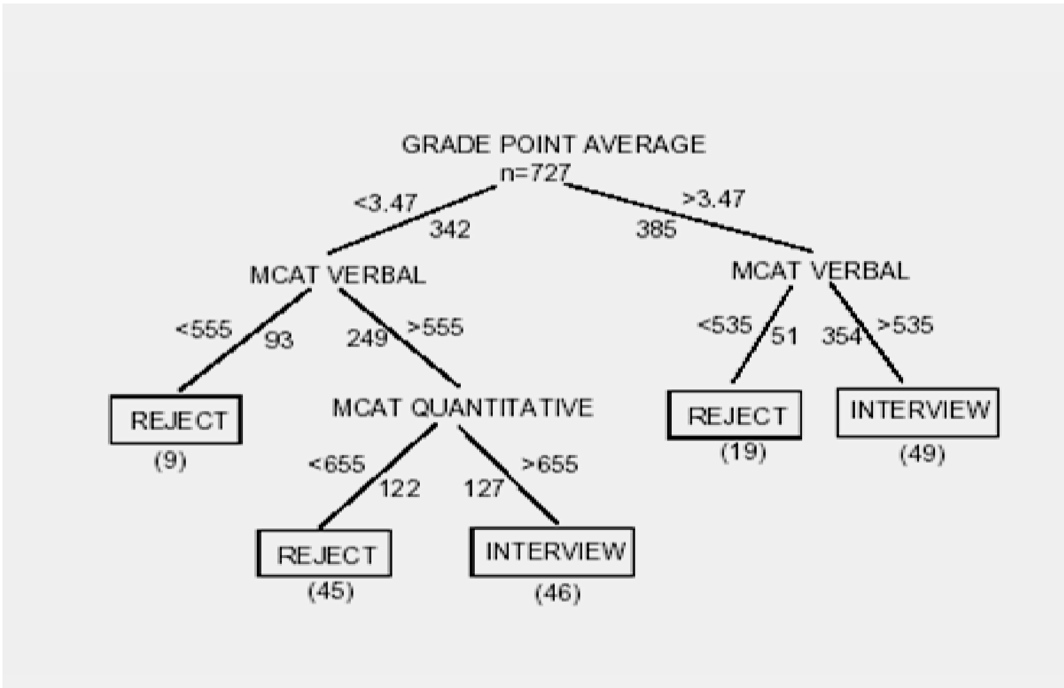


Figure 2.4 is an example of a simple Regression Tree which is used as a decision tool to decide or predict admission of a student to medical school. This case illustrates the possible dual capability of a Regression Tree model as a prediction tool and as a decision support tool. In this example 727 candidates are evaluated for admission (n=727). The decision maker would enter the tree at the top root node and determine

whether the applicant has a Grade Point Average (GPA) greater than or less to 3.47. If the applicant's GPA is greater than 3.47 then the decision maker will follow the branch down to the right and analyze the Medical College Admission Test (MCAT) Verbal score. If the MCAT Verbal score is greater than 535 then the candidate should be interviewed. If the MCAT Verbal is less than 535 the candidate should be rejected. Conversely if the candidate has a GPA less than 3.47 then the MCAT verbal score is again analyzed. If the verbal score is less than 555 then the candidate should be rejected. If the score is greater than 555 then the MCAT Quantitative score should be analyzed. This is continued until a decision to reject or interview is made. An applicant can also use this tree to predict the probability of being accepted by analyzing the applicant's GPA and MCAT Verbal and Quantitative scores (Wilkinson,1992).

One of the primary differences between Classification and Regression Trees and the Fault Tree is that that the Classification and Regression Trees are driven by the data provided. The Classification and Regression Trees are useful when large amounts of complex data are available in some sort of data base. Through the use of modern computer software a complex data set can be sorted to identify statistically significant relationships and depicting these relationships in the tree structure.

Figure 2.4: Regression Tree for Admission to Medical School (Wilkinson, 1992).



Data mining can be used with Regression trees. This process is common vehicular safety studies. Most state departments of transportation maintain a large accident data base containing thousands of data points from multiple years with information specific to every accident. Examples of the information contained within this data base would be, age of driver, driver history, sex of driver, number of passengers, age of passengers, sex of passengers, type of vehicle, weather conditions, road surface, speed of vehicle, and time of day. Data mining can be used to interpret the information, identify relationships, and determine statistical probabilities. Information concerning the relationship between age of driver, type of vehicle and probability of being involved in a fatality can be determined through the use of data mining and a regression tree analysis. "Data mining has become a very valuable data analytic process for detecting interesting patterns and clusters in large data sets" (Hardin, et al., 2002, pg. 2).

As discussed earlier the Fault Tree is better suited for variable identification. It is through the variable identification process that a relevant data base can be developed. This dissertation focuses on the use of the Fault Tree to identify variables present in an IED attack. At the present time there is a limited unclassified data base available for analysis. This prevents the use of a regression analysis in IED attacks. Exploration of the application of a regression based process should be more thoroughly explored once a sufficient IED attack data base is established.

Simulation

Once the variables associated with an IED attack are determined a system of presenting this information in a usable format is required. The format must allow our military forces the capability of interpreting the information contained in the Fault Tree and translating this information into identifiable points on the ground that meet the criteria for an IED location. This transfer of data from an analytical analysis to useable and actionable information will allow the military the ability to neutralize an IED location and minimize the catastrophic effects of an IED explosion. In order to be effective, and to guarantee use by the average soldier on the battlefield, the information must be presented in a clear and easy to understand format. This simplicity is critical. The battlefield is a complex environment which places enormous physical, mental, and emotional stress on the soldier. Experience shows that if information is presented in an overly complicated manner it simply will not be used.

This dissertation focuses on presenting a method of using the computer simulation program Paramics to interface with the Fault Tree Analysis in a C-IED application. Paramics is an extremely diverse and flexible transportation engineering and simulation software package capable of performing a multitude of tasks. This dissertation emphasizes the use of one specific application and discusses other capabilities of the software. The following paragraphs outline the basic principles of simulation, the capabilities of Paramics, and discuss a few research initiatives which use Paramics. Additionally, an explanation is included as to why Paramics was selected as the method of integrating the information contained in the Fault Tree into actionable information, which can be used defeat the threat associated with the IED.

Simulation has proven to be a practical and cost effective method of replicating and anticipating actions and behaviors within a system. Simulation is the “process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behavior of the system or of evaluating various strategies” (Ingalls, 2002, pg.7). At the most basic level simulation can be considered as a form of Cognition. Cognition is the action or process of acquiring knowledge about an entity (Sklenar, 2007). There are numerous ways to obtain information or acquire knowledge about a system, however most methods can generally be broken down into three general categories. The three general ways to gain information about a system are (1) conducting a real world experiment, (2) analyzing available information, and (3) running a simulation. The Fault Tree will answer the "how" questions of system failure but is not able to clearly and independently answer the "when" and "where" questions of system failure. This is where simulation can assist. Simulators are an economical and feasible method of understanding and evaluating system operations and network behavior for abstract and complex systems (Craig, 1996).

Simulation compliments the Fault Tree and will provide an interface illustrating the information obtained in the Fault Tree Analysis. There are several principles used to guide a simulation process. The investigator must determine what type of simulation is best suited to achieving the desired endstate. The appropriateness of each method is dependent on what information is to be extracted, the complexity of the system, and how the time variable is to be represented.

There are three basic simulation techniques or strategies which may be employed by the investigator to model the system behavior and obtain system information. These strategies are (1) Discrete Event Simulation, (2) Continuous Simulation, and (3) Combination Continuous and Discrete Event Simulation. The selection of the appropriate technique is dependent on the system and the information desired. Each of these approaches has several common elements. Different investigators might refer to these elements with different terms but the fundamentals remain constant.

The components of a simulation are the Model, the System State, the Entity, and the Activity. Models can be mathematical, logical, descriptive or a combination of each of these forms (Banks, et al., 1986). The model is the object which is created to represent the system to be studied. For this dissertation the model will be the road network and operating environment.

The System State is “a collection of variables that contain all information necessary to describe the system at any point in time” (Banks, et al., 1986, pg.17). The System State contains all of the specific variable information required to represent the system at any specified point in time.

The Entity represents the information which is to be extracted from the simulation. The Entity is the knowledge the investigator wishes to obtain from the simulation and represent or reproduce in the model. Entities can be simple or complex depending on the system and may be comprised of several variables. An Entity could be any subsystem such as a part or piece of machinery (Banks, et al.,1986).   For this dissertation the Entity would be the anticipated or predicted IED location.

The Activity often represents the time element and is associated with the time variables of the simulation. The length of the activity may be “constant or random (specified by a probability distribution), or represented as a function of present or past system state” (Banks, et al., 1986, pg. 17). The application of this concept is addressing the duration or period of time the simulated is going to represent. This concept can be used to allow the military the ability to gain insight on when exactly IEDs are being placed or how many IEDs could be anticipated in a 48 hour period. This application is beyond the scope of this dissertation but with enough information is achievable.

Discrete Event and Continuous Simulation

One way to understand the difference between Discrete Event Simulation and Continuous Simulation is how each type of simulation incorporates the time element in regards to data output and analysis. In Discrete Event simulation the system state is changed at a specific set of points often referred to as event times. The system state at the discrete point or event time is represented as a snapshot of the system at a specific period. Discrete Event simulations change or increase the time period the simulation is attempting to replicate and updates the associated system state. As this occurs, the simulation is providing information as it pertains to the specific point in time (Banks, et al., 1986).

The information extracted from the simulation represents the behavior of the system at a specific point in time. Discrete Event simulations are used to extract information about a specific time period. Once the information pertaining to the simulated time period is extracted, the simulation continues until information pertaining to another specific point in time is desired. This definition is best represented with an example.

A banker might use Discrete Event Simulation to understand the effect on inflation and fluctuations in the stock market on the price of a specific type of house in a specific area over a 30 year period. The banker could use a Discrete Event Simulation to predict the price of the house at every five year period. The banker would build a model representing inflation, fluctuations in the stock market, and market price information on a house. The banker requires price information at the 5, 10, 15, 20, 25, and 30 year period. The prices at these specific periods are snapshots.

Discrete Event simulation have a multitude of applications and are often seen in areas of manufacturing, the service industry, business process evaluation, and risk analysis (Ball, 1996).

Continuous Simulation represents time as "a continuous variable and expresses system changes in terms of a set of differential equations representing the system state of variables" (Seila,1995, pg.10). In a Continuous Simulation the information does not represent a snapshot or frozen moment in time, instead it represents time as a continuing and flowing illustration of system behavior. Integration of time equations are used to replicate system behavior in a fluid manner. Continuous Simulation can be used to understand how traffic interacts on a freeway during a high volume periods. The investigator is not interested in freezing time or obtaining a "snap shot", instead the investigator is interested in observing the overall freeway flow. The investigator is interested in the fluid interaction and movement of vehicles as they flow through the high volume period. This application would require a continuous simulation. Continuous Simulations are often mathematically complex, using detailed calculus based algorithms to accurately integrate the time variable.

There are some simulation packages which are capable of combining the principles of Discrete Element and Continuous Simulation to provide the investigator the flexibility of creating one model and obtaining information about specific periods of time and understanding the fluid behavior of the system. Paramics is an example of this type of simulation package.

Paramics

Paramics is an extremely powerful transportation research tool which is capable of performing a wide variety of transportation engineering and planning functions. “Paramics is a suite of microscopic simulation modules providing a powerful, integrated platform for modeling a complete range of real world traffic and transportation problems” (Paramics-Online, 2007, pg. 1). Paramics is a stochastic, microsimulation package developed in the Edinburugh Parallel Computing Center in Scotland and stands for PARAllell Micro-Simulation (Fries, 2007).

There are three primary methods of representing vehicle movement in a traffic simulation. These methods are Macroscopic simulation, Mesocopic simulation, and Microscopic simulation. Macroscopic simulations deal with overall flow of all vehicles across individual links of a road and do not address individual driver behavior (Klefstad, et al., 2005). In Macroscopic simulations all vehicles are addressed as a single large group. Mesoscopic simulations break vehicles down into platoons and represents smaller groups of vehicles traveling on similar paths with some attention placed on vehicle behavior (Klefstad, et al., 2005). Microscopic simulations represent networks, traffic control elements, and movements of individual vehicles as individual components (Wai, et al., 2004). In Microscopic simulation the individual behavior of each vehicle is modeled independently. “Microscopic simulation models are superior for understanding real traffic because driver personalities and likely behavior can be described and propagated through the simulation" (Klefstad, 2005, pg. 1).

The main Paramics Project Package is comprised of three primary components, these components are the Modeller, the Processor and the Analyzer (Quadstone Paramics, 2006). The Modeller is the primary network construction and visualization component and is essentially the brain of the simulation package. The Modeller requires two key pieces of information specific to the transportation environment for accurate operation. These two pieces of information are geometric network data and traffic information (Quadstone Paramics, 2006). The network data is everything associated with the road layout and the physical environment to include the all geometric information, intersection data, and lane markings. Traffic information is volume and travel demand data as well as turning movement information and signal timing. Volume information includes all items associated with the amount, types, and time of occupation of all vehicles which utilize the network. The Modeller is capable of handling an immense amount of information associated with an entire city's traffic data.

The information specific to the road network can be loaded into the Modeller by a variety of methods. One method is manually reproducing the network based on field measurements. This method is very time consuming but does provide the user flexibility. Paramics also has the ability to convert AutoCad or Microstation, (engineering design packages) and multiple GIS products, to include imagery, directly into the system (Paramics-Online, 2007). The ability of Paramics to use existing network files and overhead imagery is very important because it saves valuable time and provides flexiblity.   This flexibility lends itself to military operations since imagery of a military area of operations is usually obtainable.

The Processor is the brain of Paramics simulation. The processor executes the simulation directives. Paramics is capable of conducting Discrete Element simulations, Continuous Simulations, and a combination of both methods. Paramics simulations can be manipulated to provide a wealth of information and simulate extensive and complex operations at various levels of sensitivity (Paramics-Online, 2007).

The Analyzer is the component which interprets the simulation data and provides the user with decision making information. "The Analyzer is the post-data-analysis tool used for custom analysis and reporting of model statistics" (Paramics-Online, 2007, pg.1). The Analyzer provides report templates and is capable of managing large amounts of data. Additionally the Analyzer can be programmed to present information in a specific format. The Analyzer interprets the information from the simulation model and provides this information in a graphical representation of the simulation results.

A unique capability of Paramics is the ability to customize the simulation to perform non-standard simulations. This is accomplished through the use of the Application Programmer Interface (API). The API provides the investigator with a great deal of flexibility by providing a method of conducting simulations which may be considered outside the primary intent or scope of software designers. "Using the API the user can override the core models used by the simulation engine such as car following and lane changing rules" (Lee, et al., 2001, pg. 842). The API provides the investigator the ability to transform the simulation platform into a tool which can be effectively used to model new ideas, even if the simulation package was not originally designed for such applications (Lee, et al., 2001). Using the API will allow Paramics to interface with the Fault Tree.

Paramics is also capable of providing a two and three dimensional visual representations of road networks using The Graphical User Interface (GUI) and can graphically depict network information in multiple formats (Paramics-Online, 2007). This capability is of considerable importance for military applications. With this capability a soldier will be able to run a three dimensional drive through simulation of an area and identify locations on a three dimensional model which meet IED placement criteria.

Paramics Projects

Leftwich Consulting Engineers, Inc (LCE) executed a future year analysis for the City of Miami, Florida. Leftwich built models of three districts of Miami. The districts were the Brickewell area, the Downtown Core, and the Omni areas, and included all roads east of I-95, north and south of 15^{th} Road, west of Biscayne Bay, and south of North 20^{th} Street (Leftwich, 2004). The city was interested in comparing the effects of converting two-way streets to one-way streets, depressing freeways to an at-grade tunnel system, creating light rail lines, and building a tunnel under the Miami River. The firm was tasked to conduct an operational analysis for the year 2025.

Before beginning this project Leftwich consultants conducted an extensive comparison of the different micro-simulation packages. It was important to select a program which was capable of conducting accurate simulations of complex networks and process vast amounts of information. “Having examined a number of other software products to handle the mammoth traffic microsimulation task, the Paramics modeling suite was selected primarily for its ease of application, excellent 3D visualization capabilities and scalability that allowed fast and accurate modeling” (Leftwich, 2004, Paramics-Online).

The engineering company Edwards and Kelcey completed an analysis of a construction upgrade. The project was a border inspection facility between Canada and Massena, NY. Edwards and Kelcey were tasked to evaluate the most effective construction plan in which various configurations, circulation directions, lane openings, signal timings as well as management techniques were being considered. Edwards and Kelcey were tasked to determine which plan would allow for the most efficient and secure operation of the crossing point (Edwards, 2004).

The firm selected Paramics because of its ability to effectively customize vehicle maneuvers associated with inspection points, the ability to integrate, evaluate, and analyze traffic variables, the ease in which various designs could be assessed, and the clarity of understanding associated with the graphical representation (Edwards, 2004).

Paramics has also been used in several incident management studies which analyze the effectiveness of different incident response strategies. An example of two incident response strategies in which Paramics were used are evaluation of Freeway Service Patrols (FSP) as well as “Quick Clearance” legislation.

In these studies the investigators were looking for quantifiable data to assess the effectiveness, in terms of incident durations, of various FSP strategies. These strategies included dispatch procedures, use of different types of FSP vehicles, and headway (Yongchang, et al., 2007). Paramics provided a clear understanding of the operational impacts associated with legislation which require vehicles involved in minor traffic accidents to move quickly from the main roadway (Hamlin, et al., 2007).

Paramics was selected for use in these incident response investigations because real world field tests were considered impractical and microscopic traffic simulation would create a realistic representation of actual conditions (Yongchang, et al., 2007). "Paramics is a time-step, behavior based microscopic traffic simulation model, which can incorporate detailed network and traffic control information to provide a realistic estimate of traffic operation conditions" (Yongchang, et al., 2007, pg. 6). Additionally the ability of Paramcis to create an API allows for the creation of unique research applications." The API allows users to customize many features of the underlying model and develop their own modules to interface with Paramics" (Hamlin, et al., 2007, pg.6).

Paramics and IED Identifion

The information contained in this section has been removed to allow for open publication.

Geographic Information Systems

Introduction

A Geographic Information System (GIS) provides a visualization capability which can be used to translate analytical variable information into an actionable format by identifying recognizable locations on the ground. In other words, GIS systems allow the representation and analysis of information relative to locations on the earth's surface.

Stated more formally, GIS is an organized collection of computer software, computer hardware, geographic information, and specially trained geographic experts, which are used to capture, store, update, manipulate, analyze and display all types of geographic information. (Environmental Systems Research Institute, 1992).

GISs are extremely powerful tools which, like simulation, are capable of integrating large amounts of complex data and are adaptable to a wide variety of applications. This section will address the principles of GIS, the transportation safety and military applications of GIS, as well as detail how GIS can be used in Counter-IED (C-IED) operations.

Principles of GIS

The capability which distinguishes a GIS from other types of graphical programs is the ability to analyze and process spatial information. This differentiates a GIS from more dedicated programs such as Computer Assisted Cartographic (CAC) systems, which are used simply to design and create maps, or Computer Assisted Drafting (CAD) type programs used to create graphic images (DeMers, 1997). A GIS is comprised of several components which provide the complete ability to store, update, manipulate, analyze and display all forms of geographic information. On page nine of his book Fundamentals of Geographic Information Systems, Michael DeMers states that a standard GIS has four subsystems. The subsystems are as follows:

1. A data input subsystem that collects and preprocesses spatial data from various sources. This subsystem is largely responsible for the transformation of different types of spatial data.

2. A data storage and retrieval subsystem which organizes the spatial data in a manner that allows retrieval, updating, and editing.
3. A data manipulation and analysis subsystem which performs tasks on the data, aggregates and disaggregates, estimates parameters and constraints, and performs modeling functions.
4. A reporting subsystem that displays all or part of the database in tabular, graphic, or map form.

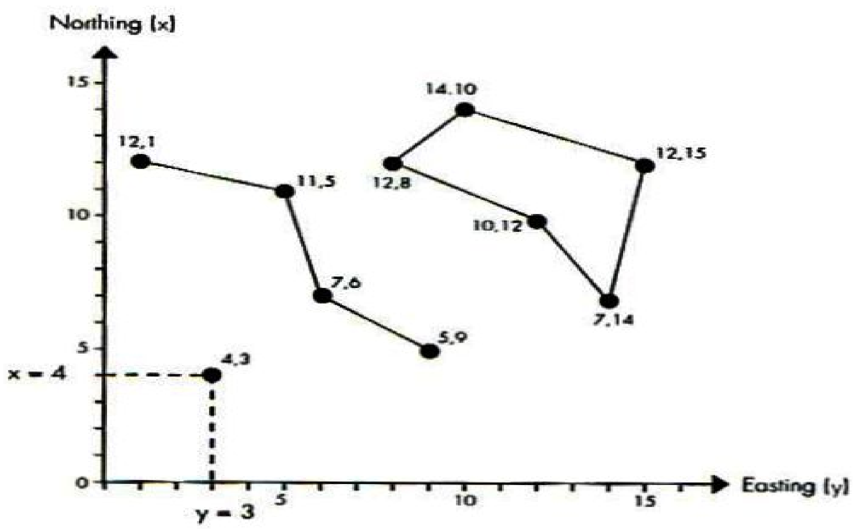
The data manipulation and analysis subsystem is what provides the critical and unique capability of the GIS. The analysis subsystem allows the user to compare and contrast, measure, and describe, information obtained in the database (DeMers, 1997).

A GIS is able to create a digital representation of geographic elements for analysis. The digital representation of the geographic model is usually the foundation for subsequent data manipulation and analysis. A GIS is able to depict real world relationships through models involving geographical geometry, geographical attributes, and relationships (Bernhardsen, 2002). There are two basic types of models used in GIS; Vector Data Models and Raster Data Models. These categories describe how digital information is created, interpreted, and stored by the GIS (Bernhardsen, 2002).

Vector Data Model

In the Vector Model GIS digitally represents data in the model and operates under the principle that the real world can be portrayed into specific elements, each of which contains an identifiable object with a specific geometry. The geometry is comprised of points, lines or areas. "Points, lines, and areas, are mathematical figures used to describe the position and extensions of geographical objects" (Bernhardsen, 2002, pg 55). Coordinate systems such as "northing" and "easting", are used to define the specific point, line or area data in the geographical system. Figure 2.5 provides an illustration of a vector data model.

Figure 2.5: Vector Model (Bernhardsen, 2002, pg. 56)



The point is the basic building block of the vector model. Points are considered zero dimensional because they possess no extension and are represented by a pair of coordinates. Lines are multiple points linked together and an area consists of a continuous single line that closes on itself to create an enclosed space. In a vector model the geographical data is mathematically defined by describing the information specific to each point, line, or area in a database. This mathematical description and graphical representation is accomplished by assigning a computer code to each point, line, or area. The point, line and area are often referred to as the graphical primitive as they represent the smallest unit of information (Delaney, 1999). The computer code describes and categorizes each primitive for use in the GIS subsystems.

Raster Data Model

A Raster Data Model is the second method to digitally represent the information in a GIS. A Raster Data Model divides the geographical information into cells. A raster model applies a grid to a surface of the geographic entity and dissects the grid into basic cells. The cell is the basic geographic entity or geographic primitive. The size and shape of the cell is uniform throughout the model and is assigned a number code in the database which describes the geographic information specific to the cell. The cell is usually square in shape and contains one number or key code, which is the link to the specific information or data for the individual cell. The size of the cell is dependant on the size of the geographic model to be surveyed and the amount of detail desired from the model.

The smaller the cell, the greater the degree of digital accuracy and detail in the model. Applying multiple layers of grid cells provides the user the ability to provide more detailed information for use in analytical activities. Figure 2.6 is a simple display of a Raster Model.

Figure 2.6: Raster Model (Bernhardsen, 2002, pg. 74)

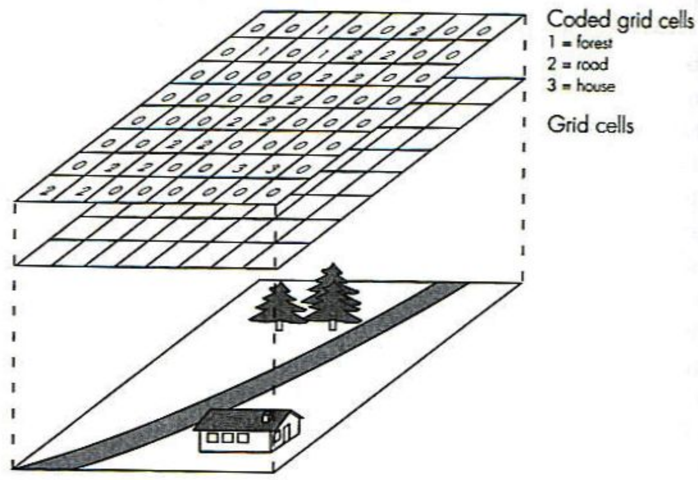
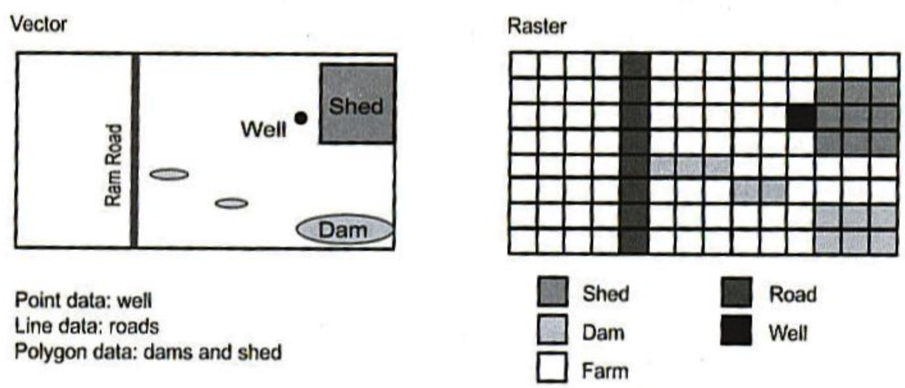


Figure 2.7: Vector vs. Raster Model (Delaney, 1999, pg. 18)



Raster Models and Vector Models each have their advantages and disadvantages. Raster Models are more compatible with computer technologies as most computer monitors use raster type displays. Additionally, remotely sensed imagery, such as satellite or aerial imagery, uses Raster theory and therefore is more easily integrated into computer systems (Delaney 1999).

Conversely, Vector Models possesses a higher degree of spatial accuracy, as information can be pinpointed to an individual location defined as a specific point with a specific coordinate cell, and specific characteristic. (This is more discrete than the Raster Model.) Most GIS have the ability to combine Raster and Vector models for use in GIS subsystems.

Real World GIS Applications

GIS has been used extensively in the fields of transportation safety and in military operations. Transportation safety programs regularly use GIS which provides users the capability to geographically visualize accident data. Many Departments of Transportation (DOT) have developed GIS based accident location and analysis systems (Souleyrette, 1998). These GIS based systems allow for the integration, sharing, and interpretation of accident and safety information. Through the establishment and integration GIS database users have the ability to customize data requests and query and analyze accident related information. These queries can be set up to identify accident locations which meet specific characteristics. Search results are able to be displayed in several formats to include tabular or graphic which provides for a more easily understood interpretation of results and promotes the analysis of accident patterns and causal relationships (Soulyrette, 1998).

The analysis capability of GIS for transportation safety applications is only limited by the amount and accuracy of information contained in the accident database. In order to fully identify patterns, understand relationships, and identify causal factors a detailed and accurate accident database is essential. With GIS, users can create visualization products such as maps displaying information contained in the accident data base. The types of information often found in a transportation safety accident database are provided in the bullets below (Khan, 1998).

- General Information: Year, Month, Day, Hour,
- Location: Street, Intersection, Location Coordinate, Milepost
- Driver and Passenger Information: Age, Sex, Seat Belt, Car Type, Passenger Location, Injuries, Driver's License Category, Past Traffic Citations.
- Road Environment: Road Type, Road Category, Weather, Lighting, Road Surface, Road Conditions, Volume of Traffic, Vehicle Speeds
- Road Geometry: Horizontal Curve, Vertical Curve, Superelevation
- Vehicle Information: Vehicle Type, Vehicle Year, Mileage

A researcher can create GIS visualization products which are tailored to research objectives based on queries specific to any individual or set of variables contained in the database. The locations of these accidents can be displayed on a map. The maps provide the ability for personnel identify locations which meet specific characteristics.

The military uses GIS products throughout the planning and execution phases of most military operations. Understanding the terrain and the operational environments is a key tenet of military doctrine. GISs provide this capability. Military personnel use GIS in a multitude of applications such as cartography, terrain analysis and management, battlefield management, and intelligence (Satyanarayana, 2002). GIS products are critical to the military decision making process as they allow the military decision maker the ability to visualize the operational environment.

The majority of military activities are terrain sensitive. Understanding the impacts of terrain is critical to military success. Terrain has a direct impact on the operation, effectiveness, and mobility of personnel, weapon systems, and equipment. Terrain Characteristics such as elevation, soil type, density of vegetation, type of vegetation, water conditions and land use all influence the effectiveness of military operations and are critical elements of the military's decision making process (Baijal, 2008). . History is full of examples where a smaller force, possessing a clear knowledge of terrain, has defeated a larger, better equipped force lacking this knowledge.

With an accurate and detailed database military planners can create terrain queries which are specific to certain military operations and use GIS products as decision support tools. An example of how GIS can support military operations can be found in the identification and selection of vehicle mobility corridors (Baijal, 2008). For example, if a military commander is attempting to locate the best location to cross a particular river a GIS query can be created to identify all points where the river depths and currents will permit vehicular crossing (eg, river depth less than five feet and river current less than one mile per hour). Another example would be if a tank commander is attempting to select the best route between two points, a GIS query can be established to identify all routes between the two points where the road widths are a certain dimension, overpasses are of a specific height, and bridges are structurally capable of supporting the weight of vehicles involved (Baijal, 2008).

These examples show the versatility of GIS applications. In all cases the effectiveness of the GIS product is very much dependent on the level of detail provided in the database. A carefully created and well maintained database, with established variables, is of critical importance to the decision maker. It is also directly related to, and a critical element of, an effective GIS product.

GIS and C-IED Operations

The information contained in this section has been removed to allow for open publication.

Insurgencies

In order to have a full understanding of why the IED is employed one must have a appreciation of the operational environment in which it is used. It is therefore important to understand the military and political nature of insurgent warfare - the history, nature, and objectives involved. This includes the objectives of the enemy and why in Iraq today the IED is a major asset of the Iraqi insurgent.

This section examines the characteristics of an insurgency and follows with a brief analysis of three historical campaigns: (1) the 2nd Boer War in South Africa from 1899 to 1902, (2) the “Banana Wars” of Central and South America which took place in the early 1900’s, and (3) The Algerian War of Independence, from1956 to 1962.

These military campaigns are selected as they provide historical relevance and contain lessons which can be applied to ongoing operations in Iraq and Afghanistan. The Boer war provides an example of an engagement where Great Britain was engaged in military operations against an opponent which employed insurgent tactics. The Banana

Wars, which are relatively unknown to the majority of Americans, illustrate a time in America's history were our nation's military had first hand exposure to fighting classic insurgencies. The Algerian War of Independence provides a more recent example of an Islamic based insurgency, when a relatively smaller force was capable of defeating the significantly larger and stronger military of France, a major Western power.

In 2006 the United States Army and United States Marine Corps published a manual on counterinsurgencies which states that "Insurgency and its tactics are as old as warfare itself, and is defined as an organized movement aimed at the overthrow of a constituted government through the use of subversion and armed conflict" (FM 3-24, 2006, pg. 1-1). This style of military operation is based on the philosophy that superior political will, when correctly employed, can defeat an opponent with greater economic and military power. Insurgencies employ all available political, social, economic, and military resources with a goal of convincing the opponent's political decision makers that their goals are either too costly or unattainable for the perceived benefit (Hammes, 2006).

"Fourth Generation Warfare" is a term which is often used within military channels to describe insurgency warfare. It is based on the accepted evolution of the way military battles are fought. The first generation of modern war was manpower intensive with large numbers of personnel often standing shoulder to shoulder in large formations at close range. The intent was to dominate the opponent through the use of personnel engaged in relatively close quarters combat and did not emphasize maneuver or advanced weaponry. This style of warfare culminated with the Napoleonic Wars. The second generation of warfare saw the domination of firepower. As seen in World War I, front lines became relatively stationary with opponents emphasizing the use of firepower and weapon systems to dominate the enemy. The third style of warfare used speed and maneuver (as seen in World War II, DESERT STORM, and the early phase of OPERATION IRAQI FREEDOM) forces gained the advantage by the use of swift maneuver (Hammes, 2005).

Insurgencies often employ terrorist and guerrilla tactics to achieve specific objectives. Although the terms "terrorism," "guerilla warfare," and "insurgency" are sometimes interchangeably, there are differences worthy of discussion. "Most analysts define terrorism as the threat or use of physical coercion against non-combatants to create fear in order to achieve political objectives- Guerilla warfare, by contrast, consists of hit-and-run attacks against police and military and the physical infrastructure that supports them" (Taber, 2002, pg. ix).   Insurgents often employ both of these styles of warfare.

Insurgents often have limited resources in comparison to the opponent and usually refrain from engagements where the insurgent's military resources could be quickly and decisively defeated. Most insurgents are aware that a military campaign consisting of deliberate, sustained, conventional military engagements, against a state sponsored and technologically advance military superpower, would rapidly sacrifice the insurgents' resources. The comparatively limited resources available to the insurgent are why insurgents often employ guerrilla and terrorists tactics as this style of engagement limits risk of a decisive defeat. One decisive defeat of the insurgent force has the potential to cripple their ability to conduct sustained operations. History shows that sustained operation are critical to accomplishment of insurgent objectives.

A key issue and primary objective of an insurgency is the desire to influence political power. “Stated another way, an insurgency is an organized, protracted politico-military struggle designed to weaken the control and legitimacy of an established government, occupying power, or other political authority while increasing insurgent control” (FM3-24, 2006, pg. 1-1). The insurgent seeks to influence the political process and uses every available asset to include guerilla and terrorist tactics to accomplish this goal.

In his book “War of the Flea” Robert Taber defines an insurgency as “ a conflict between a government and an out group or opponent in which the latter uses both political resources and violence to change, reformulate, or uphold the legitimacy of one or more of four key aspect of politics- those aspects are (1) the integrity of the borders and composition of the nation state, (2) the political system, (3) the authorities in power, and (4) the policies that determine who gets what in society” (Taber, 2005, pg. viii).

The 2^{nd} Boer War, 1899-1902

Great Britain has extensive experience with insurgency warfare. The British Empire has been involved in insurgencies throughout the majority of their existence. The Boer Wars are an example where a somewhat conventional military campaign evolved into struggle between a conventional force and an opponent who employed guerilla style tactics. The 2^{nd} Boer War was fought in the present day country of South Africa between the various nationalities within the British Empire, (England, Canada, New Zealand, and Australia), and the Dutch-Afrikaner settlers of the region, commonly referred to as the Boers.

Settlers of Dutch and German decent first settled along the Cape of South Africa in 1652 (Weber, 2007). Britain took over the colony in 1814 and the Boers, refusing to live under British rule, moved north to the highlands and set up an independent republic. Throughout the 19th century the British and the Boers maintained a tense co-existence. During the late 1800's tension increased when the Boers began to suspect the British were positioning themselves for ultimate control of the territory. In 1880 the British and the Boers fought a short indecisive war with the goal of establishing supremacy of the region. When it was determined that the region was rich in natural resources, specifically diamonds and gold, tension again triggered armed conflict.

In 1899 the Boers attacked the British and initiated a four year military struggle for control of the area. The Boer War can be described in three phases. The first phase was from October to December 1899 when the Boers were able to capitalize on the mobility associated with a strong mounted force and were able to defeat the mainly dismounted British Infantry (Australian, 2007). The second phase covered the period from December 1899 to September 1900. British forces mounted a deliberate counter-offensive which resulted in the British gaining control of most of the major towns in South Africa (Australian, 2007). The third phase began in September 1900 and ended in May of 1902. This period of the conflict was basically a guerilla war fought between British mounted troops and Boer irregulars.

Like most insurgency campaigns this period found the larger conventional British forces deployed across the countryside attempting to disrupt Boer activities and enforce British policy. Most engagements consisted of hit and run attacks by small groups of

Boers against larger conventional British forces (Australian, 2007). The British experienced difficulty achieving a decisive militarily defeat of the Boers because they lacked sufficient troops to adequately cover the countryside and therefore were not able to efficiently disrupt Boer activity.

This difficulty is often witnessed when a conventional force is required to engage in the guerilla style tactics witnessed in an insurgency. The British did possess military control of the major population centers but struggled to pinpoint, engage, and eliminate small bands of rebels. The Boers guerillas were difficult to identify, quick to assimilate into the population, and engaged in small harassing engagements where condition usually favored of the smaller force. Although the British eventually prevailed, with the majority of the Boers accepting British occupation and rule, the Boer's caused great frustration for the British through the use of guerrilla style tactics.

Banana Wars

Some believe that the Vietnam War and America's current involvement in Iraq and Afghanistan are America's only experience in insurgency warfare. In actuality, The United States' involvement in insurgency warfare is much more robust than Vietnam, Iraq, and Afghanistan. In the early 1900's The United States became involved in a thirty year Caribbean campaign known as the Banana Wars. During this period America was heavily involved in providing stability to a civilian population, creating a pro-American political system, and defeating armed guerilla style combatants.

The Banana Wars define the period of American history following the Spanish American War, beginning in roughly 1906 and ending in 1934. The foreign policy of the

United States became heavily engaged in the affairs of the Caribbean as well as South and Central America. Specifically, the countries involved are current day Cuba, Nicaragua, Mexico, Haiti, and Dominica Republic.

American involvement stemmed from several issues. These included the financial interests of American entities in the region, security concerns associated with the views of neighboring political leaders, and a strong belief (pre-dating WW-I) that the United States had a right and duty to participate in the affairs in region. As a result America became involved in a large, complex, and sustained, counterinsurgency operation in the Caribbean, Central and South America (Langley, 2002).

The intricacies of individual campaigns during this thirty year war are complicated and beyond scope of this dissertation. What is significant is that the American military, specifically the United States Marine Corps, conducted a sustained and complicated support and stability operation while simultaneously engaged in non-traditional warfare.

Marines were forced to deal militarily and politically with multiple national and regional organizations, each with diverse objectives, and often times with lethal force. The intervention in civil wars, rebellions, or revolutions which leaders of the era usually lump together under the description of “disorder and chaos” routinely turned out to last longer and become more problematic than initially anticipated (Langley, 2002).

American military forces participating in the Banana Wars were attempting to create and strengthen independent governments sympathetic to American interests while providing stability and security to the general population. The United States Marine

Corps was the dominate military force engaged in this campaign. The Marine Corps was forced to develop new doctrine focused on stabilizing and resolving extremely complicated intertwined political and military situations. The lessons learned and doctrine established during this period was placed in print in the US Marine Corps Small Wars Manual published in 1940.

The Small Wars Manual was one of the American military's first counterinsurgency manuals and many of the principles identified remain true today. In the Mission section on Page 2 of the Small Wars Manual it is stated that "In a major war, the mission assigned to the armed forces is usually unequivocal- the defeat and destruction of hostile forces. This is seldom true in small wars. More often than not, the mission will be to establish and maintain law and order by supporting or replacing the civil government in countries or areas in which the interests of the United States have been placed in jeopardy, in order to insure the safety and security or our nationals, their property and interests" (Small Wars Manual, 1940, pg. 2).

The Banana Wars illustrate that insurgent campaigns have the potential to become lengthy military endeavors where a force is required to simultaneously execute a wide variety of operations ranging from stability and support to direct combat. These operations are often intended to defeat a force who wishes to de-stabilize a region, undermine the legitimacy of a government or change a social or political structure.

The Algerian War of Independence, 1956-1962

In 1954 France experienced first hand a religious based Islamic insurgency. This confrontation took place between a portion of the Islamic population in Algeria and the ruling French government. A classic insurgency, this struggle is relevant for inclusion because of some parallels with the Iraq insurgency. This struggle in Algeria ended with the French military and government completely withdrawing from Algeria in 1962 (Riley, 2007).

The war of Algerian Independence began on November 1, 1954 when the guerrilla forces of the National Liberation Front (NLF), an Islamic based organization, initiated several coordinated attacks in multiple locations in Algeria. These attacks were against the military installations, police posts, warehouses, communications facilities, and public utilities (Armed, 2003). It was the stated messages of the NLF to "call on Muslims in Algeria to join in a national struggle for the restoration of the Algerian state, sovereign, democratic, and social, within the framework of the principles of Islam" (Armed, pg 1, 2003). Algeria was a long standing colony of France dating as far back as 1830. Many French citizens considered Algeria an integral part of the French Republic.

France deployed as many as 500,000 troops to Algeria in an attempt to maintain control, but in the end were unable to defeat the roughly 10,000 men of the NLF (Connelly, 2004). As with the Banana Wars the French became consumed with maintaining stability and order among the civilian population, maintaining a pro-French political system of government, and defeating armed insurgents who participated in guerilla and terrorist style attacks. The French, who were militarily superior, became entangled in an intense and complicated military and political struggle. As often the case in insurgent campaigns there was much indiscriminate brutality and blood shed which would strongly influence the position of the civilian population. Although the NLF were never able to control any part of Algeria or decisively defeat the French Army in any military engagement they were able to accomplish their political objectives. The effective use of all available political, social, and military resources enabled the NLF to degrade French political and military will and convince French decision makers that their goals are either too costly or unattainable for the perceived benefit. As a result, in April of 1962 France withdrew from Algeria.

In summary a study of the IED must address the style of warfare associated with its employment. The three historical provide lessons relevant to the conflict in Iraq from which the modern IED problem has evolved. In each case, (2nd Boer War, Banana Wars, and Algerian War) and others not discussed (e.g Vietnam), specialized tactics and weapons emerged which demanded effective counter response.

Improvised Explosive Devices

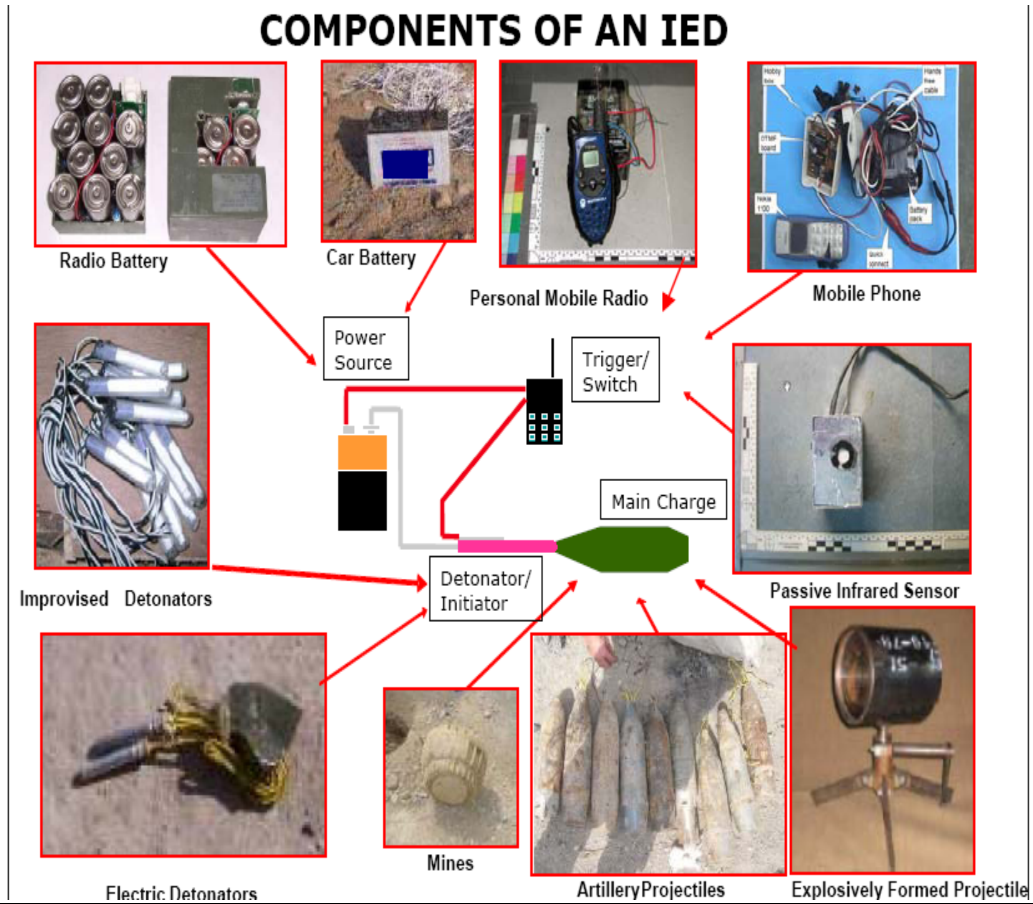
The IED is the weapon of choice of the insurgent because it allows the insurgent the ability to attack under its own terms. IEDs are relatively cheap, simple to construct, and inflicted serious casualties on Coalition personnel in Iraq. This section provides an overview of the fundamentals of IED construction and employment. It is not intended to serve as a "how to" guide to IED construction nor is it intended to make the reader an explosive expert. The information provides a basic understanding of the common types and components of IEDs found on the battlefield in Iraq. All of the information in this section was obtained from unclassified internet sources. (A great deal of information is available on the internet providing information on how to construct an explosive device.) Insurgents have learned that the internet is an effective information distribution source which can be as a venue for distributing IED related information. This section will provide a basic overview of the IED as well as categorical information used in this dissertation for referencing types of IEDs and IED initiation systems commonly found in Iraq. A brief discussion on how insurgent IED cells operate is provided. Additional details specific to the IED device and explosive theory is also located in the Fault Tree development section of this dissertation.

There are several definitions available for an IED. A 2005 congressional report prepared by the Congressional Research Service defined an IED “as a low-technology exploding mine, usually "homemade" that is typically hidden beside a roadway and set off using a variety of trigger mechanisms. IEDs can utilize commercial, military, or homemade explosives, and often the IED builder has had to construct the IED with the materials at hand” (Wilson, 2005). The Australian Army and the Joint IED Defeat Organization defines the IED as “a device placed or fabricated in an improvised manner incorporating destructive, lethal, noxious, pyrotechnic, or incendiary chemicals and is designed to destroy, incapacitate, harass, or distract. It may incorporate military stores but is normally devised from nonmilitary components” (Australian Department of Defense, 2008 and JIEDO 2008). Common to both definitions is that the explosive device is a “homemade” or “fabricated” device constructed from a variety of materials and is intended to explode and cause some type of injury or destruction.

IEDs have four main components. These components are the power source, the trigger or switch, the detonator, and the main charge (Australian Department of Defense, 2008).

- The Power Source: Usually a battery, the power source is what provides the initial supply of energy to the IED used to initiate the explosion sequence.
- The Trigger: This is the mechanism which initiates the IED detonation. Triggers are generally one of three types; the remote or radio controlled initiation system, the command wire initiation system, or a victim operated initiation system.
- The Detonator: This is a device which usually contains a small amount of explosives and which upon receiving an output from the trigger is used to initiate the main explosive charge.
- The Main Charge: This is the main explosive component of the IED. The main charge can usually be broken down into three categories depending on the materials used for construction, and are: Military Munitions, Conventional Explosives, and Homemade Explosives.

Figure 2.8: Components of an IED (Australian Department of Defense, 2008)



The IED Main Charge

As is the nature of the device, the main charges of IEDs found in Iraq have been constructed out of a variety of materials and explosives. The main charge can be generally classified into three categories and are done so within the body of this research. The categories used are based on a description of the composition of the main charge.

Conventional military munitions describe a category where the main charge of the IED is comprised of a military ordnance of some type. Military munition IEDs consist of IEDs where the main explosive component consist of a conventional munition employed in a modified method and functions in manner different from the original design or intent. There are many cases where artillery rounds, land mines, and mortars have been modified and used as the main charge of an IED. These types of IED are common in Iraq as a result of the large military stores present in Iraq at the beginning of OPERATION IRAQI FREEDOM. At that the beginning of OPERATION IRAQI FREEDOM there were thousands of caches of military munitions throughout the country containing an estimated 650,000 to 1 million tons of explosives (Atkins, 2007).

The Conventional Explosives category of IED describes the use of conventional explosives as the primary explosive component of the main charge. In this category the explosive component is some type of commercially manufactured explosive. Examples of commercially manufactured explosives are TNT, dynamite, black powder, plastic explosives (C-4), or the explosive material extracted from a military munition. In 2006 investigators in Iraq noticed that bombmakers were using acetone to remove the explosive materials from artillery rounds. This process allowed the explosive component to be molded into more portable shapes and concealable containers which could be more easily concealed and placed (Atkins, 2007).

Figure 2.9: IED Main Charge Constructed out of Military Munitions (U.S. Department of Defense, 2005)

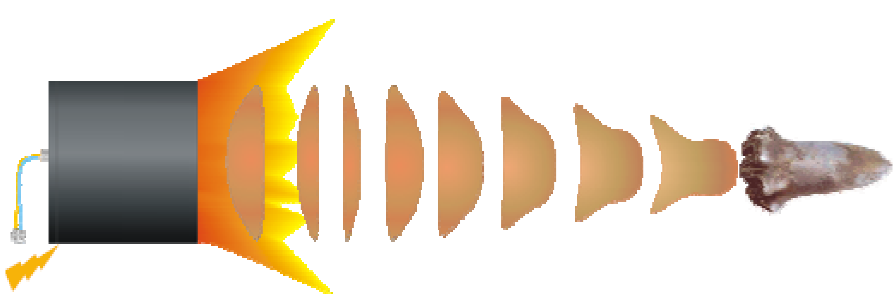
The main charge of an IED can also be constructed from homemade explosives. These are derived from common commercial products and chemicals. Potassium chlorate, peroxide, ammonium nitrate, aluminum powder and urea nitrate can all be used to create a high explosive material.

When required, insurgents have been known to use homemade explosives developed from the nitrate component found in fertilizer. The explosive is mixed in large containers like children’s swimming pools and then dried on the rooftops of houses and placed in large sacks (Atkins, 2007).

A unique type of IED found in Iraq is the Explosively Formed Projectile or (EFP). Some experts define an EFP as an independent category however for the purpose of this dissertation an EFP is considered a conventional explosive as based on the explosive material commonly used in the main charge. An EFP is unique type of improvised device which, when correctly constructed and employed, has the capability to penetrate some of the armor found on military vehicles.

Often created from copper, an EFP is created by placing circular metal disc of specific material and shape usually measuring between two inches to 11 inches in front of a high explosive which is densely packed behind the metal disc. When the explosive is detonated the explosive wave moving in excess of 8,000 meters per second transforms the metal disc into a metal slug traveling at several thousand meters per second (Atkins, 2007). An eight inch diameter copper EFP was recorded to have thrown a seven pound slug at six times the speed of sound, or over 2000 meters per second (Atkins, 2007). By comparison, a .50 caliber bullet is one of the most lethal rifle projectiles used by the military. A .50 caliber bullet weighs approximately two ounces and travels at a maximum speed of 900 meters per second (Atkins, 2007). Figure 2.10 describes the explosive sequence of an EFP.

Figure 2.10: Diagram of EFP Operation (Australian Department of Defense, 2008)



The IED Trigger

As discussed earlier the trigger is the component which actually detonates (or initiates) the IED. The method used to trigger an IED is only limited by the imagination and experience of the IED maker and the materials at hand. For the purposes of this dissertation IED triggers are defined in three separate categories relating to how the trigger is activated. The three categories are remote initiated, command wire initiated, or victim operated triggers.

Remote initiation systems (also referred to as radio controlled initiation systems) rely on radio waves to transmit a signal from the triggerman to the device. The trigger is activated when the device receives a specific radio signal. An insurgent with a remote transmitter can send a firing signal to a receiver located several hundred meters, or miles, depending on the power of the transmitter. The receiver which is linked to an electronic firing circuit causes the detonation of the device. Key fobs, cell phones, walkie-talkies, remote controlled cars, wireless doorbell buzzers, and cordless phones have all been used as remote initiation systems in Iraq (Atkins, 2007). The stand-off the triggerman can achieve with a remote initiation system is dependant on a variety of variables to include the power of the transmitter.

The Coalition has expended a great deal of effort to deny the use of remote initiation systems in Iraq through the use of radio jammers and other technologies. This effort continues today.

With Command Wire initiation systems the triggerman initiates the device by sending the firing signal through some type of command wire. Command wire system are usually copper but can be any a material that is capable of carrying an electric signal. A typical command wire firing system would include an electric blasting cap connected to the main charge of an IED. The electric blasting cap is connected to a copper wire which traces back several hundred yards to the insurgents firing location. At the appropriate time the insurgent initiates the system by attaching the copper wire to a battery which sends an electric current to the electric blasting cap causing the main charge to detonate.

Victim operated initiation systems describe an initiation system which is in some manner activated by the intended victim of the device. This action can be stepping on a pressure plate, tripping a trip wire, or activating a motion detector. Firgure 2.11 is a picture of a pressure plate type initiation system. The pressure plate operates on the principle that when the two metal plates are pressed together to make contact, as would occur when run over by a vehicle tire, or stepped on by a soldier, the two metal plates connect. This connection of the two metal plates completes an electronic firing circuit which causes the IED to detonate. Victim operated initiation systems are placed in close proximity of the main charge.

Figure 2.11: Example Pressure Plate/Victim Operated Initiation System (Department of Defense, 2008)

Passive infrared detectors are another type of victim operated initiation system. An infrared sensor, which is connected to a firing system, detects a heat signature from a person or vehicle. When the detector senses the heat source a firing command is sent to the device (Atkins, 2007).

Insurgents organize IED efforts and personnel into IED cells. The IED cell is usually comprised of five to ten members each of whom performs a specific function relating to an IED attack. Each member has a specific function and often includes a financier, bomb maker/explosive expert, placement personnel, triggermen and sometimes a cameraman. IED cells often videotape their exploits to be used as a propaganda tool in the insurgency. It is thought that in 2007 there were approximately 160 different IED cells operating in Iraq (Atkins, 2007).

There have been thousands of variations of the IED used by insurgents in Iraq. There are an infinite number of variations which can be used to construct and detonate an IED. The type of IED constructed is dependent only on the creativity of the cell and the bomb maker and resources available.

CHAPTER 3: RESEARCH METHODOLOGY

Introduction

As described earlier the overall research project identifies and analyzes specific variable relationships related to an IED incident with the aim of effectively combining the principles of Fault Tree modeling, Geographic Information Systems (GIS), simulation, and military doctrine to present a Fault Tree based process which can be used to anticipate IED activity. The information learned will be consolidated into a multi-step IED prediction process which can be applied to any threat force and region in the world.

This chapter explains the methodology as well as the anticipated end result of this study. This study is conducted with intent of developing a framework which can eventually lead to the anticipation of IED locations by development of a Fault Tree based process for analyzing IED activity. The information included in this study is presented for consideration and further development by those organizations interested in IED threat prediction and which possess the data and resources to fully validate and utilize the concepts contained in this study.

Research Questions and Hypotheses

This research will be presented in two phases relating to three specific objectives: (1) identification of IED variables and variable relationships, (2) integrating threat data with the a Fault Tree model and visualization assets, and (3) development of a process which can be used by decision makers involved with C-IED operations to understand threat activity and identify potential threat locations.

The Fault Tree Model is the foundation for this research and the model in which all related activities are based. The Fault Tree will illustrate the interaction of identified variables, provide a platform from which to integrate threat information and incorporate visualization software, and is the baseline entity from which a decision support process is developed. The information derived from this research is presented with suggested implementation guidance intended to describe to those associated with C-IED operations how to fully utilize and understand the real world application of the concepts and theories addressed in this dissertation.

This research project will prove or disprove three separate hypotheses relative to the use of the Fault Tree Failure Model, the locations of Improvised Explosive Devices, and the use of visualization assets in threat prediction. These hypotheses are subjective in nature.

The first hypothesis (the details of this hypothesis have been removed for purposes of publication) is associated with establishment of identifiable variables and variable relationships between specific events associated with a successful IED incident against a military vehicle on a road. Through the establishment of these variables and relationships information can be obtained which will allow for the identification of IED locations. H1o represents the first null hypothesis where H1a represents the first alternative hypothesis. IEDV represents IED variables and IEDL represents decision IED locations.

$$H1o: IEDV = IEDL$$

$$H1a: IEDV \neq IEDL$$

The second hypothesis is that a Fault Tree based model can be used as a decision support tool in C-IED operations and in the prediction of IED activity. Specifically, employment of a Fault Tree based process can serve as an effective decision support tool with multiple applications including anticipation and identification of IED activity and locations. The null hypothesis for this question can be stated as a Fault Tree model equals a beneficial IED decision support tool. The alternative hypothesis can be written as a Fault Tree model does not equal a beneficial IED decision support tool. For this hypothesis H1o represents the first null hypothesis where H1a represents the first alternative hypothesis. FTM represents the Fault Tree Model and DST represents decision support tool.

$$H1o: FTM = DST$$

$$H1a: FTM \neq DST$$

The third hypothesis is presented to determine the effectiveness of various visualization assets in the identification of IED locations and evaluate their utility in C-IED operations. It is also intended to help guide research activities. It is believed that a visualization tool can be integrated with the Fault Tree in an effective manner to provide clear and understandable information relative to threat locations. Specifically when required, visualization platforms can be us in conjunction with the Fault Tree to translate data into a visually recognizable location. The null hypothesis for this question can be stated as visualization assets can be integrated with a Fault Tree to visualize anticipated IED locations. The alternative hypothesis can be written as visualization assets can not be integrated with Fault Tree to visualize anticipated IED locations. For this hypothesis

H1o represents the first null hypothesis where H1a represents the first alternative hypothesis. VFT represents the integration of visualization platforms and Fault Tree and AIEDL represents anticipated IED locations.

$$H1o: VFT = AIEDL$$

$$H1a: VFT \neq AIEDL$$

<u>Design of the Research</u>

It is emphasized that this research is theoretical and general in nature using a hypothetical data set as well as information collected through open source channels such as the internet, journals, books, and articles. Due to the sensitive nature of IED incident information real world data from Iraq and Afghanistan cannot be used. No classified or official information is used.

<u>Phase 1: Fault Tree Development</u>: This phase provides the foundation of this research and is dedicated to the detailed analysis and of the IED threat. This provides the foundation from which all IED research is based and is essential to understanding IED activity.

A Fault Tree Failure Model is used to identify and understand the variables and the relationship between the variables which are present during an IED attack. Specifically, a Fault Tree Failure Model will be developed which will identify the variables present for a failure to take place. In this case a failure is defined as an IED attack against a military vehicle on a road network. Information pertaining to the specifics of each attack can be analyzed, integrated, and compared to threat data in order to anticipate threat activity and can be effectively used as a decision support tool for those involved in C-IED operations.

As discussed in the Literature Review section the Fault Tree will describe the interaction (through the use of “and gates” / “or gates”) of variables present during a failure. By understanding the components necessary for an IED incident to occur, Fault Tree principles, and variable interaction it will be possible to create a Fault Tree that illustrates a top down description of what events and components must be present for a failure to occur. This will be developed as a logical framework constructed by focusing on the question, in order for this event to take place, what must happen?

Once the basic Fault Tree is created, numerical probability information specific to each variable can be integrated into the Fault Tree and the minimal cut set will be determined. The minimal cut set will be determined through the principles of Boolean Algebra and with the assistance of a computer program called Relex Architect. Relex Architect aides in the graphical representation of a Fault Tree and the computation of complex minimal cut sets. The minimal cut set will determine the overall probability of a failure for specific criteria as well as illustrate which combination of variables has the highest probability of contributing to an overall event.

<u>Phase 2: Implementation Guidance:</u> Once the Fault Tree is complete a process will be developed to serve as employment guidance on how to use the Fault Tree as a decision support and threat prediction tool. Phase 2 is described in two sections: Phase 2(A) Process Overview, describes a general process for using the Fault Tree model in C-IED operations. Phase 2(B) Theoretical Case Study, utilizes a hypothetical scenario to

illustrate described process and integration of threat data with the Fault Tree and visualization assets.

Since real-world IED attack information is not available a hypothetical data set is presented to provide numerical information to illustrate the variable analysis process. The data set is created by identifying several theoretical IED attack locations in the city of Richmond Hill, Georgia. Richmond Hill was selected as it provides the author an opportunity to test the feasibility of the proposed data collection techniques and requirements.

Visualization assets are included to illustrate a method of translating threat data and Fault Tree exposure information into visually identifiable areas. Two visualization software packages are used in this study. The transportation simulation software package Paramics and the GIS package ArcInfo. The visualization models are intended to provide clarity to the process and allow for easier interpretation of location information.

Summary of Research Methodology

The two research phases of this dissertation are intended to illustrate a new way of analyzing the IED threat by utilizing a Fault Tree Failure Model to understand the IED environment, identify variables present during an IED incident, as well as the interaction and relationship of identified variables. Once the variables have been identified, the relationship established, a process is developed to describe how the proposed concepts can be used as a decision support tool to anticipate IED activity and threat locations.

The proposed process is intended for consideration and use by those engaged Counter-IED activity.

Due to the sensitive nature of real-world IED data only unclassified open source data was used. This study is intended to provide a description and framework for ultimate validation by those with the resources and information available to fully test the suggested process. It is strongly believed that the theories described in this research initiative are worthy of consideration and further development.

CHAPTER 4: ANALYSIS OF RESEARCH AND FINDINGS

The information contained in this chapter has been removed to allow for open publication.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The information contained in this chapter has been removed to allow for open publication.

APPENDICES

The information contained in this section has been removed to allow for open publication.

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