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EXPLORING FIRST RESPONDER TACTICS IN A TERRORIST CHEMICAL ATTACK

by

Kong Pin Gilbert Foo

December 2008

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**EXPLORING FIRST RESPONDER TACTICS
IN A TERRORIST CHEMICAL ATTACK**

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THESIS DISCLAIMER

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

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LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

AAR	After Action Review
ABS/ABM	Agent-based simulation / Agent-based modeling
AMSAA	Army Materiel Systems Analysis Activity
ANFO	Ammonium Nitrate Fuel Oil
AFRL	Air Force Research Lab, United States
C2/C3	Command and Control/ Command, Control and Communications
CA	Chemical Agent
CAD/CAM	Chemical Agent Detector / Chemical Agent Monitor
CEP	Circular Error Probable
CIED	Chemical Payload, Improvised Explosive Device
CBRD	Chemical, Biological, Radiological Defense
CBRE	Chemical, Biological, Radiological and Explosive
CBRE DG	CBRE Defence Group, Singapore
CSV	Comma-Separated Values
DOE	Design of Experiment
EOD	Explosive Ordnance Disposal, Singapore
EMS	Emergency Medical Service
EMT	Emergency Medical Team
FRC/V	Fast Response Car/Vehicle
FTX	Full-Troop Exercise
GUI	Graphic User Interface
ICP	Incident Command Post
IED	Improvised Explosive Device
IM	Incident Manager
IPE	Individual Protective Equipment
IT	Influence Tool
JI	Jema’ah Islamiah

KE	Kinetic Effects
LCt50	Lethal Concentration over one min, 50% of population death incurred
LOS	Line-of-Sight
M&S	Modeling and simulation
MAS	Multi-Agent Simulation
MHA	Ministry of Home Affairs, Singapore
MINDEF	Ministry of Defence, Singapore
MOE	Measure of Effectiveness
MOH	Ministry of Health, Singapore
MOP	Measure of Performance
MTRY	Monterey
NOLH	Nearly Orthogonal Latin Hypercube
NSCCC	National Security Coordination Centre, Singapore
PACOM	Pacific Command, United States Navy
PSI	Pounds per Square Inch
PTU	Police Tactical Unit
RC	Restorative Capability
SCDF	Singapore Civil Defence Force
SMG	Submachine Gun
SMRT	Singapore Mass Rapid Transit
SOC	Special Operations Command
SPF	Singapore Police Force
SAF	Singapore Armed Forces
TATP	Tri-acetone Tri-peroxide
TOPOFF	Top Official, US
TRAC	United States Army Training and Doctrine Command Analysis Center
VBIED	Vehicle-Borne Improvised Explosive Device
XML	Extensible Markup Language

EXECUTIVE SUMMARY

The Republic of Singapore values the importance of multiagency exercises as a critical part of "Total Defence," particularly when local, regional and global security trends over the past seven years require increased vigilance from Singapore's defense and security agencies. While Singapore adopts a multilevel approach to implement counterterrorism measures, its security agencies continue to acknowledge the complexities of a joint emergency response. These complexities arise out of the need to take into consideration all dimensions of its society in the creation of counterterrorism measures, such as military defense, internal security, border and infrastructure security, civil defense, medical readiness, and psychological preparedness. At the heart of these counterterrorism measures is the need to establish clear roles and actions for all agencies during a confirmed incident.

The Singapore Armed Forces (SAF), in conjunction with the Singapore Ministry of Home Affairs (MHA), have conducted three major exercises in the past involving nonconventional terrorist attacks against an urban population setting, the most recent being Exercise NorthStar V. The nature of such efforts are neither unique to the country, nor have they been implemented recently, as many developed countries that demonstrate established frameworks of emergency preparedness and response, engage in large-scale emergency exercises. The dynamics and aftermath of the September 11 attacks, however, as well as the London train and bus bombings, show that no exercise can fully inoculate a populace against a terrorist event.

A major caveat of large scale, full-troop exercises is that such organized events alter their test environments by introducing administrative elements and invariably contaminate exercise evaluation results when troops and exercised elements interact with administrative elements. In addition, it is common for the political and social objectives of a public exercise to gain more emphasis than the learning goals of the event, resulting in these exercises becoming nothing more than a panacea against terrorism.

It would therefore be prudent to accept the limitations of mass exercises and acknowledge the need to augment their value with additional analysis tools.

Modeling and simulation (M&S) has become an important enabler for military experimentation. It is therefore timely that the Singaporean National Security Coordination Centre (NSCC) is also interested in using data mining techniques, such as the efficient use of information and high-performance computing (HPC), to enhance national security. This study proposes that, with the use of HPC as a key technology enabler, a simulation can be generated for urban military and counterterrorist operations, given a specific terrorist threat (such as improvised explosive devices) and area of operations (such as high-risk public and private buildings). Findings from such a design could help improve real incident response.

This study applies a suitable M&S technique to analyze a theoretical scenario. The intent is to gain additional insights into the interactions between civilian behavior, the tactics, techniques and procedures (TTPs) of emergency responders, and the impact of chemical agent effects on both civilian and first responder populations. The objectives are to apply a suitable computer simulation technique to analyze a multiagency emergency response to an improvised explosive device with a chemical payload (CIED) in Singapore. The establishment of a suitable framework for achieving this can extend to the assessment of installation-specific consequence management, the design of chemical, biological, radiological and explosive (CBRE) support operations, and multi-agency planning. The use of agent-based simulation (ABS) allows for the potential observation of emergent behaviors in a scenario, granted the requirement that the simulation appropriately represents the key behaviors under study. For the purposes of this study, analysis is conducted on the immediate response by Singaporean police, civil defense (medical and fire service), and military CBRE to a theoretical activation of a CIED along a major shopping belt in downtown Singapore, and scoped to the following research questions:

- How feasible are existing operational templates, TTPs, and information-making processes?
- How robust are current procedures for containing civilians exposed to chemical agents?
- What factors influence the efficiency of emergency response procedures?

- To what degree does civilian compliancy affect the performance of casualty treatment?

To design a believable scenario for the simulation, the study refers to several major regional and global incidents, as well as the open source details on Exercise NorthStar V. The simulation models the acute phase of the emergency response, a multisided event that sees various interactions between the affected environment, the populations involved, and the leadership available in these conditions. Given these considerations, several features in Pythagoras 2.0.3—an agent-based platform that was initially developed under the United States Marine Corps' (USMC) Project Albert, lend themselves well to the simulation of a crisis response. A visualization of the resultant simulation model generated in Pythagoras is shown in Figures ES1 and ES2.

Figure ES1. Global view of scenario map generated for study, illustrating isolation zones and approaches of different emergency response elements.

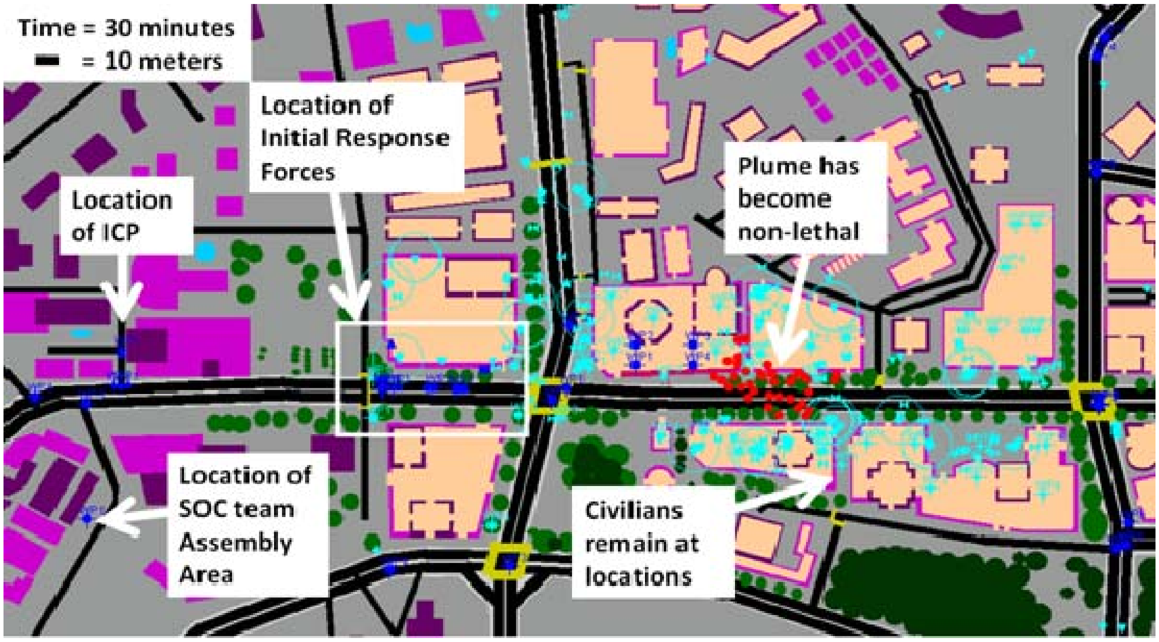

Figure ES2. Enlarged view of incident site activity after 30 minutes into the response, showing the location of the chemical hazard (in red), civilians (in cyan) and emergency responders (in blue).

The experiment involved data farming techniques that used high-performance computing (HPC) to generate data from multiple experimental design points. Specific design parameters, selected as variables, are varied systematically and efficiently in an efficient way to broadly explore the experimental design space and the interactions between various factors. The primary measure of effectiveness (MOE) of interest is the change in survivorship of the civilian population with the emergency response, the improvement of which is determined in this study as the primary focus of the emergency response. Four incident conditions were studied using the same experimental design techniques;

- A simulation without emergency response;
- A theoretical activation of an indoor CIED with an emergency response to the incident site;
- An outdoor activation of the same CIED, and
- A response to a Vehicle-Borne IED (VBIED).

As the primary DOE technique, the study used a “Combined Nearly-Orthogonal Latin Hypercube” (NOLH) design, using both controllable and uncontrollable factors in the NOLH configuration. Scenarios were run on the Air Force Research Laboratory (AFRL) HPC cluster. Two prototypes, four full scenarios, and one re-run were submitted, totaling 16,460 design point replicates. Nineteen uncontrollable factors, representing the environment outside the influence of the responders, were analyzed to determine the most influential factors. To enable a more robust analysis, these were implemented with 21 controllable factors related to the emergency response, generated a 29-factor combined NOLH experimental design. The completion of all experimental runs, including administrative time, error correction and re-submission, took only 32 days using the HPC cluster.

Data analysis of the simulation results determined the following:

- With respect to the percentage of civilians injured by an indoor CIED incident, there is a statistically significant, but marginal increase associated with emergency response activation. The few actions associated with a statistically significant decrease in the percentage of civilians injured only improve the percentage injured by 1 to 4%.
- The follow-on force, particularly with respect to the patrol officers who conduct much of the site clearance, must complement the efficiency of the initial first response car (FRC) patrol officers. The Incident Manager should compensate for a less effective effort in the initial response by the FRC patrol officers, or an operational situation that hinders police influence, with more follow-on police officers. An increased maximum influence on the part of the patrol officers is positively associated with a reduction in the average percentage of injured civilians, subject to a reduction in influence by the special operations command (SOC) tactical officers.
- To limit the potential increase incurred with an emergency response, factors that prevent the exacerbation of civilian injuries include the earlier entry time of first responders and follow-on police officers, the reduced maximum influence of SOC tactical officers, and potentially the later arrival of larger elements from the Singapore Civil Defence Force (SCDF).
- The early arrival of response elements, particularly security cordon and decontamination elements may inhibit the civilian intentions for self-preservation. The data suggests the association of lower average percentage of injured civilians with the later arrival of such elements, and vice versa. Interestingly, the earlier arrival of follow-on police officers is always associated with positive gains.
- No direct association of medical assets is observed in the statistical analysis for CIED incidents. If there is any influence, the possible response is likely to

tend towards reducing mean percentage deaths and transferring the saving of civilian lives to an increase in the mean percentage injured.

- Panic associated with the incident site demonstrates itself in varying degrees. In the context of the simulation, the representation of panic is subject to sequestering and proximity to the incident site.
- Increasing chemical agent detector (CAD) broadcast range is beneficial in scenarios involving a chemical agent (CA). This ranges from six to nine meters.
- For a VBIED incident, the early arrival of security and cordon elements before the SCDF leader and his associated elements may be significant in limiting civilian injuries.

Following the analysis, the study reaches the below-mentioned conclusions to the initial research questions:

- Assessment of the feasibility of the response gave some counter-intuitive results. When focused on improving civilian survivorship, simulation results prove inconclusive in showing any statistical difference between civilian deaths incurred from an indoor CIED incident and subsequent emergency response, vis-à-vis no response. The percentage of civilians injured associated with the emergency response to the same device prove significantly higher than would be expected with no response. Key actions associated with the response, however, are inversely associated with a decrease in civilian casualties. In general, earlier arrival of the first responders improves civilian survivorship, while increased influence over the population by security forces serves to increase civilian injuries.
- Current procedures are robust as the flexibility of the initial and follow-on configurations allow Incident Managers (IMs) and response force leaders to manage the consequences of complications, in the time and compliancy domains. If a direct relationship is assumed between the responses and the experimental factors, then several follow-on actions can be implemented to compensate for problems reducing responder arrival time and civilian compliance. The entry time of the first responders composing the initial response is a significant factor in limiting the exacerbation of casualties at the incident site. The maximum influence that each response forces exerts on the affected population should vary in relation to the impact it has on the civilians. Security and cordon elements should be careful in limiting their control of the population. Rescuer influence should be slightly greater than that of patrol officers.
- Assuming that the civilian behavioral model is valid, the intrinsic compliancy of civilians is not as dominant a deciding factor of civilian casualties, as much as the size of the population is. This suggests that irrespective of his

compliance towards an emergency response, the civilian is likely to be able to find a way to escape the hazard. Public compliancy towards emergency responders should, therefore, not be a primary concern to emergency planners, who should focus instead on the proper identification of persons affected by the incident.

Major obstacles, preventing the use of Pythagoras Agent Based Modeling (ABM) for studying emergency response procedures to a terrorist chemical or explosive attack, include:

- The exponential increase in simulation run time with larger scenarios,
- The man-hours required to generate large, new maps, and
- The need to accommodate for caveats in the decision-making processes of individual agents in Pythagoras.

In addition, future research efforts that may expand out of this study include the following:

- Simulation and analysis of the effectiveness of medical decontamination and support during an emergency response.
- Simulation and analysis of secondary device search during an emergency response.
- Analysis of human intangibles via low-resolution simulation.
- Command, Control, and Communications (C3) analysis for emergency response.
- Scenario analysis for a multi-pronged terrorist incident.

This study represents a combined analysis of emergency response procedures, crowd behavior, and a non physics-based simulation of chemical release and IED effects. Granted, the findings are controversial and prompt more questions than they can currently answer. The insights, data, and calculations performed here, however, provide a good foundation for planning and analyzing effective response from an operational research point of view.

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ACKNOWLEDGMENTS

"Dulce et Decorum est"

First, I thank Our Lord God for His grace and mercy, in sending His Son down to die on the cross, in propitiation for our sins. It is by His grace that He surrounds me with the people in my life. It is through His manifold wisdom that I understand the purpose of the work open before you now. For this, I give thanks.

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It is also fitting that I thank my family—my parents, for doing their best; my brothers Edmund and Kelvin, because we stuck it out together. They never had any expectations of me, so they gave me no boundaries to what I could achieve. Thanks also go to Dr Ivan Lim and brethren at NLBPC for their trust, support, thoughts and prayers.

My friends and colleagues, this acknowledgement bears your names because of your help and influence in this finished work, my career, and my life, as much as I hope to make a difference in yours. Thank you all.

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I. INTRODUCTION

Knowing how to exploit the potential of technology will help us to create new solutions to deal with emerging security challenges. The increasing sophistication of IT systems now makes it possible to conduct complex analysis of massive amounts of data. Data mining, link-analysis technologies and sophisticated intelligent systems can help to provide us with early indications of threats and opportunities.

Professor S. Jayakumar,
Deputy Prime Minister, Coordinating Minister for National Security
and Minister for Law, 27 March 2007

A. BACKGROUND

The Republic of Singapore values the importance of multiagency exercises as a critical part of their nation's "Total Defence" framework. This framework comprises military, social, psychological, economic and civil defense. Since realizing that Southeast Asia would continue to evolve into a major theater for terrorist operations, Singapore has had to become more proactive in dealing with transnational threats (Boey, 2006). Its military and para-military forces conduct island-wide exercises on an annual basis to establish and maintain cooperation across different government services. Normally, the Singapore Armed Forces (SAF) is responsible for island defense, with the Singapore Police Force focusing on internal security and the Singapore Civil Defence Force (SCDF) dealing with major civil emergencies. These exercises are platforms for Singapore to demonstrate its defense capabilities to both its populace and international observers. Such events would typically be conducted with a military or para-military agency as the main coordinating authority.

1. Chemical and Explosive Terrorist Devices

Global and regional security trends over the past seven years now require increased vigilance from Singapore's defense and security agencies. Homeland security elements now adopt a global and regional approach to assess terrorist trends on their likelihood of occurrence in the country. For example, recent chlorine tanker truck attacks in Iraq demonstrate their feasibility as a crude chemical weapon (Multi-National Corps – Iraq, 2007a, 2007b). In response to this, the SCDF has implemented satellite tracking and vehicular immobilizers for all land-based hazardous cargo carriers (Sua, 2007). Similarly, the 2004 Madrid and 2005 London train bombings (The Stationary Office, 2006) demonstrate the technical sophistication of terrorists and their shift towards a campaign targeting public transport systems. The result of this is the establishment of a transit police department, specifically focused on patrolling Singapore's extensive underground train system, as well as an extensive media blitz to educate the public on their role in countering attacks in these public places.

Domestic terrorism falls under equal purview. For example, in 2006, an incident occurred involving an incendiary device released a "stinging smoke" after being left on a public bus (Teh, 2006). In a separate incident, the accidental release of gaseous chlorine at a recreational club in a residential part of Singapore sparked panic and concern over the security of public and private establishments, causing an outcry on whether establishments were prepared in the event of a terrorist attack (Chong, 2005). Public concerns continue to persist over the country's readiness against a real chemical attack; a good example of which is the 1995 Tokyo subway attack (Kaplan, 2000).

Perhaps nothing else can summarize Singapore's need for vigilance in peacetime than the realization of the Jema'ah Islamiah (JI) terrorist network's plans to attack several Singaporean and U.S.-related targets in 2002, as part of an assumed collaboration with al Qaeda (Internal Security Department, 2003). To this day, authorities have no confirmation on the whereabouts of four tons of ammonium nitrate fertilizer procured by JI, which was initially meant for the construction of truck bombs to be used in Singapore and the region. Singapore, however, continues to be associated with the West, and thus is an "ally of the enemy" to Islamic extremists. This is reason enough for first responders and their parent agencies to conduct interagency exercises, thus enabling a combined effort against such possible events in the future.

2. Incident Response and Management in Singapore

While Singapore adopts a multilevel approach to implement counterterrorism measures, its security agencies acknowledge the complexities of a joint emergency response. These issues arise out of the need to take into consideration all dimensions of its society in the creation of such measures, such as military defense, internal security, border and infrastructure security, civil defense, medical readiness, and psychological preparedness. At the heart of this is the need to establish clear roles and actions for all agencies during a confirmed incident. For example, the Ministry of Home Affairs (MHA) educates the public on the measures and responsibilities of the individual citizen in the event of a possible attack, with the hope that better public knowledge will improve emergency response. The SAF maintains chemical, biological, radiological, and explosives (CBRE) defense and response capabilities on a high-readiness standby, which are activated in response to improvised explosive devices (IEDs) and weapons of mass destruction (WMDs), as well as post-blast investigation teams that facilitate forensic analysis of bombing incidents. The Singapore Police Force has a dedicated tactics team to deal with terrorist incidents and has revamped its service with operational and logistical support in preparation for counterterrorism operations.

These efforts are neither unique to the country, nor have they been implemented recently. The United Kingdom, Australia and the United States, each with an equally sophisticated security framework, put as much emphasis on their own emergency response exercises as Singapore, if not more so. The dynamics and aftermath of the September 11 attacks, however, as well as the London train and bus bombings (The Stationary Office, 2006) show that no exercise can fully inoculate a populace against a terrorist event.

B. EXERCISE NORTHSTAR V

> *It's a little bit artificial…you assume that people will take two hours to turn up…now they turn up in 10 minutes.*
>
> *Hiccups are always welcome because we can learn from them. We find the bottlenecks and deal with them.*
>
> Khaw Boon Wan
> Health Minister, Ministry of Health
> on Exercise NorthStar V

The SAF, in conjunction with the Singapore Ministry of Home Affairs (MHA), have conducted three major exercises in the past involving nonconventional terrorist attacks against an urban populated setting. The most recent exercise, NorthStar V (Henson, 2006), involved a scenario similar to the London bombings demonstrating a multiple-location attack on the island's public bus and rail public transport system (Singapore Civil Defence Force, 2006).

As it is common for the political and social objectives of a public exercise to gain more emphasis than the learning goals of the event; lessons learned from table-top exercises (TTX) conducted prior the actual full-troop exercise (FTX) are retained to augment the lessons learned during the FTX. In the case of NorthStar V, 170 officers from participating agencies conducted an indoor planning exercise prior to the FTX (Sua and Goh, 2006), to expose and correct operational and administrative gaps in a multiagency effort. This activity is driven by the need to publicly demonstrate that responding agencies have the capacity to respond seamlessly, allowing Singapore to "remain an oasis of safety" in a region threatened by terrorism (Ng, 2006). Nonetheless, for any "emergency-preparedness exercise" to be effective, certain elements must be fulfilled. One point is the suspension of the participants' "disbelief," by creating enough "exercise realism" to facilitate exercise troop responses close to real operations. Since exercise planners and organizers have little control over this factor, more resources are channeled towards implementing the following three aspects, which are kept in consideration to ensure that not only exercise objectives are successful, but that they also remain relevant.

1. Stressing of the Emergency Response System

Overloading systems and processes in an emergency response helps determine weaknesses inherent in existing protocols. Doing so exposes process and organizational flaws that may not otherwise demonstrate themselves at lower workloads.

2. Effective After-Action Review

The documentation of lessons learned from an exercise entails a separate collection agency called the neutral observer, charged with the sole responsibility of reporting key observations and critical operational shortcomings. Nonetheless, under-reporting and the omission of the neutral observer's findings can occur. The modernization of military instruction and doctrine development in the SAF has encouraged the central reporting of findings to a separate exercise control group. At times this agency may not have the capacity to influence the implementation of change in doctrine or established standard operating procedures (SOPs), which are commonly assigned to the agencies at the forefront of the response, and hence, the primary participants in an exercise.

3. Review of Lessons Learned

Commonly, evaluators address lessons learned in an exercise as soon as possible to determine if proposed solutions really work. Otherwise, their documentation serves as a reference for the following year's exercise. Roginski (2006) describes this in the United States context for Exercise TOPOFF, emphasizing the need for quick documentation, implementation, and comprehensive analysis at the end of the major exercise to gain final insights into the qualities of the response. Similarly, for the SAF, the SAF Operations and Training Hub implements a sound series of training and evaluation processes to ensure that as many beneficial lessons as possible can be learned.

C. THE PANACEA OF PUBLIC EXERCISE

A major caveat of large-scale, full-troop exercises is that such organized events alter their test environments and invariably contaminate exercise evaluation results. Locations are made accessible and are cordoned off, the public is given several days' notice on what to expect during the exercise, and (as in the case of NorthStar V) a high degree of civilian compliancy is observed. It would be difficult to gauge whether control over the public is the direct result of personnel operating directly in exercise roles or simply because the civilians have already preempted their roles in the context of an exercise.

For example, a public poll by a major news agency in Singapore suggested that although the majority of Singaporeans believe that a terrorist attack can occur in Singapore, only 50% of them truly know what to do in the event an attack occurs (Boey and Tan, 2006). While public exercises are rare, there needs to be a way to understand the implications of civilians on emergency first response, a caveat that cannot be completely observed by elaborate exercises. For example, in NorthStar V, the public was prewarned that the exercise would be held during a weekend in January, 2006, and the participating agencies were given as long as six months to prepare. The exact date, time and locations of the exercise were not disclosed until 15 minutes before the drill commenced, but the expectation of the exercise is reason enough for the populace to respond accordingly and comply with responders and support staff when encountered.

In addition to the caveat described above, several operational issues prove difficult to solve or even observed in a controlled exercise, and may not be answered easily without a fair degree of subjective assessment.

1. Friend or Foe Identification

Identifying a friend or foe in a public location under a security lock-down presents certain challenges. An excitable force of responders may act against uncooperative civilians. Civilian resistance and failure to respond to police instruction may hamper the overall effectiveness of the response effort, and it is to this degree that civilians must understand their roles when encountering a counterterrorist response or risk being engaged by security elements. This was evident with the shooting of a Brazilian national in the aftermath of the London bombings, resulting in several repercussions for the London Metropolitan Police (Independent Police Complaints Commission, 2007).

2. Multiple Secondary Devices

Secondary devices threaten emergency responders as they force a change in zoning and a shifting of forces, in an attempt to ensure the security of working areas. This results in a response lag, a need for work site re-organization and (depending on the magnitude of the secondary event) an activation of a new tier of responders. Existing protocols have to be flexible enough to accommodate a relocation and troop reinforcement, if necessary.

3. Maintenance of Public Order

Public order remains a challenge to maintain in any populous city when hysteria spreads at the occurrence of a terrorist attack (Stokes, 1997). Responders need to contain any hysteria that may ensue from the panic of civilians directly affected by an incident. Civilians under emotional distress complicate the emergency response, or they may respond poorly to authorities or disregard public peace.

D. THE CONCEPT OF SIMULATION IN SINGAPORE

It would therefore be prudent to accept the limitations of mass exercises and acknowledge the need to augment their value with additional analytic tools. This method should demonstrate limited political undertones, to avoid resistance by users, and ensure that exercise objectives are fulfilled and recommendations can be tested. Computer-based modeling and simulation (M&S) is proposed as the ideal tool, providing planners with a versatile range of decision support tools. M&S allows decision makers to draw useful insights from various theoretical scenarios commonly put into play in mass exercises. Defense applications have been the major drivers for the use of M&S in the government sector in Singapore (Tay, 2006). Owing to the organizational needs of a peacetime military, the experience of the country's defense research arm is heavily grounded in enabling highly virtual simulations, or in the design and production of simulator aids for live training.

In recent times, M&S has also become an essential technology and tool for military experimentation. More recently, the defense services and defense science organizations have begun applying M&S for operational mission planning and rehearsals, decision support, as well as testing and evaluation. Several academic efforts have demonstrated the use of multi-agent simulations in the context of Singaporean defense applications, such as in the tracking of surface vessel intent in Singaporean ports (Tan, 2005) and the study of emergent behavior by swarm robotics employed for search and detection missions (Ho, 2006). Central to these ideas is the need for a flexible platform, schema for abstracting various operational elements such as civilian behavior and time (Tan, 2007), as well as map-sets and scaled data configurations to improve implementation (Roginski, 2006).

Thus, it is timely that the Singaporean National Security Coordination Centre (NSCC) is also interested in using data mining techniques to enhance national security (Jayakumar, 2007), though it is likely that current plans will tend towards efforts in horizon scanning and threat "prediction." This study proposes that a simulation can be generated for urban military and counterterrorist operations, given a specific terrorist threat (IEDs and WMDs) and area of operations, such as high-risk public and private buildings. Findings from such a design could help improve real incident response.

E. PROBLEM STATEMENT

Exercise planners and staff previously restricted by the caveats of a live simulation can be presented with new options by employing MAS in conjunction with future mass exercises (Lucas, Sanchez, Sickinger, Martinez, & Roginski, 2007). This thesis project applies a suitable M&S technique to analyze a theoretical scenario in an attempt to garner additional insights on civilian behavior, the tactics, techniques and procedures (TTPs) of existing first responders and the impact of chemical agent effects on both civilian and first responder populations.

F. MOTIVATIONS AND BENEFITS OF RESEARCH

The main motivation is to capitalize on high-performance computing power to augment consequence management planning. Applying simulation to study emergency responses in the context of Singapore allows us to revisit and explore scenarios practiced in prior exercises. This allows the assessment of solutions prescribed during these exercises to determine their validity, *in silico*. Of course, this must be demonstrated first.

Analyzing emergency procedures by simulation also allows planners to explore different scenarios that would not normally be achievable in the context of a physical troop exercise. Simulation analysis techniques allow for the assessment of factors responsible for limiting casualty numbers to both civilians and first responders.

In brief, the objectives are to apply a suitable computer simulation technique to analyze the multi-agency emergency response to an IED with a chemical payload (CIED) in Singapore. This study focuses on the first hour of activation after an incident occurs. The second objective is to provide a methodology for the implementation of MAS in analyzing multi-agency emergency response to a terrorist incident.

Ultimately, the establishment of a suitable framework for the computer-based simulation of an emergency response to a CIED in a civilian environment can extend itself to the following:

1. Installation-Specific Consequence Management Planning

The vulnerability of staff and personnel to terrorist devices can be assessed using installation-specific simulations. Military camp layouts and duty staff procedures can be analyzed for their efficacy in responding to a bomb threat. The possibility of such a scenario has been suggested by information from the Internal Security Department (ISD) that the JI cell in Singapore had considered an attack on at least one military installation with a car bomb (Internal Security Department, 2003). As such, more can be done in the planning and assessment of installation-specific consequence management. A demonstration of this by the United States Pacific Command (PACOM) for a civilian port (Smith, 2008) is based on the works by Kent (2005) and Roginski (2006).

2. Design of CBRE Support Operations

The process of developing the scenario in this research can be extended to assessing render safe procedures for the disposal of CBRE threats, either in peacetime settings, peace-support operations or post-war operations. Current response plans and procedures in Singapore either use fixed isolation zone templates which do not accurately reflect the severity of the hazard in context of the environment or physics-based simulation software that is limited to only modeling the threat.

3. Multi-agency Planning

Joint planners and multi-agency task forces can reasonably demonstrate the result of combined efforts in a simulated setting. The implications of joint operations with a heterogeneous force organization can be tested in a simulation. Factors such as arrival time, process rates, information flows, and command responsibilities (such as leadership), can all be accounted for in an agent-based simulation (ABS) such as a Pythagoras ABS or Map-Aware Non-Uniform Automata (MANA).

G. APPROACH

The use of ABS allows for the observation of emergent behaviors in a scenario, granted that the simulation appropriately represents the key behaviors under study. This study generated a Pythagoras ABM for a theoretical emergency response situation. The choice of Pythagoras as the software platform is due to its capacity to model human “soft” factors such as desires, tolerances, leadership traits, and “color” sidedness (Bitinas, Henscheid & Truong, 2003). The study also uses simulation analysis concepts and design of experiment (DOE) methodology suggested by Sanchez (2006) to analyze the measures of effectiveness (MOEs) that are outputs from the scenario, allowing the investigator to draw reasonable scientific conclusions to the demonstrated behaviors while relating them to the operational problems being studied. Across this analysis is the ability to investigate many potentially influential factors and sources of uncertainty (Lucas, et al., 2007).

H. SCOPE

This research focuses on the immediate response by Singaporean police, civil defense (medical and fire service), and military CBRE to a theoretical activation of a CIED along a major shopping belt in downtown Singapore. The scenario attempts to base the response of these forces on the open source information published in Singaporean media for Exercise NorthStar V, relevant first response procedures within the SAF. Where appropriate, weapon, sensor, and communications data available in open source and from United States Army Training and Doctrine Command Analysis Center Monterey (TRAC-MTRY) is used.

The work focuses on the following research questions:

- How feasible are existing operational templates, TTPs, and information-making processes?
- How robust are current procedures in containing civilians exposed to chemical agents?
- What factors influence the efficiency of emergency response procedures?
- To what degree does civilian compliancy affect the performance of casualty treatment?

I. THESIS OVERVIEW

The following chapters will provide specific background on the simulation area, details on the development of the model, the manner in which the data will be collected for analysis, and the resultant conclusions. Figure 1 shows an illustration of the scientific design and approach.

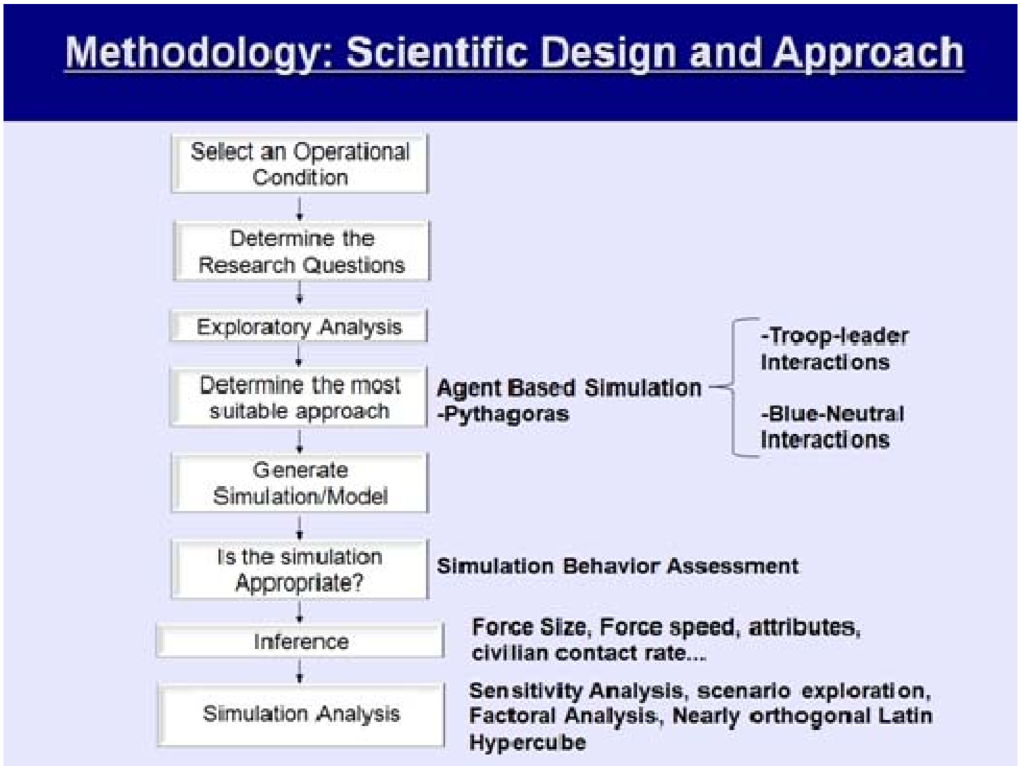

Figure 1. Scientific design and approach taken in the course of the research (From: Sanchez, 2006).

Chapter II describes in detail the framework of the Singaporean Incident Response and Management system and serves as a primer to the reader in understanding the procedures conducted by elements under the MHA and the SAF. For creating the simulation scenario, the study also references pertinent historical examples that serve as major case studies to the Singaporean system. To scope the design of the model, this research interprets the Critical Operational Issues (COIs), MOEs and Measures of Performance (MOPs) for the emergency response. The study elaborates on these using various scenarios for the simulation.

Chapter III describes the modeling methodology used to create the scenario, inclusive of the how various elements are captured in the modeling of agents and the environment. Chapter III also draws attention to certain qualitative factors of importance. It describes how this study departs from the works of Kent (2007) and Roginski (2006), which this study builds on. Chapter IV describes the experimental design and simulation analysis, followed by the treatment of output to extract the relevant MOEs. Chapter V summarizes the data, introduces the analytical tools, and an assessment is made using data plots, curve fitting, regression trees, and other simulation output analysis methods. Chapter VI discusses the results from the analyses and draws conclusions relevant to the research questions posed. Chapter VI also discusses the suitability of Pythagoras for modeling deliberate and emergency responses at the national level. The chapter concludes the research by suggesting future research opportunities and extensions, based on the current work.

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II. SCENARIO OVERVIEW

A. HISTORICAL REFERENCES

To design a believable scenario for the simulation, the study relies on a select number of historical examples, much in the same way Exercise NorthStar V referenced recent terrorist events. Figure 2 shows scenes that represent critical functions in the emergency response during these historical incidents.

Figure 2. Images from historical incidents used for reference in the study. Each image demonstrates a specific role required for emergency response. (A) Casualty evacuation: Tokyo subway attack; (B) Site security: London train bombings; (C) Site decontamination: Tokyo subway Attack; (D) Post blast investigation: Jakarta Marriott bombing (A and C from http://aboutjapan.japansociety.org; B from www.bbc.co.uk; D from Associated Press).

NorthStar V incorporated the characteristics of the following major incidents (Singapore Civil Defence Force, 2006):

1. Tokyo Subway Attack (1995)

The attack executed by the Japanese cult Aum Shinrikyo on March 20, 1995, was the deadliest and most notorious attack that involved the use of a chemical warfare agent on a target population in a public place. A total of 600 grams of 2-(Fluoro-methylphosphoryl)oxypropane, commonly known as sarin (NATO classification GB), was used in the form of multiple devices distributed and released in an underground subway station running under several prominent government buildings. In total, 12 people were killed and thousands were injured, with official numbers for injuries estimated at below 4000 (Kaplan, 2000). It was acknowledged by the Japanese authorities that, of the majority of victims treated by hospitals within the first 24 hours of the incident, close to 74% could be classified as "worried well," as they had no evident signs of nerve agent exposure (Stokes, 1997). The Tokyo subway attack is significant as it demonstrated the effectiveness of a small chemical payload in generating both physical casualties and mass hysteria. As a landmark incident, the attack lends itself to replication by terrorist groups as a means to create fear. The impact of mass hysteria is also a significant research question, as the impact of a panicked population may affect both the efficiency of an emergency response and unnecessarily load the public healthcare system.

2. Jakarta JW Marriott Hotel Bombings (2003)

The vehicular bomb used by JI in the execution of this incident exemplified an emerging trend in terrorist attacks in the region, one that was repeated September 28, 2008 in Islamabad, Pakistan, targeting another hotel under the Marriott label. The earlier incident involved an IED concealed in a mini-van on the periphery of the JW Marriott Hotel in South Jakarta, killing 12 people and injuring 500 bystanders, mostly Indonesian with the exception of a few Danish and Chinese tourists (Associated Press, 2003). The second incident was reported to have involved a dump truck as the vehicle bomb, which exploded at the security fence of the hotel (Rupert & Sharif, 2008). These incidents signify a prolonged association of such private organizations with the real targets of the perpetrators. This association is a case for concern for private and public institutions alike and often means that collateral damage is unavoidable. With this in mind, prior planning for consequence management can mitigate the impact of such events in the future. A thorough understanding of the environment surrounding a high profile target can improve emergency response. A series of scenarios will be generated in this study to demonstrate an analysis to prove this point.

3. London Public Transport System Bombings (2005)

The bombings in London are of particular interest to the Singaporean MHA, given the similarities between London and Singapore, and also because of the Singaporean reactions following the Madrid train bombings in March 2004. The London bombings also differed from the prior experiences of the British with domestic terrorism by the Irish Republican Army (IRA), where the impact of large payload devices would at times, be mitigated by deliberate tip-offs from the IRA (Dillion, 1996). For instance, the 1993 Bishopgate bombing involved an activation of a one-ton fertilizer bomb within a dump truck in London, resulting in a single death and 44 casualties (Schmidt, 1993). By comparison, the 2005 London bombings were an unannounced but coordinated multi-effort attack, distributed over both underground and surface levels, the latter in buses, resulting in 52 dead and 700 injured from four man-portable devices. In response to the bombings, Singaporean authorities immediately enforced security measures on the public transport system, drastically altering the public security landscape. Armed patrols established themselves within mass rapid transit (MRT) stations by police officers from the special operations command (SOC) (Singapore Police Force, 2005a). The government proposed plans for closed-circuit television (CCTV) installation in all trains and buses. Then, to assure public concerns, the MHA updated the public on the progress of the planned MRT security unit (Singapore Police Force, 2005b), unlike in the past, when the public would go about their lives unaware of such matters. Security was also enhanced for the 117th International Olympic Committee (IOC) session in Singapore, in addition to the dedicated response force elements already allocated for the two weeks of the session's assembly. It can be said that the occurrence of the London bombings have resulted in a shift in resources to the daily assurance of public security vis-à-vis deliberate operations for high profile events. It would therefore be interesting to observe the effect of routine armed patrols at popular venues, such as Orchard Road, a major shopping belt in the business district, or Holland Village, a residential area known for its large expatriate population.

B. EXERCISE NORTHSTAR V

Exercise NorthStar V was a national exercise involving a "worst-case scenario" terrorist attack across the island of Singapore, a scenario that was based on the events of the above historical examples (Singapore Civil Defence Force, 2006). As a part of the nation's concept of "Total Defence," the exercise's further motivations include the following:

- The continued implication of Singapore as a probable terrorist target (Internal Security Department, 2003; Henson, 2006).
- The need to assess the responsiveness of the existing protocols for the different agencies involved in a response (Loh, 2006).
- The (then) global trends in terrorist actions on public train and bus systems.
- The increased dependence of the population on this infrastructure in the future.
- The need to ensure emergency preparedness for subterranean incidents.

Five attacks (five explosive, with one chemical payload) were role-played at four train stations and one bus interchange within a span of 15 minutes (Henson, 2006). The "impact" of the attacks was meant to affect 13 different underground train stations and lead to a 3-hour emergency response period followed by a longer post-blast investigation phase. Figure 3 illustrates the distribution of these affected areas by geography.

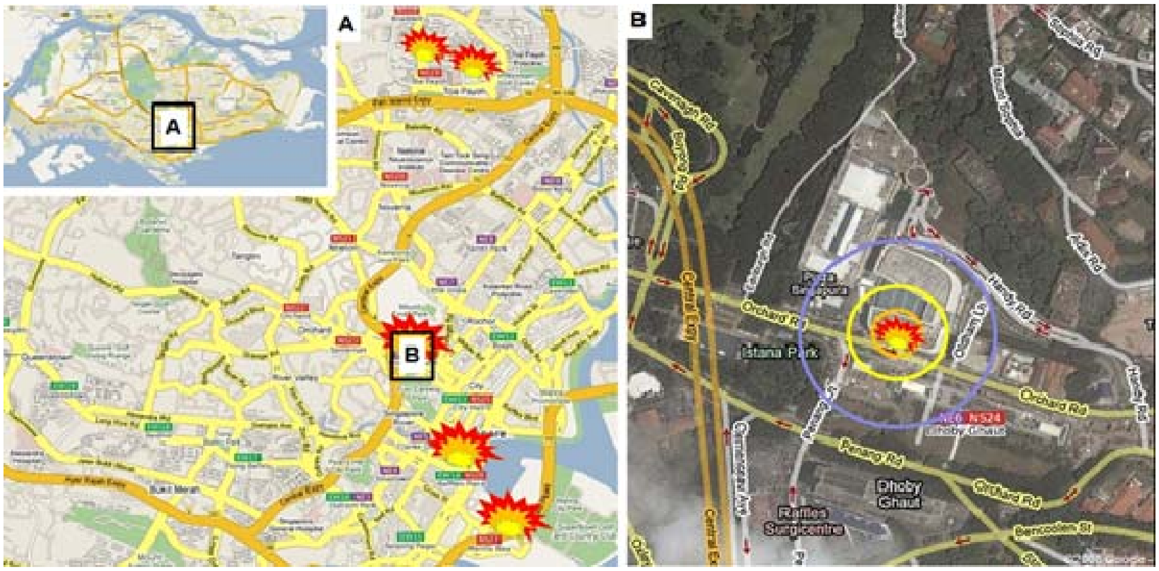

Figure 3. Affected areas in Exercise NorthStar V, Singapore (From: Google Earth and Google Maps, 2008; locations From the New Paper, 2006).

It is difficult to determine if future responses will be typified by that demonstrated by NorthStar V because of the considerable administrative preparations prior to the exercise event, reported to have taken place as early as six months before the incident. Nonetheless, local press brought attention to several observations worth mentioning (TODAY News Desk, 2006):

1. Response Time of CBRE Responders

CBRE elements took up to 30 minutes to arrive at the major incident sites in the exercise. It was explained by the SAF that the CBRE elements would respond with an advanced party on site within 15 minutes and a main body within 30 minutes. At a glance, this issue appears to be a routing problem from the main base of the CBRE elements to the rest of the island, a problem that is common to all elements responding to the incident. This research attempts to capture this response time as a reference and determine the impact of first responder arrival time on the civilian casualties incurred. The research will not answer the question on routing or base camp placement because it is beyond the scope of the experiment.

2. Exposure of Non-ambulatory Casualties to the Environment

Two instances suggest an apparent lack of focus on limiting the exposure of non-ambulatory casualties to the environment. One observation noted a deficit of chemical respirator hoods for casualties as they were transported out of a "sarin-contaminated" incident site on gurneys. Another observation involved the exposure of casualties to the open rain. In the context of a low-resolution simulation, exposure can be demonstrated by the continued presence of chemical agents in the affected area, up to the time of reasonable dilution to non-lethality. Constant interaction of civilian casualties with these agents can therefore be recorded as an accumulation or degradation of a civilian attribute, an abstraction of human health. When configured this way, the impact of specific actions scripted in a simulation might be able to determine what actions or policies would be best for reducing casualty exposure to the natural elements; however, it is a factor that is not considered in this study.

3. Administrative Break in Exercise Realism

The press and public alike observed administrative breaks, such as the early preparedness of public hospitals before the incidents occurred and the cessation of public use 15 minutes before the exercise. This research scenario will assume no preparation other than that expected for daily staffing of standby activities. In addition, the civilians in the scenario are implemented in a way to demonstrate continuous use of public areas, and have actions and behaviors shaped by the environment, such as the service capacity of walkways, roads, road curbs, and pedestrian crossings.

C. DESCRIPTION OF INCIDENT RESPONSE IN SINGAPORE

Based on this author's personal experience, correspondence with senior staff in the CBRE Defence Group and open-source literature, the study focuses on a multi-agency incident response. In the event of a civil emergency due to a chemical agent release or IED explosion in a public area, the SCDF becomes the central coordinating agency for the consequence management (Singapore Civil Defence Force, 2006). This obligates command authority of SCDF and police assets to an SCDF officer acting as the incident manager, usually the senior Commander of the Division where the incident occurred. Figure 4 illustrates a possible arrangement of forces at the incident site.

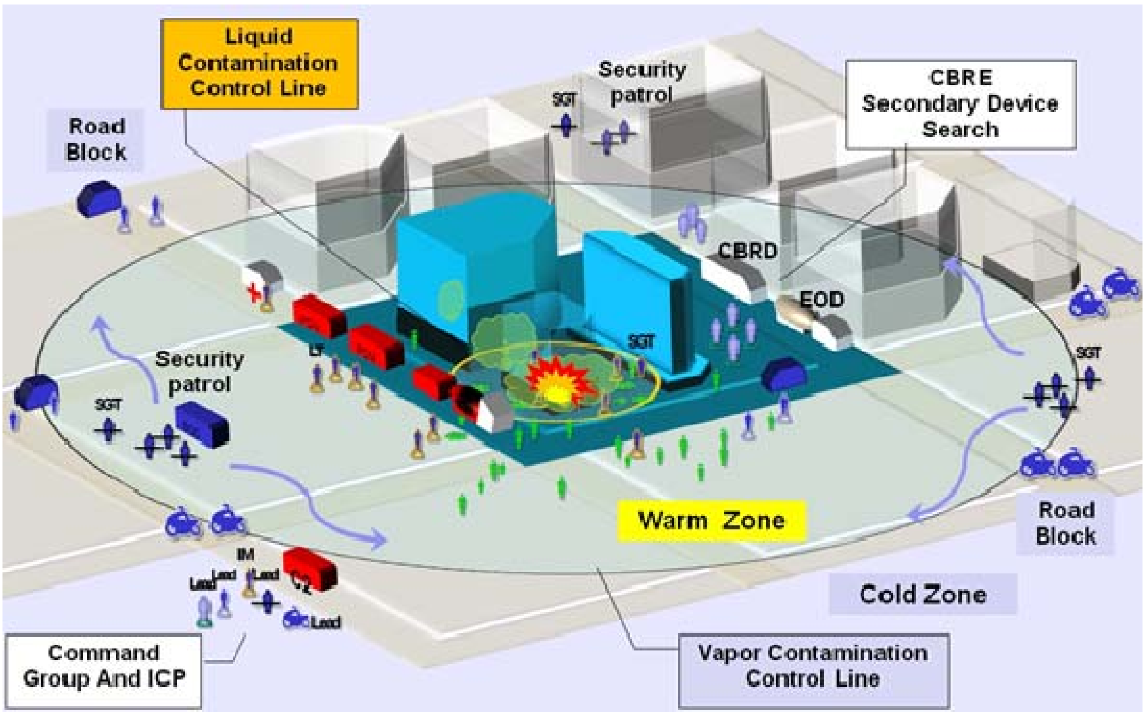

Figure 4. Arrangement of emergency responders at the incident site (From: The New Paper, 2006).

Depending on whether chemical agents are involved in the incident, medical support is provided by emergency medical technicians (EMTs) using an on-site triage, after which further care is provided at the nearest public hospital (The New Paper, 2006). When chemical agents are suspected or confirmed, mass casualty decontamination will occur onsite, prior to evacuation to hospitals (CBRNe World, 2007). In the event of a bomb blast or a multiple-bomb blast situation, a joint emergency response in Singapore will consist of the following elements:

1. Singapore Civil Defence Force (SCDF)

Depending on where the incident occurs, divisional fire companies respond to a reported incident by sending an initial first response consisting of an emergency medical service ambulance and a fire pump engine. Each pump engine is now equipped to conduct the quick wash-down of contaminated individuals (termed "hasty mitigation"), to reduce the dwell time of chemical agents on civilian casualties. The pump-engine team members are each equipped with fireproof "bunker" gear and a non-circulating self-contained breathing apparatus (SCBA) set that provides a degree of protection against inhalation hazards. Where necessary, the pump team may use butyl-rubber suits in place of their bunker gear flame-retardant vests. The leader of the pump team takes on the role of the breathing apparatus chart officer (BACO) and becomes the first coordinating commander until the SCDF incident manager (IM) arrives on scene.

In the event of reported chemical agent attack, the SCDF sends a hazmat detachment, which is equipped to conduct emergency snatch rescues in a chemically contaminated environment, as well as the sampling and containment of a suspect contaminant. Compared to the first-response rescuers staffing the pump-engines, the hazmat detachments are equipped with a greater assortment of individual protective equipment (IPE) suits, detectors, and chemical agent mitigation apparatus to control residual hazardous material, once casualties are rescued.

Emergency medical service teams arrive in two phases. One team arrives with the initial fire pump engine as a first response vehicle. The second team arrives to provide additional support with the follow-on SCDF force and to augment the first team in the set up of a triage area for chemical and bomb casualties. The arrival of the second ambulance also allows the first to conduct any necessary evacuation to the hospital. The SCDF incident command post arrives to support the entire operation and serves as a nucleus for the distribution of information to all SCDF assets and adjacent agencies.

2. Singapore Police Force (SPF)

The SPF facilitates and helps in the rescue of casualties, secures and preserves the scene of the incident to facilitate evidence gathering, and conduct crime and post-blast investigation to apprehend the perpetrators (Singapore Police Force, 2006). Other actions would include protecting the public and key installations from further attacks, providing information and assistance to the affected public, and public reassurance to facilitate a speedy return to normalcy.

Like the SCDF, the SPF is organized into separate ground divisions that preside over the policing of different parts of Singapore, with fast response cars arriving on-scene within seven to ten minutes. Divisional patrol officers responding to the scene of a terrorist attack would immediately proceed to secure the incident site and roads to facilitate the ingress and egress for emergency response teams and vehicles to the site. Patrol officers facilitate evacuation management, preserve the incident scene and look for eyewitnesses, while the SCDF conducts rescue operations and provides first aid to victims. Roadblocks and increased checks would be carried out by police at the vicinity and other locations to look for suspects connected with the incident. A team of criminal investigators, trained in post-blast investigation, would descend on the scene soon after and process the crime scene to identify the type of explosive, device, or method used. Witnesses identified by patrol officers prior to their arrival would be interviewed, and CCTV footage from MRT stations, transport operators, and other possible sources would be retained and reviewed. Subsequent investigation may lead to the contact of regional and international foreign counterparts.

3. Singapore Armed Forces (SAF)

The SAF provides CBRE standby teams maintaining explosive ordnance disposal (EOD), chemical, biological, and radiological defense (CBRD), detection and identification, and post-blast investigation elements. An additional CBRE officer serves as an alternate subject matter expert (SME) to support the team leader’s analysis and command decisions. The CBRE officer acts as a liaison between the Incident

Management Group and IM to the CBRE standby team. The standby team is equipped with assets for the overt search and identification of IEDs and chemical agents (CAs). It has its own vehicular platform and an EOD bomb containment vessel that can allow the movement and disposal of a small explosive payload. The CBRE standby team ensures survivability and provides defense against secondary payloads that may be placed on-site to target first responders.

4. Other Elements

The Singapore Ministry of Health (MOH) and Ministry of the Environment play a role in post-response mitigation. The MOH assigns specific hospitals to deal with chemical and biological threats, where on-site facilities are available to cater for casualty care. The Ministry of the Environment is responsible for post-incident co-ordination with the SCDF or SAF to facilitate the decontamination and disposal of contaminated material, to return the affected area to normalcy.

D. DELIBERATE VERSUS STANDBY RESPONSE

A deliberate response effort varies from a standby response effort in the sense that the deliberate response is a one-off, pre-conceived plan in support of a larger, high-profile event, whereas a standby response is a continuous obligation required to maintain a degree of high readiness in anticipation of a sudden, unexpected civil emergency. Based on these definitions, an example of a deliberate response was demonstrated for the International Monetary Fund (IMF) Conference in Singapore in 2006 (Boey, 2006) and the IOC meetings of the same year. An example of a deliberate response effort in simulation is demonstrated by Roginski's Baltimore model (2006), where police and EMT units are available on site in a public carnival celebration. The research scenario implemented in this study will instead demonstrate a standby response, where the affected area is devoid of emergency responders and civilians must manage in the presence of the hazard for a brief period, before responders arrive on scene.

E. CRITICAL OPERATIONAL ISSUES (COI), MEASURES OF EFFECTIVENESS (MOE), AND PERFORMANCE (MOP)

Central to the emergency response are COIs and accompanying MOEs central to the standby response to a CIED incident. Based on the author's studies, a select number of COIs are summarized in Table 1. MOPs refer to one or many quantifiable measures from which the MOE may be determined. Some of the COIs and MOEs will be selected to guide the construction of the simulation. Returning an incident site to normalcy occurs as part of consequence management for a CIED incident. Limitations of the simulation prevent their analysis in this research. As such, a degree of abstraction is required to relate the performance measures derived from the simulation to the real-life MOEs.

NO.	CRITICAL OPERATIONAL ISSUES	MEASURES OF EFFECTIVENESS	MEASURES OF PERFORMANCE
1	Effectiveness of the Emergency Activation	Improvement of Civilian Survivorship Over No Response	Civilian Survivorship Arrival Time of Standby Forces
2	Treatment of Civilian Casualties	Change in Civilian Survivorship Over No Response	Percent Alive, Injured and Dead civilians with/without Response Probability of Survivorship with Response is Better Than No Response
3	Securing and Control of Incident Site and population	Reduction in Civilian Panic	Degree of Panic/Calm Experienced by Civilian
4	Survivability of Emergency Responders	Survivorship of Responders Reduction in Hazard Exposure	Amount of CA Exposure to responders Number of Responders Sustaining Injuries
5	*Return to Normalcy*	*Speed to which site is returned to normalcy.*	*Numbers of days taken for site to return to public use.*

Table 1. MOEs and MOPs for COIs considered in study. COI 5 (Return to Normalcy), in italics, will not be addressed in the study, although it is no less important an issue in the response, as early actions will affect how easy a return to normalcy can be achieved.

Central to the emergency response is the need to reduce civilian casualties and implement site control. The study elaborates on these two issues in the later chapters.

F. SCENARIO FOR THE INCIDENT

Taking into consideration the historical and current state, as well as certain COIs to the response, a theoretical scenario is crafted for the simulation. The study describes a typical morning along Orchard Road (1° 30’45” N, 103° 83’26” E), an urban shopping belt within the central business district of Singapore. The scenario takes into account a terrorist group with a considerably high degree of technical expertise, in that they are able to construct concealed devices and obtain hard -to-find components for chemical agents and vehicular bombs.

1. Environment: Urban Shopping Belt

a. Basis for the Scenario

To replicate the operational pressures presented in the London bombings, multiple bomb attacks were scripted in NorthStar V. This involved four underground transit train stations, and one bus station located in a major residential hub. The train station attacks proved difficult to model in Pythagoras, which cannot model effects over multiple surface layers. In addition, major bomb attacks on surface-level targets are more common. Based on recent terrorist incidents in Asia, ground-level attacks, particularly using concealed vehicular bombs, are more prevalent. The recent occurrence of the Marriott hotel bombing in Islamabad, Pakistan, is an example of a vehicular bomb attack at ground level that had been stopped by a primary barrier fence (Rupert & Sharif, 2008). As such, the scenario generated for this research is limited to incidents at ground level; however, floor elevation and ceiling height of terrain features such as buildings, trees and passages will also be represented.

b. Characteristics of the Environment

This study chooses to focus on a theoretical attack on a department store located within a major shopping belt in Singapore. This would be a visible incident that would undermine both domestic and international confidence in Singapore's security. The location has the following characteristics:

- A low level of security prevails, in that there are few elements that screen and process the crowd and environment for any security threats. Although routine patrols by the SOC have been put in place at this shopping belt since 2005, for the purpose of the study, the assumption is made that this measure serves as a patrol and reactionary force, but not a security screen.
- A hybrid sector-nuclei type topographical layout, shaped by the pre- and post-historical arrangement of roads in Singapore, that differs from typical grid-type urban geographies in the United States.
- A heterogeneous population of individuals with their own goals and directions. Certain goals are shared while some are varied, but movement and behavior to achieve the objectives are consistently guided by major factors such as accessibility of entries and exits, public transportation, corridors for mobility and known-obstacles.
- A transient density of people per unit area of land, in that the density of people in a given area will change as long as the service levels of passages are adequate enough to limit the formation of lines and bottlenecks at any particular place.
- A moderate flow rate of service areas, as several improvements over the lifespan of the shopping area has led to improved pedestrian service standards.
- A standard building height, in that urban planning and fire safety regulations fix the maximum building heights of retail and office establishments, so they do not vary greatly over a map grid area.

These characteristic details are illustrated in Figure 5, which show an aerial view of the affected area in the scenario.

Figure 5. Affected area of scenario and characteristic details. (A) Marriott Hotel and Tangs Shopping Centre. (B) Wheelock Place. (C) Takashimaya and Ngee Ann City. (D) Plaza Singapura shopping center exterior. (E) Junction of Orchard and Scotts Roads. (F) Orchard Road MRT entrance. Satellite imagery from Google Earth. All inserts from Flickr (www.flickr.com).

2. Terrorist Target

The target store is situated near notable buildings and establishments that have been linked to Western influence, such as the Marriott Hotel. This store shares its location with a busy street junction and acts as a viable thoroughfare from all directions of the junction. Near the target is a public underpass that sees a high level of pedestrian service, as they link two opposite sides of Orchard Road.

3. Chemical and Explosive Device

Devices of varying payloads and quantities have seen use in many urban terrorist incidents, ranging from man-portable devices (Schmidt, 1993; Kaplan, 2000) to vehicle bombs (Rupert & Sharif, 2008). The main characteristic to be modeled for the device is its area of influence, which would be translated from the payload and the blast kinetics related to it. This study models both a device of the maximum size possible to remain concealable in a store, as well as a device that can be transported reasonably within a mini-van travelling along the major road through the shopping belt. The scenario uses an equivalent chemical payload as that in the Tokyo subway attacks (10 to 600 grams of liquid sarin) in the agent-based scenario for the initiation of the emergency response.

4. Civilian Behavior

a. Basis for the Scenario

Common principles applying cognitive sciences to computer simulation (Kaminka & Fridman, 2007), civil engineering, and emergency planning (Sime, 1995) allow for the intelligent design of urban areas and consequence management. The human intangibles involved, however, are still theoretically subjective and simulation-specific limitations restrict the complexity of how definitive such behaviors can be described. To characterize civilian behavior in the scenario, an appreciation of crowd psychology is needed. This research will therefore suffice with a low-resolution model of crowd psychology, focused on its impact on the motor behavior of the individual.

One prominent idea used to describe civilian behavior in crowds, termed the Social Comparison Theory, is that when a group is presented with the same stimulus, individuals begin to compare and associate themselves to others that are in the same situation, and thereby imitate common behavior (Festinger, 1954). This may lead to social attachment to leader figures and risk collective peril (Mawson, 2005). This concept, however, has often been disproved by historical examples. An elaboration of the idea is that members in a crowd can behave consistently with individual identities and be governed by the social norms of the situation. This proposition explains why mass panic manifests rarely and the public behaviors resulting out of this panic can often be varied, ranging from self-centeredness to pure altruism. This study attempts to model this range in the context of panic and compliancy; the intrinsic compliancy of civilians changes under stress, as does the degree of public hysteria that the civilian is able to withstand, before he/she ultimately succumbs to panic.

This study focuses on the initial phases of the emergency response and will therefore concentrate on the typical behaviors demonstrated in response to the physical hazards. The simulation implements a simple model for two aspects of stress: the physical stress that comes with bodily harm, resulting from both the physical injury that may come from the IED and gas effects, and the psychological stress that may affect the civilians' response to others. The personalities of each individual civilian will first be characterized in general by their tendency to comply with instruction, their propensity to panic, and their desires for movement. The stress incurred by each civilian will influence his or her movement in the simulation. A stressor will influence the motor behavior of the civilian in that he may physically respond in a rational manner (i.e., extricate himself from a threat) or an irrational manner (i.e., move randomly or freeze in place). The behavior will therefore demonstrate the civilians' exposure, and hence their response, to the stressors in the simulation.

b. Civilian Interaction with Government Agents

In the event of an emergency response, civilian interaction with emergency responders is expected. Civilians will behave differently to what they perceive to be sources of authority. There are social, cultural and intrinsic behaviors that may influence a civilian's response to a person of authority, such as a police officer or SCDF specialist. This research will not discuss the factors governing this and will instead classify them as noise factors in the environment with which the emergency responders must manage. First responders will therefore have to work with crowds of varied disposition—either compliant, neutral (ambivalent) or non-compliant (more "self-serving" in this context).

c. Civilians in the Scenario

In the context of the scenario, the civilians in the simulation represent the early morning shopping crowds that throng the shopping district. Major department stores are easily populated with sparse, but directed, crowds that move along major thoroughfares linking the inside of the shops to the outside environment.

5. Description of the Response

The following descriptions will explain the emergency response procedures generalized from multiple open-source references and used here to create our scenario. Several aspects of these procedures are made transparent and known to the public to facilitate the emergency response. Figure 6 shows illustrations from one such effort, a civil defense handbook distributed to all households for public education for emergency preparedness given a terrorist attack. It demonstrates the flow of the response activity from the civilian's point of view.

Figure 6. Initial response to CIED incident. A device is hidden in a public location (A) and activated, leading to casualties (B) and the reaction by the public (C). Emergency calls to the police central radio dispatch (D) activate both initial response units to the site, and subsequently follow-on SCDF presence to treat civilians, who must register for decontamination or contact tracing purposes (F). From SCDF Emergency Handbook 2007.

a. Incident Management Cascade

The response time for the activation of each individual force to a CIED incident is shown in Table 2. Timings are based on open source information and some approximation is accommodated. For the purposes of this study, only the acute phase of the response is described in the following table.

No.	Event	Action Authorities	Forces and Means to Arrive On Site	Time (Minutes)
1	Reporting of Incident	Divisional Police	NA	T + 0
2	Initial Assessment	Divisional Police	Police Fast Response Car Patrol Officers (acts as IM)	T + 7
3	Activation of Initial Response Force	Divisional Police Divisional Fire Company	SCDF Pump Engine SCDF Rescue Crew SCDF Duty Pump officer (new acting IM) SCDF Emergency Medical Team (1)	T + 15
4	Activation of Follow-on forces and Incident Management	Divisional Police Traffic Police (TP) Divisional Fire Company Divisional hazmat Detachment SAF CBRE DG Civil Medical Authorities(MOH) Infrastructure Authorities (Public Utilities, Environment, media and Info-communications, Gas and Power, Land and Building)	Incident Command Post SCDF Leader (new acting IM) Divisional Police Leader TP Motorbike Officers TP Leader Hazmat Team Hazmat Control Vehicle SCDF Decontamination Pod SCDF Emergency Medical Team (2) SAF CBRE Standby Team SAF Leader Bomb Containment Vessel SAF CBRE Response Vehicle	T + 30
5	Security and Cordon	Divisional Police SOC	Police Tactical Units SOC Leader Divisional Police Patrol Officers Criminal Investigation Department Team	T + 45
6	*Initial Investigation*	*SPF (Criminal Investigation Department), SAF*	*SAF Post-Blast Investigators*	*T + 60*
7	*Decontamination*	*SCDF* *SAF* *Civil Authorities (health, environment and public utilities)*	*As Above*	*As required*
8	*Verification, Monitoring, and Disposal*	*SAF* *SCDF* *Civil Authorities (environment and public utilities)*	*As Above*	*As required*
9	*Return to Normalcy*	*SCDF* *Divisional Police* *Traffic Police* *Infrastructure Authorities*		*As required*

Table 2. Incident management (IM) cascade for standby response to CIED incident. Events in italics are considered outside of the acute phase.

b. Initial Response Forces

The scenario takes place in the central business district, so the responding police division is the central police division. On the confirmation of an emergency police calls reporting a possible CIED incident, one or two first response cars (FRC) arrive on the scene within five to fifteen minutes. Patrol officers with the FRC will provide initial assessment of the incident, to be relayed by radio back to the divisional headquarters. Patrol officers with the FRC would attempt to proceed to secure the incident site and roads to facilitate the ingress and egress for emergency response teams and vehicles to the site. The patrol officers continue to treat the site as having possible criminal activity. One fire pump engine and an emergency medical team on a SCDF ambulance will also arrive on activation. These assets are expected to arrive slightly later than the FRCs, as they are larger and slower vehicles. The duty pump officer will decide on the initial isolation zone and protective action zone, based on the information that the patrol officers can provide. The duty pump specialist and firefighters will proceed to adopt a protective posture to attempt a snatch rescue of any non-ambulatory casualties. If a chemical agent is detected, a hasty decontamination procedure will be attempted using the fire pump engine and fire hose spray on ambulatory and non-ambulatory civilians affected by the chemical agent.

c. Follow-On Forces

When a central dispatch authority activates emergency procedures for a CIED incident, SCDF hazmat, SAF CBRE standby teams, traffic police (TP) and the Police Tactical Unit (PTU) from the SOC will be activated to send a detachment to the incident site. Each detachment will originate from different headquarters and their approaches to the incident site are expected to be different. Depending on the scale of the incident and assets on site, vehicular incident command posts may be activated and called on site. An SCDF senior commander will be installed as the principal IM.

Divisional police will send more patrol cars to create a buffer zone around the Incident Command Post (ICP). These patrol officers will have orders to stop civilians fleeing the site and, if they are believed to have been casualties or are chemically contaminated, order them to proceed to the casualty decontamination point and triage site set up by the follow-on SCDF elements. This is to facilitate mass-casualty decontamination, as well as to prevent the contamination of other health-care facilities on the island (CBRNe World, 2007). The PTU will conduct a roving patrol within the security area and perimeter of the warm zone. The PTU is equipped with tactical combat gear and is meant to specifically target human threats, such as terrorist instigators. At the same time, they direct civilians and ambulatory casualties to the SCDF treatment sites.

TP motorbike officers will arrive with a leader, who will coordinate with the IM on the establishment of the road cordon. TP motorbikes will secure and block off road routes in accordance with the implemented zoning template. They will facilitate the evacuation of road-vehicles out of the incident site and ensure the fast entry and exit of the responders. They also keep non-essential personnel out of the affected area in order to minimize congestion that may hamper follow-on forces.

The SCDF hazmat team conducts a more definitive sweep of the chemically contaminated area to look for more casualties and conduct chemical agent identification. The decontamination pod and teams set up an additional two lines for the decontamination of civilians by gender. The follow-on ambulance sets up a triage site to process casualties after decontamination and evacuate civilians, if necessary, to a hospital equipped for chemical casualties.

The SAF CBRE standby team will arrive on-site to conduct secondary device searches for the work area. They will also confirm, independently from the SCDF, the chemical verification results to facilitate criminal investigation. If a secondary device is discovered, they will proceed with render safe and disposal procedures. The CBRE leader, in conjunction with the IM, will implement re-zoning for a chemical hazard, if necessary.

Leaders from the different response elements co-locate with the SCDF ICP, which will be located on the perimeter of the warm zone. Liaisons from various civil authorities plan at the SCDF tactical headquarters (HQ) to work on the appropriate consequence management actions.

d. Command, Control, and Communications

The emergency response may be executed with multiple tactical HQs for each component force on-site. Alternately, a common ICP may be arranged for the collective coordination of efforts for consequence management. Each individual response organization maintains its own chain of command, but efforts are coordinated through each organization's leader for on-site activities, to the IM from the SCDF. Ideally, these leaders share and update information on the locations and activities of the emergency responders: data that is monitored centrally at the ICP.

Communications employed in the emergency response exist mostly in the form of independent radio networks that are set up on-site. These "radio-nets" may be encrypted or open-channel and it is the responsibility of each component response force to provide a link to the ICP. The ranges and effectiveness of the communications are not available for publication in this research.

III. MODEL DEVELOPMENT

This chapter describes the modeling methodology used to create the scenario, inclusive of the how various features and elements central to the scenario are captured in the modeling of agents and the environment. This chapter also draws attention to certain qualitative factors of importance. Additionally, it explains how this study departs from the works of Kent (2007) and Roginski (2006), which this study builds on.

A. GOALS

The simulation models the acute phase of the emergency response in the scenario described in Chapter II. This phase is characterized by time-sensitive elements like casualty evacuation, site security and secondary device search. The goal is to measure the impact of various tactical factors on the effectiveness of emergency response. The research questions are kept in mind to facilitate our design of the simulation:

- How feasible are existing operational templates, TTPs, and information making processes?
- How robust are current procedures in containing civilians exposed to chemical agents?
- What factors influence the efficiency of emergency response procedures?
- To what degree does civilian compliancy affect the performance of casualty treatment?

B. PYTHAGORAS AGENT-BASED MODELING (ABM)

1. Background

An emergency response to a crisis can be described as a multi-sided event that sees various interactions between the affected environment, the populations involved and the leadership available in these conditions. Given these considerations, several features in Pythagoras lend themselves to the simulation of a crisis response (Northrop Grumman 2008). See Figure 7 for a diagram illustrating the relationships of different factors considered in Pythagoras. In brief:

- It incorporates *soft rules* to distinguish unique agents.
- It uses *desires* to motivate agents into moving and shooting.
- It includes the concept of *affiliation* (established by *sidedness* or color value) to differentiate agents into members of a unit, friendly agents, neutrals, or enemies.
- It allows for behavior-changing events and actions (called *triggers*) that may be invoked in response to simulation activities.
- It retains traditional weapons, sensors, and terrain.

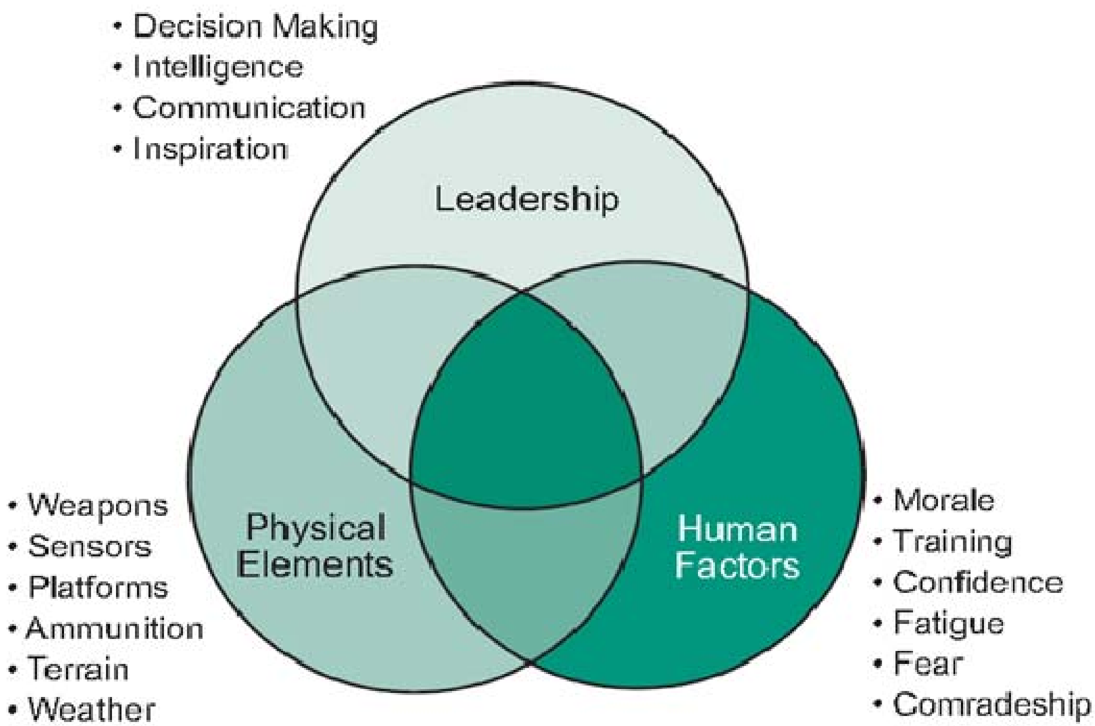

Figure 7. Venn diagram demonstrating the tightly coupled nature of leadership, physical elements and human factors (From: Northrop Grumman, 2008).

The current release of Pythagoras, version 2.0.3, has improved features over version 1.10—mainly an increase in available terrain map size and an increase in attribute slots assignable to agents.

Use of the program requires little technical experience or prior knowledge. A major strength is the capability to translate these features into a visual representation on the computer. A simulation playback screen allows for the observation of emergent behaviors based on the soft rules defined by the user. These observations may be supported by historical references or be completely counter-intuitive.

The study chooses Pythagoras because several key methods and components had already seen configuration in the form of a Pythagoras scenario, the feasibility of which has been demonstrated in the previous thesis works of Kent (2007) and Roginski (2006). Given the time limitations to learn the program from scratch, the study advantages on this existing knowledge base to reduce the time required to learn the simulation-modeling tool.

2. Complexity of Use

The complexity of the Pythagoras model depends on the complexity of the process being simulated. Ideally, the problem should be abstracted to a reasonable level that facilitates both easy configuration and logical output of data during simulation. This does not mean that Pythagoras is only limited to solving simple, tactical problems. The advantage of Pythagoras is the flexibility of design, in that no combat or operational states are defined in the program—the user conditions such behaviors. Multiple options can be configured by employing novel design techniques.

Unfortunately, a major weakness is precisely this; a tolerance for complexity results in the inclusion of excessive detail. If a process is not abstracted to a reasonable degree, the concept of using Pythagoras as a low-resolution model is lost, as designs become increasingly intricate.

Nonetheless, it is the opinion of this researcher that the only limitations to the employment of Pythagoras for the design of any scenario are time and computer processor speed. Time limits the number of behaviors configured in the scenario, while processor speed limits the reasonable return on investment (ROI) in terms of raw data obtained for the time.

C. VARIATIONS FROM PREVIOUS RESEARCH

Several notable references and comparisons are made to the works of Kent (2007) and Roginski (2006), although major differences do exist. In some areas of reference, aspects of their design were tested and altered.

1. Variations from Kent

MAJ Walter Kent's Pythagoras model, "Effects of Situational Awareness on Infantry in an Urban, Chemical Environment," studied the implications of a future-force warrior platoon having to employ nuclear, biological and chemical (NBC) protective posture. Details obtained from MAJ Kent's analysis dealt only with modeling techniques pertaining to Pythagoras. No classified material was used.

Kent implemented a scheme of troop behaviors to a chemical agent, focusing primarily on lethal and symptomatic effects. This present study requires a scheme to model approximate nerve agent behavior on both civilians and emergency responders. As such, this study adopts Kent's scheme for emergency responder behavior in response to the CA, and uses the same characteristics to generate a similar scheme for civilians, who are bereft of protective equipment or detectors.

Kent also demonstrated a Chemical Vapor Model for Pythagoras, modeled for an outdoor release over a semi-built-up area. Principal considerations for the design and configuration of the Pythagoras representation dealt mainly with modeling plume effects over such areas. The scheme of behaviors for the chemical agent pertains to a non-explosive open-air release. This present study calibrates the behavior of the agent and the model using a test scheme to tune the settings of the simulation "agent" representing sarin and reconfigures their behavior to include explosive dispersal for an outdoor and indoor release in urban terrain. Factors such as large plumes, wind tunnels, encapsulation, and volatility (as a function of time) are also added to the scheme prescribed by Kent.

2. Variations from Roginski

MAJ Jonathan Roginski's work on "Emergency First Response to a Crisis Event: A Multi-Agent Approach" forms the second major work that this study builds on. Roginski's work proposed an approach to exploring disaster and terrorist responses in an urban event by simulating theoretical scenarios for testing, evaluating and complementing national terrorism-preparedness exercises in the United States, such as Exercise TOPOFF. This work centered on a deliberately planned emergency response, whereas this study focuses on the response to a sudden event with standby SOPs. In addition, the scenario excludes the physical presence of terrorists, preferring to concentrate on interactions between the CIED, civilians and emergency responders.

Roginski's simulations employed both a "Man, woman, child" (gender/age) design, as well as a "Good-Bad-Neutral" (alignment) design to functionally characterize the behavior of civilians. This study will not take into account the gender or age of the public affected; rather, for this research, it is more apt to concentrate on modeling the *compliancy* of the civilians. In this respect, the simulation configured in this study modifies Roginski's "alignment" design, altered with considerations from Festinger's social comparison theory (1954) and the findings of Mawson (2005).

Roginski's implementation in Pythagoras also demonstrated a novel representation for an IED, the size and impact of which was based on the Oklahoma City bombings of April 1995. This study analyzed the incident and reconfigured the design for the purposes of simulating a concealable payload for stationary indoor and outdoor activation, as well as a modification of the design to simulate a moving vehicle bomb.

A major difference from Roginski's implementation of civilian distribution is that in the current study, civilian movements are dictated by the terrain, their objectives relative to their roles (shopper or pedestrian), their desires (moving to next waypoint versus staying still), and their location (sidewalk or shop). This replaces the random distribution employed by Roginski, as it is the author's opinion that civilians in the scenarios either fulfill a purpose or are in transit to fulfilling their individual objectives, and hence cannot be assumed to be randomly distributed. Nonetheless, the design framework proposed by Roginski serves as a good basis for this research to elaborate.

D. CHARACTERISTICS OF THE SIMULATION MODEL

1. Time and Scale

Time in Pythagoras is represented as discrete time steps. As such, it is important to select an appropriate scale for real-time to simulation time step, so as to avoid agent "hopping;" an artifact behavior that results in agents "teleporting" from destination to destination, without ever interacting with the environment or other agents. Other administrative factors limiting the size of representation include the availability and speed the scenario runs under high-performance computing. For this study, one time step is selected to represent four seconds in real time.

Map scale in this study is aided by the fact that Pythagoras 2.0.3 has an increased capacity for scenario map size, up to 4000 by 4000 pixels. For this purpose, the simulation is set to the scale of one pixel to represent one square meter of real space. A terrain map of 2700 by 1800 was specified to contain the simulation. This corresponds to a 2.7 km by 1.8 km square area of operations.

Height and altitude are similarly expressed in terms of pixels. Where it is appropriate to represent elevated objects, the floor height of a terrain feature is increased. Ceiling height of a terrain feature represents its maximum height in the scenario.

2. Terrain Features

To characterize major terrain elements, a total of 12 different "features" were generated in Pythagoras simulation model. Each terrain feature has a set of attributes that can be configured to reflect the characteristics of the terrain element, such as predefined height, altitude, visibility, trafficability (for human mobility), protective properties, and values for concealment, which may be defined by pixel values or an arbitrary value setting from 0.0 to 1.0. Concealment settings were set to determine the capacity for a terrain feature to conceal agents from sensors set to Channels A (olfactory for human agents, chemoreception for detectors), B (visual) or C (audio). These will be elaborated on for sensor descriptions. See Table 3 for the Pythagoras terms associated with terrain characteristics deemed important for the simulation.

Characteristics	Actual Term	Pythagoras	Scale
Height	Height (m)	Ceiling Height (pixels)	0 – 140
Concealment	Concealment	Concealment	0.0 – 1.0
Movement	Trafficability	Mobility	0.0 – 1.0
Protection	Cover	Protection	0.0 – 1.0

Table 3. Translation of terrain element characteristics to Pythagoras feature terms (From: Roginski, 2006).

Pythagoras may use terrain type settings as multipliers to modify the probabilities of detection, rate of movement, or probability of being killed by a specific weapon. As Pythagoras takes into account only the top most layers of terrain features “drawn,” the order of features is important. Table 4 lists the settings for the 12 features created, in order of implementation. With respect to the scenario location, buildings have a relatively consistent ceiling height of 100 meters for retail outlets and 152 meters for tall buildings such as hotels and offices. This is illustrated in the photograph shown in Figure 8.

Figure 8. Above ground photo showing relatively uniform height of low-level and tall buildings. Image from Flicker (www.flickr.com).

Color	Name	Height (pixels)	Concealment			Mobility	Protection
			A	B	C		
Grey 50%	Sidewalk	0.0	0.1	0.1	0.1	1.0	0.0
Light Grey	Pavement	0.0	0.0	0.0	0.0	0.5	0.0
Black	Road	0.0	0.0	0.0	0.0	1.0	0.0
Magenta	Building	100	1.0	1.0	1.0	0.0	0.2
Dark Grey	Expressway	0.0	0.0	0.0	0.0	0.4	0.0
Sky Blue	Water	0.0	0.0	0.0	0.0	0.0	0.0
Dark Violet	Tall Building	152	1.0	1.0	1.0	0.0	0.0
Tan	Inside Building	0.0	0.1	0.1	0.1	0.999	0.0
Yellow	Pedestrian Crossing	0.0	0.0	0.0	0.0	1.0	0.0
Green	Vegetation	15	0.0	0.0	0.0	1.0	0.0
Dark Green	Unpassable Vegetation	20	0.0	1.0	1.0	0.0	0.2
Maroon	Building Facade	100	0.5	0.5	1.0	0.0	0.2 - 0.5

Table 4. Terrain types, colors and major settings used in the scenario.

An object that belongs to a specific type of terrain feature is “drawn” in the terrain map using the Pythagoras graphic user interface (GUI) and stored as a collection of waypoints closed by a loop. Each terrain feature has a library of “objects” that can be accessed and copied in extensible markup language (XML) format via a text editor to another scenario file. Figure 9 demonstrates this rendering, based on a satellite image of the scenario area. To resolve certain technical limitations on agent movement, some curved passages in the map were altered to prevent agents from being “stuck” in the simulation.

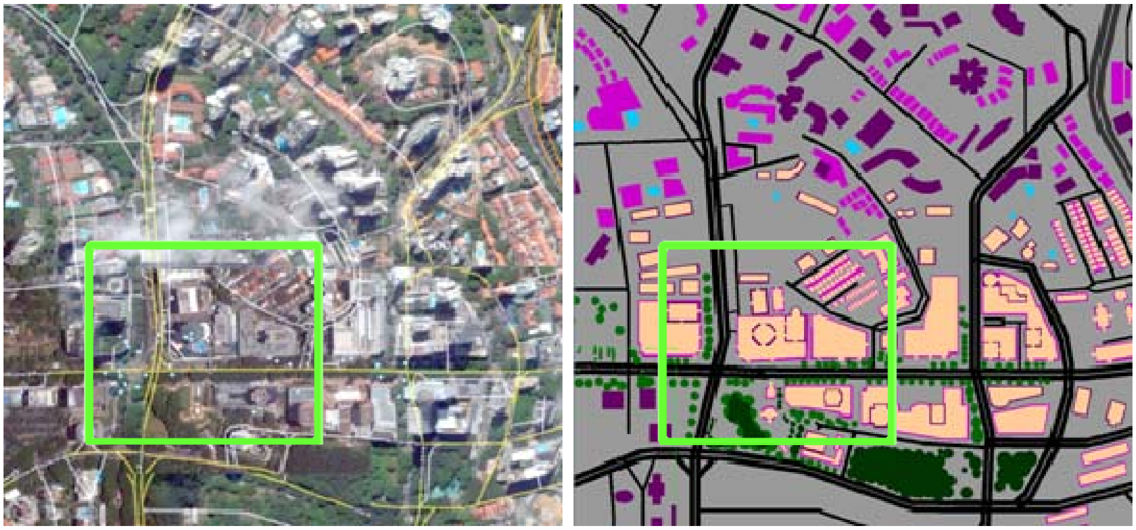

Figure 9. Segment of 2.7 by 1.8 sq. km. area of the central business district in Singapore (left), converted to Pythagoras Terrain Model (right). Location in green box corresponds to that shown in Figure 5. (Satellite imagery from Google Earth).

3. Weapons, Influence Tools and Restorative Capabilities

a. Description

Agents interact with their environment in Pythagoras via the use of weapons, which in turn may be re-termed "influence tools" if they represent effects other than a kinetic effect (KE). Weapons may alter the target's health, sidedness, or another user-selected attribute. Their effectiveness is influenced by:

- Probability of a hit associated with the weapon, as a function of range
- The marksmanship of the agent shooting
- The probability of kill or influence of the weapon, given a successful hit
- The effectiveness of a weapon (i.e., lethality)
- Vulnerability of the agent being shot
- Protection factor offered by the terrain

Table 5 summarizes the different weapons, influence tools, and restorative capabilities used in the simulation. Appendix B describes the capabilities and settings of weapons, influence tools (ITs) and restorative capabilities (RCs) used in the scenario.

Name	Type	User	Target	General Effect
9 mm Pistol (Glock 19)	KE	Police	E	Reduce Health
9 mm SMG (MP5)	KE	Police	E	Reduce Health
M4 SMG	KE	SAF	E	Reduce Health
IED (lethal Zone)	KE	CIED	F, E, N	Reduce Health
IED (Fragmentation)	KE	CIED	F, E, N	Reduce Health
IED (Flash and sound)	KE	CIED	F, E, N	Create Panic
Decontaminant	RC	SCDF decon crew	F, N	Reduce panic
Detection Alert	IT	SAF, SCDF	F	Alert for Masking
LethalChem	KE	CIED	F, E, N	Reduce Health, create panic
MiosisChem	KE	CIED	F, E, N	Alter attributes, create panic
Medical Kit	RC	SCDF Medical	F, N	Increase health, create compliance
OrdersFromCivilain	IT	Compliant civilians	F, N	Alter attributes, create compliance
Orders_to_Civilians	IT	All Responders	N	Alter attributes, Create compliance
Panic_Shouting	IT	Panicking Civilians	F, N	Alter attributes, create panic

Table 5. Summary of Kinetic Effects (KE), Influence Tools (IT), and Restorative Capabilities (RC). E = enemy; F = friendly; N = neutral.

b. Kinetic Effects (KEs)

KE refers to direct and indirect fire weapons, inclusive of the IED and chemical effects of sarin. Weaponry configured for the scenario reflects those carried by the SPF and SAF, typically small caliber arms of 9mm. Examples include 9 mm automatic pistols and MP5 submachine gun variants. United States Army Materiel Systems Analysis Activity (USMSAA) data compiled by Roginski (2006) was used to represent these weapons in Pythagoras. The effects of the IED are modeled as indirect fire weapons with a probability of kill derived either as a cookie-cutter or Carleton damage function (see Chapter III, section 9 for more details). LethalChem and MiosisChem demonstrate contaminating effects on target civilians by changing their color sidedness, in order to invoke an appropriate behavior from the emergency responders (see section 10 for more details).

c. Influence Tools (ITs)

ITs are used by one population of human agents in the scenario to exert an effect on another by increasing or decreasing the attribute levels of the intended targets. These are configured to represent instructive actions on the part of the responders' social influence of the civilians. The influence tools are configured to not cause damage, but to alter the agent attributes or color sidedness.

d. Restorative Capabilities (RCs)

Medical aid and chemical decontamination are modeled as weapons with RCs. The medical capability increases the "health" of injured civilians or friendly agents and reduces the psychological attributes responsible for inducing a panic state. This allows the injured civilian to enter a compliant state that allows him to seek further treatment or escape. The decontaminant capability reduces the color change associated by the contamination inflicted by the LethalChem and MiosisChem weapons.

4. Unit Affiliation

a. Description

Unit affiliations are represented in Pythagoras as Agent Side properties, calculated from the color "sidedness" of a particular side, a feature unique to Pythagoras (Bitinas, Henscheid & Truong, 2003). Each agent or affiliation is assigned a value for each color property—red, green, and blue. This in turn establishes their relationship relative to other agents. The calculation of color sidedness in this simulation is based on the Manhattan distance of one agent's color values to the other, when interpreted in the form of a two-dimensional plot. That is:

$$d = |Blue_2 - Blue_1| + |Green_2 - Green_1| + |Red_2 - Red_1|$$

This calculation was derived using a Microsoft Excel spreadsheet supplied by the distributors of Pythagoras. The relationships of the human agents and the CIED, relative to other agents, were determined this way.

b. Concept

Each functional group is assigned a distinct side, to enable the implementation of a single leader to be in command of the agents under the same side. Using the pair-wise color comparison spreadsheet bundled with Pythagoras 2.0.3, eight different agent sides were configured in this way to represent these affiliations. As Pythagoras will not function unless all agents have a side, the CIED is also assigned its own agent side. Given the highly integrated nature of the SCDF and SPF, as well as the visible nature of the SAF-CBRE responders, agent sidedness for all the emergency responders was assigned the color blue. The CIED side pertains to both the IED and chemical payload. The CIED was configured to take the color red. Friendly and neutral agents will, therefore, respond to the CIED (IED and sarin cloud) as the enemy only upon detection (i.e., by sight, smell, or chemical sensor).

A minor deviation from representing affiliation by sidedness is in representing chemical contamination. Only the civilians may change in color sidedness due to the influence of sarin. All the civilians begin the simulation affiliated with the color green. Each civilian may be chemically contaminated—this is modeled by an increase in red sidedness after being hit by the LethalChem and MiosisChem weapons. This combination of red and green allows emergency responders responsible for securing the site to respond appropriately to contaminated individuals and direct them to the decontamination points and triage areas. A limitation of this is that responders direct both injured and contaminated civilians to the same site for medical assistance. Table 6 summarizes the relationships of each side in the simulation. Appendix C contains more details on the implemented sidedness settings.

No.	NAME	UNIT (OWN)	FRIEND	ENEMY
1	CIED	1	None	2-6
2	Civilian	2	3-8	1
3	Division Police (Includes SOC)	3, 4	5-8	1
4	Fast Response Team Police Only	3,4	5-8	1
5	SAF-CBRE	5	2,4, 6-8	1
6	SCDF-Hazmat	6	2-5, 7, 8	1
7	SCDF-Medical	7	2-6, 8	1
8	Traffic Police	8	2-7	1

Table 6. Table of relationships among affiliations in simulation. Numbers correspond to the row numbers in table.

5. Sensors

a. Description

Sensors are configured in Pythagoras to detect a particular agent, based on three factors, the performance of the sensor in detecting an agent, the concealment factor of the terrain, and how detectable an agent is. The nature of the detection is assigned one of three different signatures, labeled A, B, and C, allowing the representation of smell (chemoreception), sight, and sound, respectively, or any other appropriate factor that the detector uses to sense the agents. The concealment of these signatures therefore, varies with the terrain, which may delay detection capacities by a factor set from 0 to 1. For a specific sensor, this can be summarized by the equation:

$$Actual\ P_{detection} = (1 - c_s) \times P_{detection}$$

where;

"c" = the concealment factor for a given terrain feature
"s" = signature, either smell, sight, or sound.

A profile for a specific sensor's detection probabilities is typified by that for the sensor representing human sight.

b. Concept

In total, six sensors were configured to correspond to actual features in real life, while one (ChemEyes) is assigned to facilitate the better simulation of the sarin gas plume. These are summarized in Table 7.

No.	NAME	REPRESENTS	SIG	USED BY
1	"ChemEyes"	Sarin Plume Behavior	B	All Chemical "Agents"
2	Eyes (in MOPP)	Vision through Gas Mask	B	All Emergency Responders
3	Eyes only	Unaided Vision	B	All Humans
4	Eyes in MOPP and Visor	Sight through Gas Mask and Perspex Visor	B	SAF, SCDF Hazmat
5	CAD	"Point" Chemical Agent Detection; i.e., by CAM, JCAD, Dräger Multiwarn	A	SAF, SCDF
6	Smell	Olfactory Function (i.e., smelling)	A	All Humans
7	Sound	Auditory Function (i.e., hearing)	C	All Humans

SIG = signature

Table 7. Summary of sensors implemented in simulation.

All human agents in the simulation are assigned detectors representing a sense of sight and smell, allowing them to sense their environment as per the settings defined for the terrain features and the agents. The exception is the CIED, which is meant to be hidden and is not visible, and the chemical "agents" that are released (signature A settings of zero). The chemical agent remains detectable by smell, and therefore can be detected by human agents that are not in a protective posture, i.e., in a state representing the use of a gas mask.

Emergency responders capable of adopting a protective posture possess additional sensors to demonstrate this, depending on their roles and functions. Since 2004, all SPF patrol officers are issued IPEs consisting of a gas mask and CA-resistant suit as part of their patrol car's trunk gear (Singapore Police Force, 2005c). In addition, follow-on forces are issued gas masks as part of a mobile supply vehicle that arrives on-site (Joihani, 2005). The simulation assumes that all follow-on forces are activated strictly in response to a chemical agent threat, and are therefore equipped to proceed to "mask up" in a protective posture. Thus, the transition of issuance of protective gear and response is omitted. SAF-CBRE and SCDF responders are assigned chemical agent detectors for their roles to detect the presence of sarin and respond accordingly.

6. Communication

a. Description

Communication is implemented in the scenario by either voice or radio devices. "Talking" is implemented as short-range line-of-sight (LOS) communication devices. Different response elements are assigned a dedicated radio "net" that may either be closed-communication (one channel) or networked to a larger system (many channels). The SPF, SCDF and TP have island-wide Terrestrial Trunked Radio (TETRA) networks. The SAF-CBRE network on site will consist of two-way radio communications, which have a shorter range compared to the digital communications of the police and fire service. Various other transmitting devices such as frequency jammers and telemetry for robotics are not modeled here, although it may be done in further research. As the scenario map does not exceed the maximum range of a typical TETRA network, all networks have a broadcast capability that spans the whole map. Centralized command, control and communications (C3) is established once the ICP is set up and all communication links reach the ICP site.

b. Concept

Three features in Pythagoras can be used to demonstrate communication—sensors, communication devices and sidedness settings. Sensors were used as a surrogate in earlier versions of Pythagoras and can represent omni-directional or LOS devices. Communication devices allow the designer to implement bandwidth as a factor in terms of the multiple channels assigned to a specific device. Sidedness settings can create "perfect" intelligence, where an agent can receive and transmit information about its unit members, friends or both. Information transmitted and received consists of:

- Agent location
- Agent affiliation
- Agent condition, in the form of generic attributes
- Agent leadership
- Resource reorder status for friendly and neutral agents

The updating feature will be explained later in the chapter.

7. Agent Behaviors

a. Description

Each agent is assigned a scheme of alternate behaviors that allow it to switch from its initial behavior when a trigger is met. This routine of behaviors can be seen as a representation of responder SOPs civilian psychology to threats or the physical behavior of non-living elements. These behaviors can be summarized as event-state-diagrams, such as that shown for leader behaviors in Figure 10.

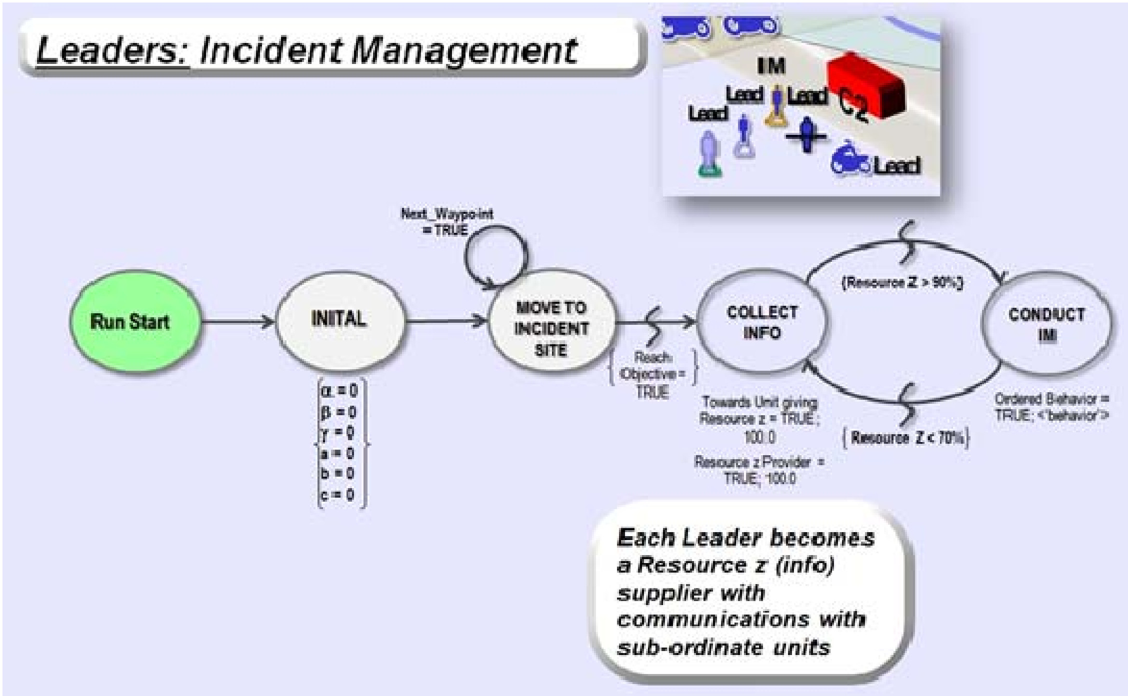

Figure 10. Event state diagram for leader behavior on activation.

A trigger is thus the "event" and the new alternate behavior is the "state." These alternate behaviors are characterized by distinct combinations of agent settings different from the initial setting. Diagrammatic descriptions of these behaviors are shown in Appendix D. In summary, the features that are variable are:

- Movement desires
- Engagement desires
- Agent attributes
- Alternate behaviors
- Leadership and obedience

b. Concept

The behavior of the chemical agent and civilian population is relatively homogenous in nature and will be described later in Sections D, part 9, and part 10, respectively. In contrast, the emergency standby response is a heterogeneous combination of behaviors that is either time- or event-dependent for triggering, and mostly specific to each emergency response force. The roles and function of each force are described as a combination of these behaviors. The assigned leaders of each force act independently to arrive at the incident site, and proceed to collect "information" configured as a resource. When the information gathered reaches a specific level, the leaders order specific behaviors in the subordinate agents. These agents proceed to the incident site and execute the next alternate behavior if the trigger condition is met, like arrival at a waypoint. To preserve the continuity of the agent's role, common behaviors such as the neutralization of an enemy threat or the execution of masking drills, cannot be shared among agents. These common characteristics are thus configured specifically for the agent. In summary, 142 different alternate behaviors describe the first hour of the emergency response, 124 of which describe emergency responder behavior. Behaviors of critical importance are described later in Section D, part 11.

8. Red: Improvised Explosive Device (IED)

a. Description and Concept

The IED is represented in the simulation as a combination of three separate elements. The first represents the primary blast wave generated from a detonation of a high explosive. The second represents the fragmentation effects generated by the blast. Each of these elements is designed as an agent assigned a specific "weapon" type that produces the bomb effects as overlapping areas of effect. Figure 11 shows the schematic representation and the visualization of the IED explosion in Pythagoras.

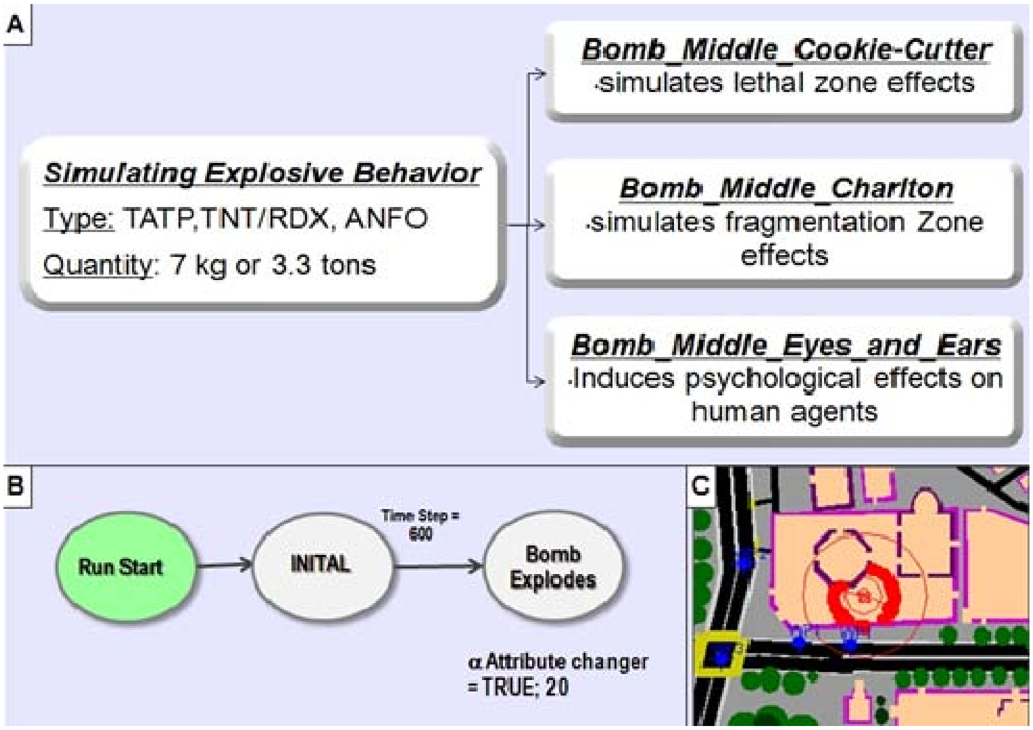

Figure 11. IED in simulation. A) Names of agents representing IED in both cases. B) Event state diagram summarizing behavior of IED. C) Screen shot of IED exploding, showing lethal (inner circle) and fragmentation (outer circle) zones. Red agents represent the sarin cloud released.

Box A in Figure 11 shows the agents that represent the IED. To separate the physical and psychological elements of the bomb for better flexibility in configuration, psychological effects from sight and sound generated by the detonation of the device are represented in "Eyes_and_Ears." This study "calibrates" the device for two cases.

(1) Man-Portable Device. A 7-8.5 kg device, with a primary payload made of TNT/RDX or tri-acetone-tri-peroxide (TATP) is selected for this device. TATP can be homemade, has a high detonation velocity, and has a 0.83 relative effectiveness factor, compared to TNT; i.e., 0.83 grams of TATP is equivalent to 1 gram of TNT. TNT/RDX is selected as it is the next most likely explosive that can be concealed in a small container and remain powerful enough to cause serious damage.

TNT is a constituent that was sought after by the JI cell in Singapore prior to the detainment of their members by Singaporean internal security (2003), while RDX is a common blasting explosive.

(2) Vehicular Bomb. The study employed a vehicle bomb equivalent to that used in the Oklahoma City bombing incident of 1995—a vehicular IED with an approximate 3.3-ton homemade Ammonium Nitrate Fuel Oil (ANFO) payload (Mlakar Sr., Corley, Sozen, & Throton, 1997). Owing to the large payload, the vehicular bomb is configured to have a slow ground speed (below 40 km/h), but will otherwise detonate on reaching its designated waypoint. Detailed calculations on the effective blast radius of the vehicle bomb are shown in Appendix A.

b. Calibration

Explosive blast and fragmentation effects are inherently hard to model. As such, the study concentrates on modeling and calibrating for the primary blast wave only, and disregard refraction and reflection of the energy generated from the blast. Factors such as reflection and absorption of the shock waves generated from an explosion, or the ejection of fragments from the device will be abstracted as part of two zones of effect—blast and fragmentation zones. Blast effects in the simulation are related to the theoretical overpressure generated by a military explosive or the experimental equivalency of a homemade explosive to a 50% RDX/TNT mixture. Explosive equivalency by mass is multiplied by the equivalent explosive factor calculated from the mass of the device casing and bare charge weight using the Proctor equation (Held, 1983). This takes into account the blast energy lost due to the casing around the payload.

$$C = 0.47 + \frac{0.53}{1 + \frac{M}{W}}$$

where:

C = the equivalent explosive factor;

M = Casing Weight (kg);

W = Explosive Weight, in terms of TNT (kg).

"C" is used to determine the effective mass of explosive that generates a blast effect. The equivalent mass of derived explosive, which is less than the actual bare charge weight, is then used to calculate the effective radius of a lethal overpressure zone. This is done by using the scaled distance derived from the expected range and payload in the relationship (Held, 1983):

$$S = \frac{R}{\sqrt[3]{Q}}$$

where:

S = the scaled Distance;

R = Effective Blast Radius (in meters);

Q = Weight of the explosive payload, in terms of TNT (kg).

Lethality in this case is based on achieving overpressure conditions that provide only a 90% probability of kill for a human being (White, Jones, Damon, Fletcher, & Richmond, 1971). This is more stringent with the general meaning applied to lethal range, which is the range of the indirect weapon that achieves 50% probability of kill. This is derived from the chart shown in Figure 12. Assuming a spherical effect, the maximum possible range to which this peak pressure may be maintained in the primary blast wave is set as the lethal zone (see Appendix A for the calculations and equations involved).

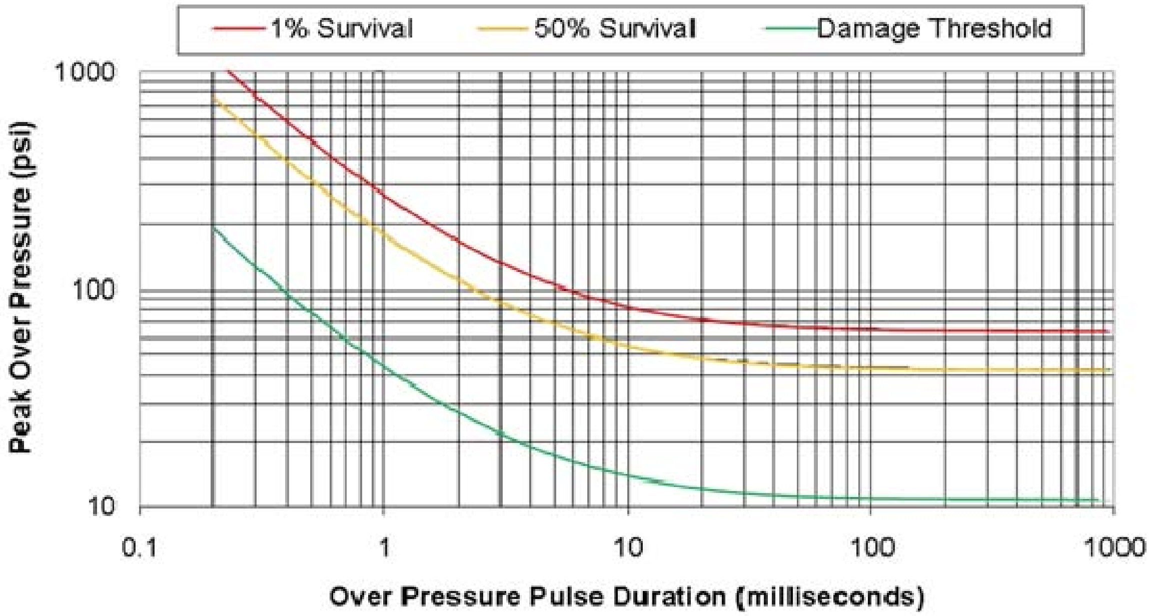

Figure 12. Human tolerance predictions for a 70-kg man in a free-stream blast wave (From: Gibson, 1994 and White, et al., 1971).

Fragmentation effects from the IED will be abstracted for the purposes of the simulation. Analysis on fragmentation effect is largely empirical in nature, so this study bases the damage caused by fragmentation on the probability of hit and the distance of the target from the epicenter of the blast.

c. Representation in Simulation

(1) Cookie-Cutter Damage Function. In Pythagoras, the lethal zone is implemented using a cookie-cutter damage function. In this case, there is no partial damage assessment. Any “human” represented by an agent in the simulation who is within the lethal zone is either killed or not, depending on the probability of a kill associated with the IED. The agent assigned to represent the fragmentation element of the IED will still affect human agents not killed by the cookie-cutter damage effects.

(2) Carleton Damage Function. The probability that a human agent outside the lethal zone is hit and injured by a fragment from the IED is calculated by a larger area-effect weapon set to use the Carleton damage function, the default choice

for the area effect of indirect fire in Pythagoras 2.0.3. The Carlton damage function describes the damage radiating out from a point of impact through the following equation.

$$P_k = e^{-\left[\frac{(distance)^2}{(radius)^2}\right]}$$

where:

P_k	= probability of kill;
distance	= distance of the target from Point of Impact;
radius	= size of the blast radius at which there is a 50% probability of being killed.

Figure 13 shows the exponential relationship between the probability of kill and the distance of the target from the epicenter of the attack. The probability of a kill resulting from this calculation is then modified by the effectiveness value of the IED "weapon" to provide the fixed amount of damage received by the agent. Other factors that modify the probability and damage incurred include the agent's vulnerability to the attack, the protection rendered to it by the terrain features between the epicenter and the target agent, and the terrain the target is on.

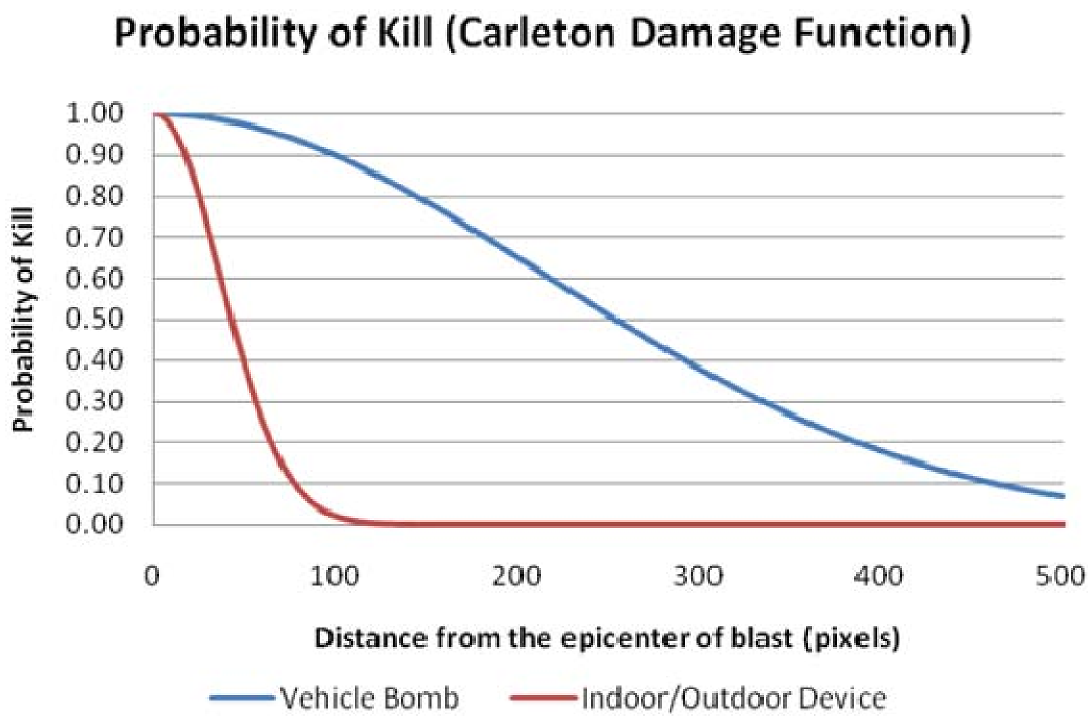

Figure 13. Probability of kill from fragmentation effect of IED, given a Carlton damage function relationship.

The psychological impact of the IED explosion is similarly modeled as an agent "armed" with an influence tool that "shoots" human agents based on a Carleton damage function (Roginski 2006). This is done under the assumption that a civilian further from the incident site would be less likely to be affected enough to go into panic state. The psychological effects of the bomb blast are thus inversely proportional to how far removed a civilian is from the epicenter of the blast.

9. Red: Chemical Payload

a. Description and Concept

The representation of the chemical agent sarin is based on a similar model implemented by Kent (2007). The chemical agent is represented by three different agent instances—“LethalChem,” “MiosisChem” and “MiosisChemPhase2.” Figure 14 summarizes the characteristics of the chemical payload in simulation. Rather than implement an earlier suggestion from the United States Air Force Research Lab (AFRL) to represent agent effect as concentric area effect weapons, this study retains Kent’s model, dubbed here the “particle model,” as it allows better interaction with the simulated urban environment.

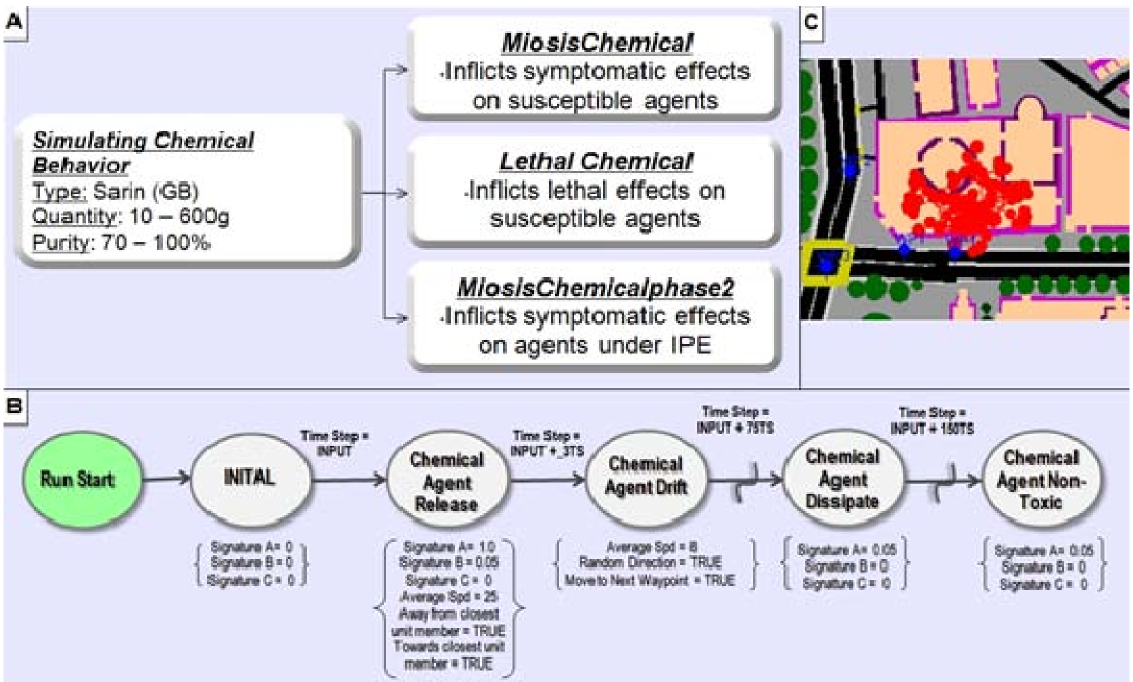

Figure 14. Chemical payload in simulation. (A) Names of agents representing the chemical payload for indoor and outdoor releases. (B) Diagram summarizing behavior of chemical agent release. (C) Screen shot of chemical agent release, showing the sarin cloud spreading inside the targeted store and out of entrances.

b. Calibration of the Chemical Agent Model

To calibrate the model to reflect the quantity and quality of the payload used, a "gas chamber" simulation was conducted to determine a representation for the median lethal concentration (LCt50) of sarin to be simulated, which would be approximated as the number of the agent instances required to generate a kill in 50% of a test population per unit time. The number of instances used was therefore benchmarked to the LCt50 values of a specific chemical warfare agent, so that a suitable number of instances would be entered into the simulation to reflect the amount of a chemical warfare agent used as a payload.

It is important to note that this is only an approximation to facilitate the suitable modeling of agent quantities in the simulation. Replicate runs of the "gas chamber" simulation did not produce any variation even with the inclusion of a variable degree of randomness in agent movements. The researcher deemed this sufficient for the purposes of the overall simulation.

The Pythagoras simulation for the gas chamber was set up to demonstrate both civilian agents and the chemical agent representations. A visualization of this is shown in Figure 15.

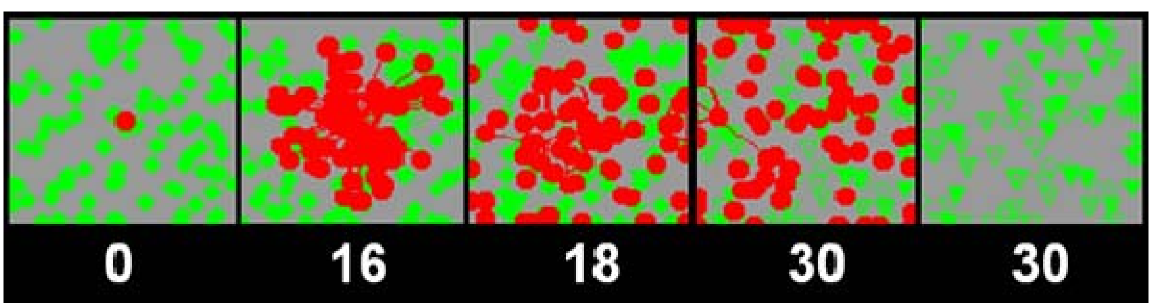

Figure 15. "Gas chamber" simulation at time steps 0, 16, 18 and 30 (with and without red agents displayed). One time step is equivalent to four seconds of real time.

One hundred civilian agents are randomly distributed and allowed to move randomly for 15 time steps (real time 60 seconds) until the agent is released to dissipate through the chamber for another 15 time steps. Thirty time steps is equivalent to two minutes. The total number of deaths was enumerated as an MOP for how effective the particle model is in representing a particular nerve agent, and was used to calibrate LethalChem, MiosisChem and MiosisChemPhase2 instances in accordance with the scenario payload quantity.

The instances (number of representations) for LethalChem agent were calibrated in accordance with the number of instances required to generate a death in 50% of the target population. The ratio of LethalChem to MiosisChem and MiosisChemPhase2 was kept constant to enable the desired plume effects, as described by Kent (2007).

10. Green: Civilians

a. Description

Civilians in the area of operations are either shoppers or in transit to some other location. The study de-emphasizes the impact of the age and sex of each individual, choosing instead to concentrate on modeling their typical behavior in the shopping district, before the incident and after. Pythagoras allows us to create civilians as a group of agents belonging to the same side, but with different initial settings.

b. Concept

The simulation models the intrinsic compliance and resultant behaviors of civilians before and after the initiation of the terrorist device. See Figure 16 for the event state diagram of civilian behavior.

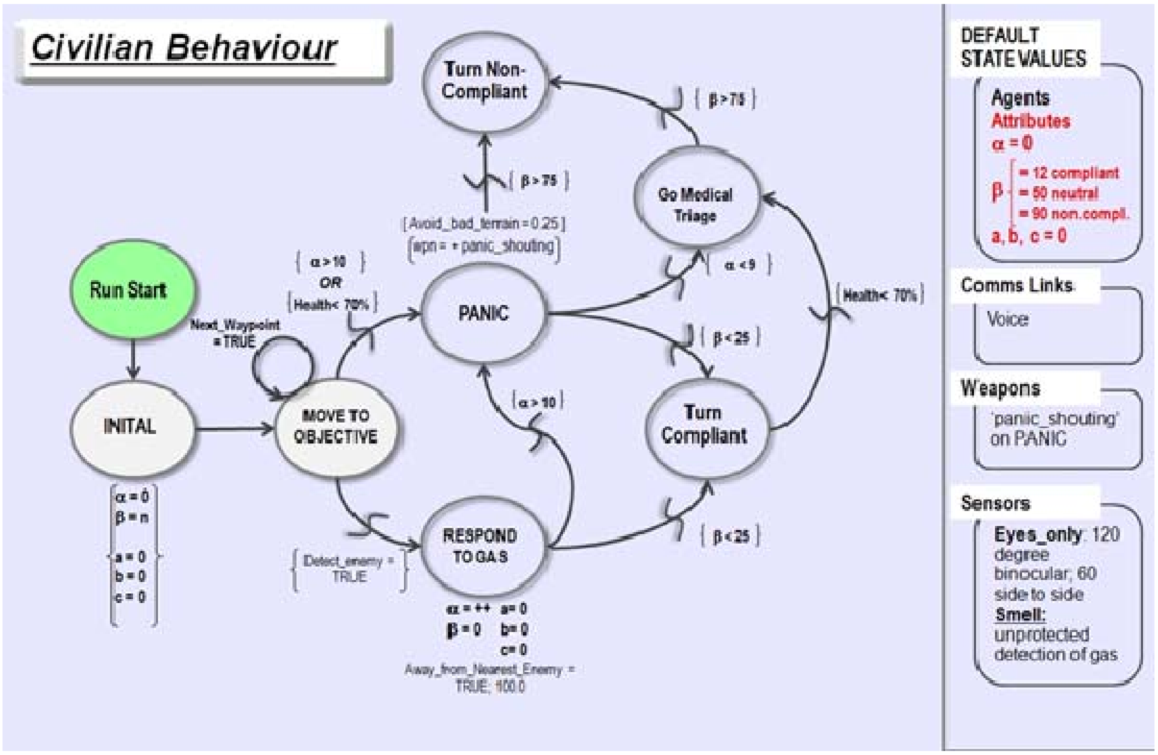

Figure 16. Event-state diagram summarizing civilian behavior.

Prior to the incident, civilians are categorized into three groups based on their tendency to follow instructional authority; i.e., whether they are compliant, non-compliant, or ambivalent (neutral). These three groups form the sub-populations using the walkways and the inner areas of buildings. Their representation may vary based on societal climate, like public sentiment to a government decision. Technical limitations for scenario runtime led the research to limiting their representation to 90 individuals per location. Walkway users move from point A to B and cycle back to represent two-way flow, whereas building users circulate through waypoints designated for each building. These two populations may inter-mingle along the façade meeting the walkways, but are otherwise orbital—they segregate to move to the next destination. Before the incident, civilians demonstrate directed movement and a strong desire to move to the next waypoint, with some tendency to stay in place, move in a random direction or maintain their existing course. Figure 17 illustrates the distribution areas for the civilians.

Figure 17. Civilian agent distribution in the scenario. Green boxes represent transit pedestrians. Cyan boxes represent shoppers. A dashed arrow represents an example of civilian movement to assigned waypoints.

In a crisis situation, civilians are influenced by both the effects of the incident and the behaviors of others. Compliant civilians tend towards maintaining public order and provide "orders" to reduce panic in a crisis. Non-compliant civilians tend toward alternate behaviors that detract from their tendency to follow orders, whereas neutral civilians begin to take on a compliant or non-compliant behavior once a crisis occurs, and respond accordingly. The study does not control the behaviors that the neutral civilians choose—this is allowed to be a product of the interaction between the neutral agent, the incident, and the existing "people" by whom the neutral civilian is surrounded.

Regardless of their compliancy, all civilians may be injured in the course of the incident. Ambulatory (i.e., walking) and non-ambulatory casualty behavior arises out of this. Ambulatory casualties seek to distance themselves as far as possible from the incident site, and may enter into a panic state whilst doing so. Non-ambulatory casualties cannot move and must await evacuation by rescuers in order to displace themselves from the incident site.

All civilians may enter into a state of panic, irrespective of whether they are injured or not. It is during this time that social comparison occurs. Panicking civilians must decide to move away from the detectable threat, stay in place, or follow the nearest "friend." The simulation allows this "choice" to be determined by the civilian agent with respect to its highest priority desire of movement, with escape as the highest. Civilians continue to stay in panic until an emergency responder interacts with them. This interaction consists of three effects: (1) the orders given to the panicking civilian by the responder; (2) the "calming" effect that responders provide to panicked civilians, modeled here as a resource; and (3) the restorative effects that responders provide using the medical kit. Sources of panic may come from being immediately affected by the explosion of the CIED, being influenced by the panic of other civilians or from the physiological impact of sarin poisoning in the human body. The latter is caused by lethal (nausea, headaches, loss of nervous-muscular control) or miosis-related (dimming and blurring of vision, eye-pain) effects (Romano Jr. & King, 2001).

11. Blue: Emergency Responders

a. Description

Emergency responders are introduced into the scenario in two parts: the initial response and the follow-on force. Force movement to the incident site is configured to represent vehicle speeds from 30 to 50 km/h, assuming average traffic volume at the time of the incident. Once agents arrive on site, they proceed with their respective functions in accordance to their roles.

b. Starting Locations

The approaches of the responders reflect their origins. These were determined by plotting the "shortest time" and "shortest distance" path possible from the parent base location to the incident site, using the "Google Maps" search engine. Based on NorthStar V (The New Paper 2006) and the author's experience, an approach was selected to best facilitate the likely arrangement with the initial response. These are shown in Figure 18.

Figure 18. Starting locations and approaches for emergency responders. (A) Traffic Police; (B) SAF-CBRE; (C) Initial Response Division Police and Civil Defence; (D) Follow-on divisional police.

c. Site Organization and Waypoints

The incident site is initially organized using a zoning template as a guide. Emergency isolation zones implemented for an indoor device differ from those of an outdoor device, in terms of the range implemented. Initial response force elements proceed up close to the incident site to conduct rescue and evacuation operations. Follow-on response elements and C3 assets are positioned outside the warm zone area bordered by a vapor contamination control line (VCCL). The ICP and force leaders move to a central location to meet and, as necessary, collect information, to enable the follow-on tasks. These elements may shift in position if the need arises, in which case the ICP relocates and force leaders head in the general direction of the information provider. TP elements arrive to erect traffic control points (TCPs) to manipulate traffic flow and ensure a feasible ingress and egress for emergency responders. The principal consideration for these roadblocks is the need to re-route traffic. As such, they do not correspond to the VCCL line, but may be approximately at or further than the template warm zone perimeter. Given the same location will be attacked with both an indoor and outdoor CIED activation; the roadblocks will be the same for both indoor and outdoor response scenarios. See Figure 19 for the approximate site organization of an outdoor and indoor incident site.

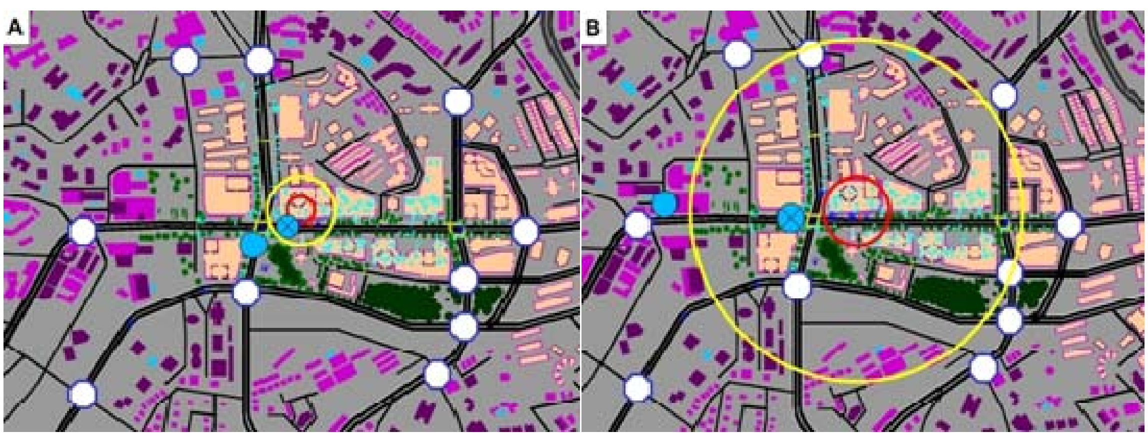

Figure 19. Approximated site organization for (A) Indoor device and (B) Outdoor device. In both cases, the blue circles with "X" denote the master waypoint for the initial response, and rescue elements. The empty blue circles represent the master waypoint for C3 and security elements. White circles represent traffic control points (TCPs).

A patrol route is implemented once divisional patrol officers and tactical units from the SOC arrive on site. The main role of the patrol officers is to clear the warm zone of unaffected civilians, while subsequently securing the ICP and directing civilians that approach it to proceed to the triage point. The tactical units proceed to each TCP to secure the perimeter of the incident site, to ensure public order, and to engage any left-behind terrorist threats. See Figure 20 for the direction of the routes taken.

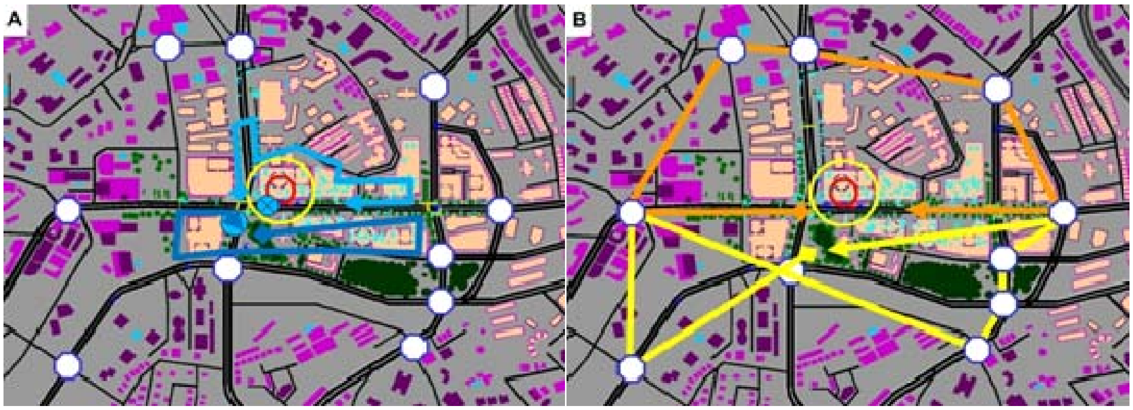

Figure 20. (A) Clearance route for division patrol officers and (B) Security patrol route for SOC tactical units.

d. Command and Control (C2)

This study provides a scheme to simulate the C2 process that occurs between the sub-ordinate units, the leaders, and incident management. Standby forces from each agency have a team leader and execute initial tasks independently of a central command structure, up until the follow-on forces arrive and the ICP is established. C2 is subsequently established hierarchically, with the SCDF senior commander (aggregated as part of the ICP) as the principal IM and each response force leader working in support of him. "Information" flows from the subordinate units to the ICP and the immediate leaders, who use the information to proceed with the imparting of orders, in the form of alternate behavior changes in the subordinate agents. When a leader begins to lose information due to consumption as a "resource," he proceeds to seek it from the ICP, which is a provider.

Communications representing blue force updates to the ICP are assigned an attribute changer that makes the ICP (as an agent) switch to an "updated" alternate behavior once the attribute is greater than a specified value. Information is depleted once the force leaders "consume" it as a resource, up until the ICP's updated attribute value fulfills the required update condition again. Sub-ordinate units are not configured to update their leaders, so the IM at the ICP has a C2 relationship with the leaders.

e. Protective Posture and Detection of Sarin

All emergency responders have the capacity to adopt a protective posture, i.e., execute a masking drill against a CA exposure. This confirms the availability of a gas mask to every responder on site. Detection will be by two methods: either the responder is not equipped with a chemical agent detector (CAD) and the responder will "mask-up" due to the smell, or the responder is equipped with a CAD and detects sarin early enough to adopt the protective posture. At the same time, the audible alarm of the CAD will inform the immediate vicinity of the detection of the sarin, prompting surrounding forces to mask-up as well. This broadcast range is short, but augmentation with transmitters could increase the range of the alarm.

12. Information and Decontamination

a. Information

Information has a qualitative and quantitative nature. The simulation defines the quality of the information in the emergency response to be time-sensitive during the acute phase of the process. This is easily achieved by the assignment of a specific channel and associated attribute changer to all the radio-nets for the updating of the ICP. The study thus assumes that the ICP has connectivity to all the communication nets used by the stand-by forces. The simulation describes the disseminative flow of information as a resource distributed from a supplier (the ICP) to a consumer (force leaders).

The timeliness and distribution of information at the incident site is represented by two mechanisms. Timeliness is demonstrated by an attribute assigned only to the ICP agent. Force leaders seek out the ICP in order to obtain information, up to the point at which an alternate behavior is triggered and the leader to its subordinates directs an order behavior. Once this occurs, leaders continue into an information consumption "loop" of orders and information receipt.

b. Decontamination

The decontamination process is meant to increase casualty survival by reducing the dwell time of the CA on the affected civilian. As this physical effect is hard to simulate in Pythagoras, the simulation models key aspects of CA contamination, relative to their importance in the response. Decontaminants are modeled as non-lethal "weapons" that reduce the red color sidedness of the contaminated casualty, while the decontamination point is modeled as a two-lane crew assigned a hazmat decontamination pod that provides decontaminants to the agents, which consume it as a resource. The decontamination lane reduces the casualty's red sidedness, supplies fuel to the casualty, and reduces its non-compliancy so that it may proceed to a triage point, indicated as a waypoint for a holding area.

E. PROOFING OF THE SIMULATION

Design details pertaining to the sarin and chemical defense model were discussed with Gerald M. Pearman, a contractor under TRAC-MTRY. Additional opinions were also sought from Bob McIntyre from AFRL on the implementation of the CA plume.

Initial trials and implementations of the simulations were conducted in part by conference during the Simulation Experiments & Efficient Designs (SEED) Center forums. Operational aspects scripted in the simulation were discussed with Ed

Lescnowicz, Research Associate with the Naval Postgraduate School, who has assisted in several thesis projects involving the use of Pythagoras.

Prototype simulation scenarios were run to generate a trial set of outputs for statistical analysis to determine the functionality of the scenario when run on a high-performance cluster. Assistance with this was provided by Steve Upton and Mary McDonald, Research Associates with the SEED Center.

F. MODEL ASSUMPTIONS, LIMITATIONS, AND ARTIFICIALITIES

The following points describe assumptions on the operation and scenarios, made because they are not of interest in this study, are valid assumptions, or they cannot be described *in silico*, given the technical limitations of Pythagoras 2.0.3.

- **No Targeting of Responders.** For the purposes of proof of concept, responders will not be attacked in the course of the simulation. Historically, there have been no cases of attacks on emergency responders in Singapore. It is possible, however, that aggressors will force activation in order to observe response procedures.
- **Equivalent Performance of Chemical Agent Detectors.** The SCDF and SAF employ different types of detectors that may or may not use the same technology. It is assumed, however, that the detectors are equivalent in performance and have a good capability in screening false positive results.
- **No Augmentation of Response Forces.** The response forces demonstrated in the simulation represent a functional organization for a single incident site. This can be augmented with additional; forces. However, to analyze the baseline response, the simulation does not allow for the augmentation of the response force.
- **High Volatility of Sarin in the Tropics.** Temperatures in Singapore range from 73 to 93 degrees Fahrenheit (National Environment Agency 2008). This suggests that the volatility of sarin is between 16,091 to 29800 mg/m^3 (United States Army 1990), and that the proposed 600g sarin plume may occupy a volume between 20 m^3 to 37 m^3. The persistency of sarin is thus expected to be low in Singapore.
- **Roadside Traffic Gives Way to Emergency Vehicles.** A common malady in Singapore is the failure of road traffic to give way to emergency vehicles. This is largely ignored in the simulation and it is assumed that responders are able to keep a consistent speed while moving to the incident site. The

variation in speed over time step for vehicular movement is thus kept to a minimum.

- **One-Hour Acute Phase.** The acute phase is limited to a 1-hour period or 900 time steps. The acute phase could be longer in a real activation, but by technical limitations, the study chooses not to exceed this number of time steps.

- **Platform-User Aggregation.** Drivers and other operational crewmembers are aggregated with the vehicle if the vehicle is meant to generate a particular function. A good example is the IM/ICP aggregation, which may include other real operators such as a telecommunication specialist. Another example is the SCDF hazmat decon pod and fire pump engine, both of which have drivers and operators.

- **No Morgue.** A morgue is not set up because of difficulties in modeling the movement of dead civilians by the SCDF rescue team. Otherwise, the requirement for a morgue influences the triage location and medical logistics support.

- **No Evacuation to the Hospital.** Following doctrine, all chemical casualties are decontaminated and triaged at the incident site. Uncontaminated physical casualties are treated in the same way, although this clearly may not be the case in a real incident.

IV. EXPERIMENTAL DESIGN

A. INTRODUCTION

For experiments, this study uses the technique of "data farming," a term coined by Brandstein and Horne (1998) to describe the running of a simulation model multiple times while simultaneously altering many input parameters. The resultant data sets generated allow the analyst to explore the "landscape" of potential outcomes given the parameter changes, to get better insight into the problem. Figure 21 summarizes the process.

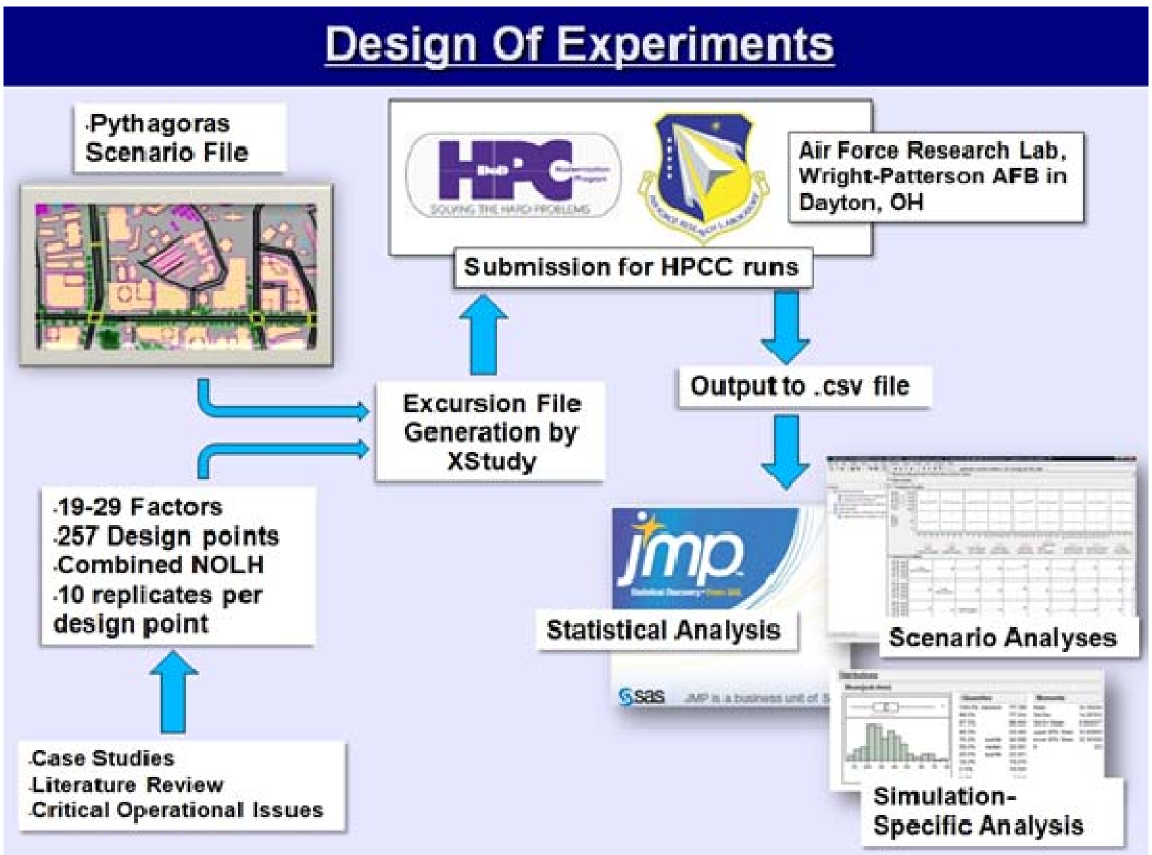

Figure 21. Diagrammatic Representation of the DOE process used in this study.

This chapter describes the experimental process of this study. In brief, specific design parameters were chosen from the Pythagoras scenario file as variables for analysis. Data were generated for statistical analysis, using highly DOE techniques and HPC. To test the feasibility of the scenario file on the HPC cluster, prototype runs were used to generate an initial set of experimental data. Data obtained from the prototyping were used to correct the scenario file, which was again run to form the basis of the base case scenario. Where necessary, some analysis on simulation-specific factors was conducted to determine the cause of technical problems in a data generation process.

This study also describes and explores, using the same DOE techniques, three different incident conditions. This chapter describes how the data were processed using commercial statistical analysis software.

B. MOE OUTPUTS

The primary MOE of interest is the survivorship of the civilian population, the improvement of which is the primary focus of the emergency response. Civilian survivorship was recorded for all scenarios used, by activating the pre-set MOEs recordable for agents in the Pythagoras scenario files.

C. VARIABLES OF INTEREST

The study classifies variables of interest as controllable factors (i.e., decision factors) and uncontrollable factors (i.e., noise or environmental factors) (Taguchi, 1987; Sanchez, 2000). Controllable factors are variables that are expected to be within the influence of the blue force, and determine the quality and quantity of the response. Uncontrollable factors are variables that are not within the influence of the blue force and therefore represent the environmental factors that the emergency responders must work with to mitigate the incident. The inclusion and analysis of uncontrollable factors is necessary to derive a degree of robustness in the simulation result, and thereby improve the researcher’s understanding of the data (Sanchez, 2006). The variables of interest have integer or continuous values, and are indicated in Tables 8 and 9. The possibility of autocorrelation was analyzed for each factor once data could be generated. This is explained in Section C.

No.	Factor	Range	Units	Remarks
1	No. of Fast Response Car Patrol Officers	*1… 4*	Persons	Number of personnel sent for standby response; i.e., force composition
2	No. of Fast Response Medical Teams	*1… 4*	Persons	
3	No. of Follow-On Medical Teams	*1… 4*	Persons	
4	No. of Pump Engine Rescuers	*1… 4*	Persons	
5	No. of Hazmat Rescuers	*1… 4*	Persons	
6	No. of Follow-On Patrol Officers	*2… 6*	Persons	
7	No. of Decon Pods and Teams	*1… 4*	Units	
8	Broadcast Range Orders to Civilians	20… 50	Meters	Represents control over the civilian population
9	Max Influence FRC Patrol Officers	*1… 10*	Persons	
10	Max Influence Div Follow-On Police	*1… 10*	Persons	
11	Max Influence Hazmat Rescuers	*1… 10*	Persons	
12	Max Influence Pump Engine Rescuers	*1… 10*	Persons	
13	Max Influence SOC tactical Officer	*1… 10*	Persons	
14	Max Influence Traffic Police Officer	*1… 10*	Persons	
15	Entry Time First Responders (SPF, SCDF)	7… 30	Minutes	For response times of initial and follow-on response
16	Entry Time SCDF Leader	7… 30	Minutes	
17	Entry Time TP Leader	7… 30	Minutes	
18	Entry Time Div Police Leader/SOC	7… 60	Minutes	
19	Entry Time Follow-on Patrol Officers	7… 60	Minutes	
20	CAD Detection Range	*30… 80*	Meters	Ability to respond to chemical threat
21	CAD Broadcast Range	*2… 10*	Meters	

Italics indicate integer values.

Table 8. Table of Controllable Factors used in the course of research.

No.	Factor	Range	Units	Remarks
1	No. of Compliant Civilians	*0… 30*	Person	Used in debugging, prototyping and scenario experiments
2	No. of Neutral Civilians at Start	*0… 30*	Person	
3	No. of Non-compliant Civilians at Start	*0… 30*	Person	
4	Non-compliance, Compliant Civilians	*0… 90*	Units	
5	Non-compliance, Neutral Civilians	*0… 90*	Units	
6	Non-compliance, Non-compliant Civilians	*0… 90*	Units	
7	P(Influence) by Compliant Civilians	0…1.00	NA	
8	P(Influence) Panicking Civilians	0…1.00	NA	
9	Smell Range	*0… 100*	Meters	Used in debugging and prototyping only.
10	Range of Panic Shouting	*1… 50*	Meters	
11	Orders Range, Compliant Civilian	*1… 50*	Meters	
12	Confusion in Panic	0… 100	NA	
13	Confusion in Panic for Compliants	0… 100	NA	
14	Panic induced from lethal symptoms	*0… 20*	Units	
15	Panic induced from Miosis	*0… 20*	Units	
16	'LethalChem' Instance	*9…40*	-	
17	'MiosisChem' Instance	*17…75*	-	
18	'MiosisChemphase2' Instance	17…75	-	
19	Detectability of Chemical Agent	0…1.00	-	

Green represents factors with respect to the civilian population.
Red represents factors with respect to the CIED.
Italics indicate integer values.

Table 9. Table of Uncontrollable Factors used in the course of research.

1. Controllable Factors

- **Number of FRC Patrol Officers.** This is defined as the number of FRC patrol officers that arrive on the scene at the start of the initial response.
- **Number of First Response Medical Teams.** This is defined as the number of medical teams that arrive on the scene at the start of the initial response.
- **Number of Follow-On Medical Teams.** This is defined as the number of medical teams that arrive as part of the follow-on response.
- **Number of Pump Engine Rescuers.** This is defined as the number of rescuers that will conduct snatch and grab rescue from the incident site in the initial response.
- **Number of Hazmat Rescuers.** This is defined as the number of rescuers that arrive as part of the follow-on response to conduct a rescue within the incident site and other contaminated areas.
- **Number of Follow-On Patrol Officers.** This is defined as the number of division patrol officers that arrive as part of the follow-on response.
- **Number of Decontamination Pods and Teams.** This is defined as the number of decontamination pods and crews that arrive as part of the follow-on response. Two teams are allocated to a decontamination pod, the allocation of which is "lock-stepped" to a single design point variable that changes the number of teams in proportion to the number of decontamination pods sent.
- **Broadcast Range of Orders To Civilians.** This is defined as the range of influence that an emergency responder's "orders" may affect a civilian of any condition.
- **Maximum Influence of FRC Patrol Officers.** This is defined as the maximum number of people a patrol officer can influence with one order.
- **Maximum Influence of Division Follow-On Police.** This is defined as the maximum number of people that division follow-on patrol officers can influence with one order.

- **Maximum Influence of Hazmat Rescuers.** This is defined as the maximum number of people that hazmat rescuers can influence at one order.

- **Maximum Influence of Pump Engine Rescuers.** This is defined as the maximum number of people that SCDF rescuers with the initial pump engine can influence with one order.

- **Maximum Influence of SOC Tactical Officers.** This is defined as the maximum number of people that SOC tactical officers can influence with one order.

- **Maximum Influence of Traffic Police Officer.** This is defined as the maximum number of people that TP officers can influence with one order.

- **Entry Time of First Responders.** This is defined as the time (in time steps) at which the First Responders enter the AO to proceed to the incident site. The entry times for the FRC patrol officers, SCDF pump engine, pump personnel and medical ambulance are "lock-stepped" to change as a single group.

- **Entry Time of SCDF Leader.** This is defined as the response time of the SCDF leader in arriving at the incident site.

- **Entry Time of TP Leader.** This is defined as the response time of the TP leader in arriving at the incident site.

- **Entry Time of Division Police Leader and SOC Tactical Units.** This is defined as the arrival time of the Division Police Leader and the SOC tactical units at the incident site. The entry times for the police leader and each SOC tactical officer is "lock-stepped" to change as a single group.

- **Entry Time of Follow-On Divisional Police Patrol Officers.** This is defined as the arrival time of the FRC in arriving at the incident site.

- **CA Detector Range.** This is defined as the maximum range at which the chemical agent detector may detect the CA.

- **CAD Broadcast Range.** This is defined as the maximum broadcast range at which an activated CAD is able to transmit a signal to another friendly agent.

2. Uncontrollable Factors

Uncontrollable factors represent environmental variables that cannot be influenced at the initial onset by the emergency responders. The uncontrollable factors used for analysis serve to better characterize the model, the scenario and the robustness of the results obtained from the simulation runs. The study will focus on two areas—the heterogeneous nature of the civilian population, and the nature of the CIED and gas hazard. Listed below are the uncontrollable factors examined in the experiments.

- **Number of Compliant Civilians.** This is defined as the number of civilians in the scenario at each location box that are initially compliant towards authority.
- **Number of Neutral Civilians at Start.** This is defined as the number of civilians in the scenario at each location box that are initially neutral towards compliance to authority.
- **Number of Non-compliant Civilians at Start.** This is defined as the number of civilians in the scenario at each location box that are initially non-compliant to authority.
- **Intrinsic Non-compliance of Compliant Civilians.** This is defined as the level of intrinsic non-compliance that the compliant civilian has at the start of the scenario.
- **Intrinsic Non-compliance of Neutral Civilians.** This is defined as the level of intrinsic non-compliance that the neutral civilian has at the start of the scenario.
- **Intrinsic Non-compliance of Non-Compliant Civilians.** This is defined as the level of intrinsic non-compliance that the non-compliant civilian has at the start of the scenario.

- **Probability of Influence by Compliant Civilians (Using Orders).** This is defined as the probability that a compliant civilian is able to reduce the non-compliancy of any targeted civilian.

- **Probability of Influence by Panicking Civilians (Using Panic).** This is defined as the probability that a panicking civilian is able to increase the panic attribute (and thus contribute to the panic) of any targeted civilian.

- **LethalChem Instance.** This is defined as the number of agents that correspond to the lethal effects of the sarin plume. This corresponds to how well sarin is able to cause lethal effects in civilians that come into close proximity with the plume formed.

- **MiosisChem Instance.** This is defined as the number of agents that correspond to the miosis-inducing effects of the sarin plume. This corresponds to how well the sarin is able to induce miosis in civilians who come into close proximity of the sarin plume.

- **MiosisChemPhase2 Instance.** Similar to Miosischem Instance, this influences the direction and expansion of the sarin plume that forms out of the release, and therefore directly impacts on the civilians surrounding the incident site.

- **Detectability of Chemical Agent.** This is defined as the delectability of the sarin characteristics, i.e., smell and miosis effects.

- **Smell Range.** This is defined as the maximum range of the human sense of smell at the given time of the day in the scenario.

- **Range of Panic Shouting.** This is defined as the maximum range in which a civilian under panic can communicate, and thus, potentially spread panic.

- **Range of Orders from a Compliant Civilian.** This is defined as the maximum range of the influence a compliant civilian is able to exert with an order.

- **Panic from Symptoms of Lethal Exposure.** This is defined as the impact that the lethal effect of the sarin plume has on inducing civilian panic. This translates the physiological effects of the sarin gas into a Pythagoras agent attribute changer that alters the agent attribute alpha.

- **Panic from Miosis Symptoms.** This is defined as the panic incurred by the impact of the miosis induced by the sarin plume.

- **Confusion in Panic.** This is defined as the desire of a civilian under panic to move in a random direction, and represents the clarity in the panicking civilian's decision-making response.

- **Confusion in Panic for Compliant Civilian.** This is defined as the desire of a compliant civilian under panic to move in a random direction, and represents the clarity in the panicking, but compliant, civilian's decision-making response.

3. Scenarios

The conditions described in Chapter III outline the "baseline" case scenario to which comparisons may be made. The following variations will be explored and analyzed using our DOE scheme.

a. Base Case: No Response

A simulation without responders will be used to analyze the interaction of an indoor CIED with the target population when no emergency response occurs. This will act as the control run for the analysis of all other scenarios and variations.

b. Scenario 1: Response to Indoor CIED Activation

Similar to that above, except this variation simulates a theoretical indoor release with an emergency response to the incident site. Emergency responder behaviors are configured to reflect the protocols meant for managing an indoor-exploded CIED.

c. Scenario 2: Response to Outdoor CIED Activation

The same device implemented in the above scenario is shifted to become a device employed in an outdoor setting. An outdoor setting allows for a larger gas plume, and requires a larger zoning protocol on the part of the emergency responders.

d. Scenario 3: Response to Vehicle-Borne IED (VBIED)

Using the same design concept for experimental design, an adaptation of the simulation employed by Roginski (2006), which itself is based on the Oklahoma City building bombing of 1995. This variation of the outdoor scenario is attempted to show proof-of-concept in the application of the simulation to large payload vehicle IED attacks. Comparisons will also be made to determine if the controllable factors that are influential on mitigating the outdoor incident are pertinent to the VBIED incident.

D. DESIGN OF EXPERIMENT (DOE)

1. Nearly Orthogonal Latin Hypercube (NOLH)

To improve the efficiency of the experiment, the study used a combined NOLH design (Cioppa, 2002; Cioppa and Lucas, 2007). Implementing the NOLH design has distinct advantages over a standard gridded design. A major advantage is that it gives a higher fidelity to the researcher, allowing better insight into the response from an entire range for each factor, while using fewer design points than a full factorial design of high and low settings. This is because of the higher efficiency and better space-filling property of an NOLH design format. This is illustrated in Figure 22, which represents the design space as a two-dimensional square plot.

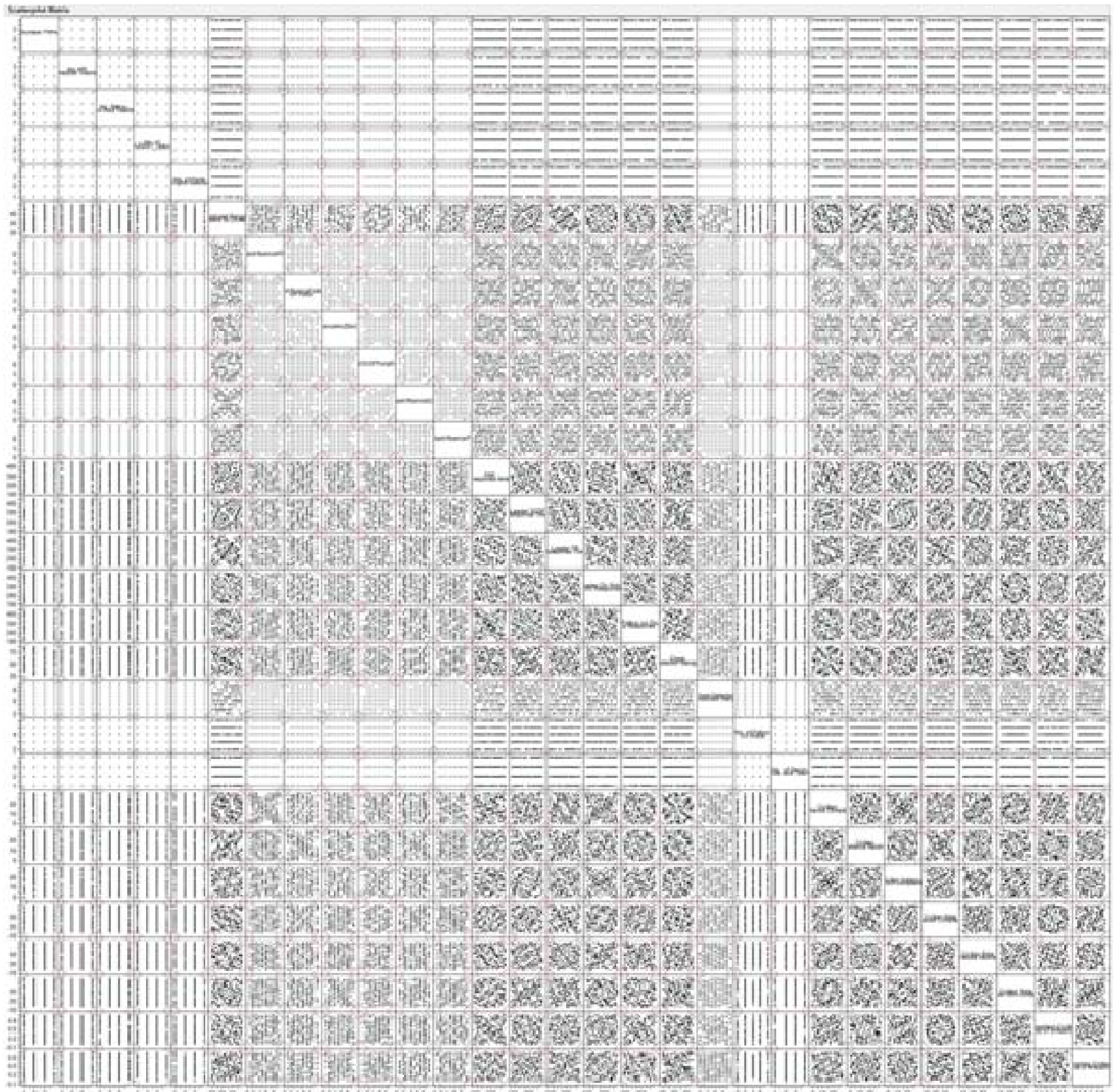

Figure 22. Scatter-plot matrix for an experimental design space of a NOLH Design. The plot represents 257 design points derived from 21 controllable factors and eight uncontrollable factors.

The NOLH was designed using a Microsoft Excel spreadsheet created by Professor Susan M. Sanchez of the Naval Postgraduate School (Sanchez, 2005). For technical purposes, NOLH size was limited to 29 factors.

2. Proofing and Debugging of Simulation and DOE

To ensure that the simulation could run on the HPC, 19 uncontrollable factors were used in a 29-factor NOLH design as an initial surrogate for the analysis runs. This generated a Cartesian product of 257 design points, each replicated 10 times, resulting in 2570 runs. The prototype was rerun with the 29-factor NOLH design to analyze the impact of the uncontrollable factors on the response (e.g., survivorship of civilians). To determine if factors were confounded, this study analyzed the correlation of their effects using the data outputs generated from each scenario run. Numerically, the maximum correlation coefficient between any two factors is 0.0786. None of the factors was highly correlated. See Appendix E for a diagrammatic representation.

The most influential uncontrollable factors were determined and used for a combined NOLH design (Sanchez 2006) with 21 controllable factors. The same NOLH design was applied to different scenarios and compared against the base case. A crossed design was considered to ensure better certainty on the results generated, but this option was not performed, given the possible simulation run-time overhead that would be generated—potentially $21^2 \times 8^2$ = 28224 design points, in 10 replicates = 282240 replicates, instead of 2,570 for a combined NOLH. Nonetheless, both designs implementing the NOLH design would still outperform the efficiency of a full-2^k multi-factorial design, with k being the total number of variables assessed (Sanchez, 2006). In contrast, implementing a gridded DOE would have resulted in 2^{29}-factorial design, generating 536,870,912 design points, with only two factorial settings for each factor, typically the boundary values, and assuming a linear response. Clearly, the implementation of an NOLH design outperforms the classical gridded design.

3. Scenario Runs on HPC Clusters

Using the factors identified and described above, the base case, indoor, outdoor and VBIED scenarios were run on the AFRL HPC cluster. Pythagoras scenario files (in XML format) and NOLH design spreadsheets (in comma separated value, [CSV] format) were input into XStudy. This is an application that presents a graphic user interface to allow a researcher to configure his simulation experiments and compile accompanying files into a submission for pre-processing and execution on the HPCs available (Upton, 2008). Steve Upton of the SEED Center did the processing required to facilitate the submission. Excursions representing the specific parameter configurations of each design point were generated for each of the scenarios. Custom Linux scripts were written to generate the job submission files for the Falcon HPC cluster, at the AFRL, Wright-Patterson AFB in Dayton, OH. Time allocation on that machine was part of the Department of Defense HPC Modernization Program (MP) User Productivity Enhancement and Technology Transfer (PET) initiative (http://www.hpcmo.hpc.mil/).

The use of an HPC cluster for running the simulation greatly improves the speed at which the data can be obtained. Supporting this is the fact that it takes seven days to edit and run the VBIED scenario submission, consisting of 2570 replications run with a mean time of 34 minutes. If run on a normal computer it would take up to 60 days (2,570 $\times$ 34 = 87,380 minutes = 1,456 hours) to run the vehicle bomb scenario to completion! By this approximation, five submissions to the cluster would take over a year to complete if run sequentially on the laptop computer used to design the initial simulation. Instead, scenario files were submitted for runs on October 4, 2008, and final submissions were returned by November 5, 2008. Completion of all experimental runs, including administrative time, error correction and re-submission, took only 32 days. Again, consider the far less astute use of the same cluster using a 2^{29}-factorial design. It would take 5.3 billion $\times$ 34 minutes = 247 millenia!

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V. DATA ANALYSIS

> We have the duty of formulating, of summarizing, and of communicating our conclusions, in intelligible form, in recognition of the right of other free minds to utilize them in making their own decisions.
>
> R. A. Fisher
> Statistician and Evolutionary Biologist
> 1955

A. DATA COLLECTION AND POST-PROCESSING

Data collected from the simulation runs were processed and analyzed in JMP 7.0, and S-plus 8.0, two commercial statistical software packages. There are two types of data obtained from the runs: the simulation-specific data that details the run times and completion of each replicate, and the scenario-specific data, detailing the response variables of survivorship for the civilian population and emergency responders. Both types of data are saved as CSV files that contain the input conditions in terms of the simulation parameters and the output data in terms of the settings configured in Pythagoras. The post-processing of data involves the calculation of the MOPs, from which the MOEs may be determined. The values from each set of replicates for every design point are then used to generate statistical data to characterize the distribution of the results. This process generates mean response values for each design point condition.

1. Cluster (Segmentation) Analysis

Where appropriate, cluster analysis was applied to identify outliers in the data set that demonstrate peculiar responses worth investigating. Cluster analysis, also called segmentation analysis or taxonomy analysis, is a way to create groups of objects, or clusters, in such a way that the profiles of objects in the same cluster are very similar and the profiles of objects in different clusters are quite distinct (Jain, Murty & Flynn 1999). This helps us identify specific objects that stand contrary to the general identity of the cluster. The study utilized COADM — "Cluster and Outlier Analysis for Data-Mining,"—a stand-alone statistical tool implemented by DSO, National Laboratories, for the purpose of cluster analysis.

2. Measures of Effectiveness (MOEs)

This research focuses on the following MOEs to answer the research questions.

a. MOE 1: Change in Civilian Survivorship with Responder Arrival Time

A general assumption for this MOE is that earlier arrival of emergency responders allows for the earlier activation for the response cascade. It may seem reasonable to expect civilian survivorship to improve with the earlier arrival of force elements in accordance with the emergency cascade. No historical evidence, however, exists to support the idea that an emergency response improves this, outside the efforts of the civilian population. This assumption will, therefore, be tested using data obtained in this study and will be discussed in Section B.

b. MOE 2: Change in Civilian Survivorship Versus No Response

Another generalized assumption is that the emergency response improves civilian survivorship, over no response at all. This assumes that civilian survival depends solely on responder actions and not on the survival behavior of the civilians affected. The focus is only on the quantitative change in civilian survivorship, as this study does not take into account the nature of the injury sustained by civilians. A statistical comparison of the percentage of civilians injured and dead out of the affected locations for both the base case scenario and the emergency response scenario will be performed.

c. MOE 3: Reduction in Civilian Panic

Security and control of the incident site requires on-site security elements to manage the affected people that are reacting negatively to the incident. Using the outdoor CIED scenario, the study analyzes this by determining the factors significant in controlling civilian panic and observing the reduction in the surrogate attribute used to signify human panic.

3. Calculation of Measures of Performance (MOPs)

To address the MOEs, a quantifiable measure is necessary. The study also analyzed the impact of increasing or decreasing the controllable factors on the MOPs, which in turn were used to determine the effectiveness of the emergency response procedures and the impact of varying the controllable factors. Data were derived from the simulations through configuring "MOE" settings in Pythagoras and were either treated as quantified MOPs for this study, or used as raw data to derive the MOPs. The data of primary interest is civilian survivorship because the main purpose of the emergency response is to limit the damage caused by the attack and protect the affected civilian population. This is evident given the COIs in Chapter II. With this in mind, this research defines the MOPs for civilian survivorship.

a. MOP 1: Percentage of Civilians Injured or Dead Out of the Affected Population

To relate the injuries and deaths inflicted on affected populations, the percentage values of each survivorship category were determined as the proportion of civilians in each state of survivorship out of the initial size of the affected population prior to device activation. Affected areas were qualified as the specific areas in the scenario map occupied by civilians that were covered by the maximum areas of effect for each device. As the civilian populations at a given site or area are composed of compliant, non-compliant or neutral populations, Pythagoras records the end point number of alive, injured and dead civilians based on these compliancy categories and for different areas. Since these population numbers vary with each NOLH design point, the target population size varies. The calculation for percentage survivorship at the affected area in the first hour of the standby response is therefore defined as:

$$\% \ Civilians_{status} = \frac{\sum Civilians_{group,status,area}}{\sum Civilians_{group,area}} \times 100;$$

where:

"group"	$\in$ {compliant, neutral, non-compliant};
"status"	$\in$ {alive, injured, dead};
"area"	$\in$ {T, SHW, LP,…}.

Survivorship values were calculated in JMP 7.0 and input as a new data column for each design point replicate. The expected counts for alive, injured or dead civilians were calculated as a mean value across multiple replicates for each design point run. This was typically ten replicates, with the exception of design points replicates that encountered "time-out" complications on the HPC cluster and therefore did not run to the end-point time step. The mean and standard deviation values for each set of replicates were then compared against their respective design parameters.

b. MOP 2: Percent Injured/Dead Civilians < Target Injured/Dead Civilians

MOE 2 requires the assessment of the improvement or decline in civilian survivorship that comes with emergency response, vis-à-vis no response. As there are no historical performance references for reducing casualties in the scenarios implemented, the analysis compares each design point response to the mean percentage injury or deaths for the entire scenario. This serves to benchmark the conditions associated with whether the performance of each design point resulted in a response below the reference value. An exception is taken for scenario #1, which can use the base case as the reference. The analysis implements the following logic to qualify MOP 2 for all conditions set by the design points of the NOLH:

$$Condition\ for\ Response\ = \begin{cases} 1\ ;\ if\ mean\ \ percent\ civilians\ injured < scenario\ mean \\ 0\ ;otherwise \end{cases}$$

The continuous response values now become a binary response variable that can be analyzed using either a logistic regression or a categorical regression tree.

c. *MOP 3: Mean Panic Associated with Compliant, Neutral and Non-compliant Civilian Populations*

As the composition of civilians at the incident site is made up of compliant, non-compliant, and neutral civilians, their reaction to both the incident and the emergency response will differ. The representation of each civilian demographic is by a singular agent class, of which multiple "instances" represent multiple people in the scenario. As such, Pythagoras will record the panic attribute for each class as an average value based on all "instances" (people) under the same class. The final "mean" value of the panic attribute for each design point replicate will be recorded at the end of the scenario. These replicates will therefore contribute to a master mean for that design point. Regression analysis will then be attempted on these values to determine what conditions can be associated with a lower degree of panic, and what commonalities exist in stemming panic across the three levels of compliancy. In notational form:

$$Panic\ of\ group\ at\ area = \frac{\frac{1}{n_{group,area}} \sum_{i=1}^{n_{group,area}} Panic\ attribute\ value_{\ i}}{no.of\ replicates}$$

where:

"group" $\in$ {compliant, neutral, non-compliant};

"area" $\in$ {T, SHW, LP,…};

"n" = number of civilians of a specific group and area.

To avoid losing resolution, the study investigates this in a location-specific manner. To maximize returns on the analysis for MOP 3, the study focuses on scenario #2, as the scenario demonstrates the capacity for the panic CIED to propagate over a large area, whereas for scenario #1, the incident is confined to the interior of the targeted shopping mall.

4. Initial Comparison of MOPs

An initial comparison of the mean percentage of injured and dead civilians gives us some initial insights. With respect to Figure 23, a comparison of the histograms generated for mean percentage injuries and deaths suggests that there is a slight difference in mean deaths and injuries for the base case and the indoor response scenario, with a slight increase in percentage injured for the latter. The outdoor scenario demonstrates a lower percentage of the target population being injured and killed. The VBIED scenario demonstrates a markedly higher percentage of injuries and deaths, although a larger spread of outlier values are noted as indicated by the outlier box plot in the right of the diagram. Outlier values also exist for the other two response scenarios and are indicated by the red circles. The mean percentage deaths also appear to have more variability in the data compared to the mean percentage injured and could be an indication of a poor association of response to the varied factors.

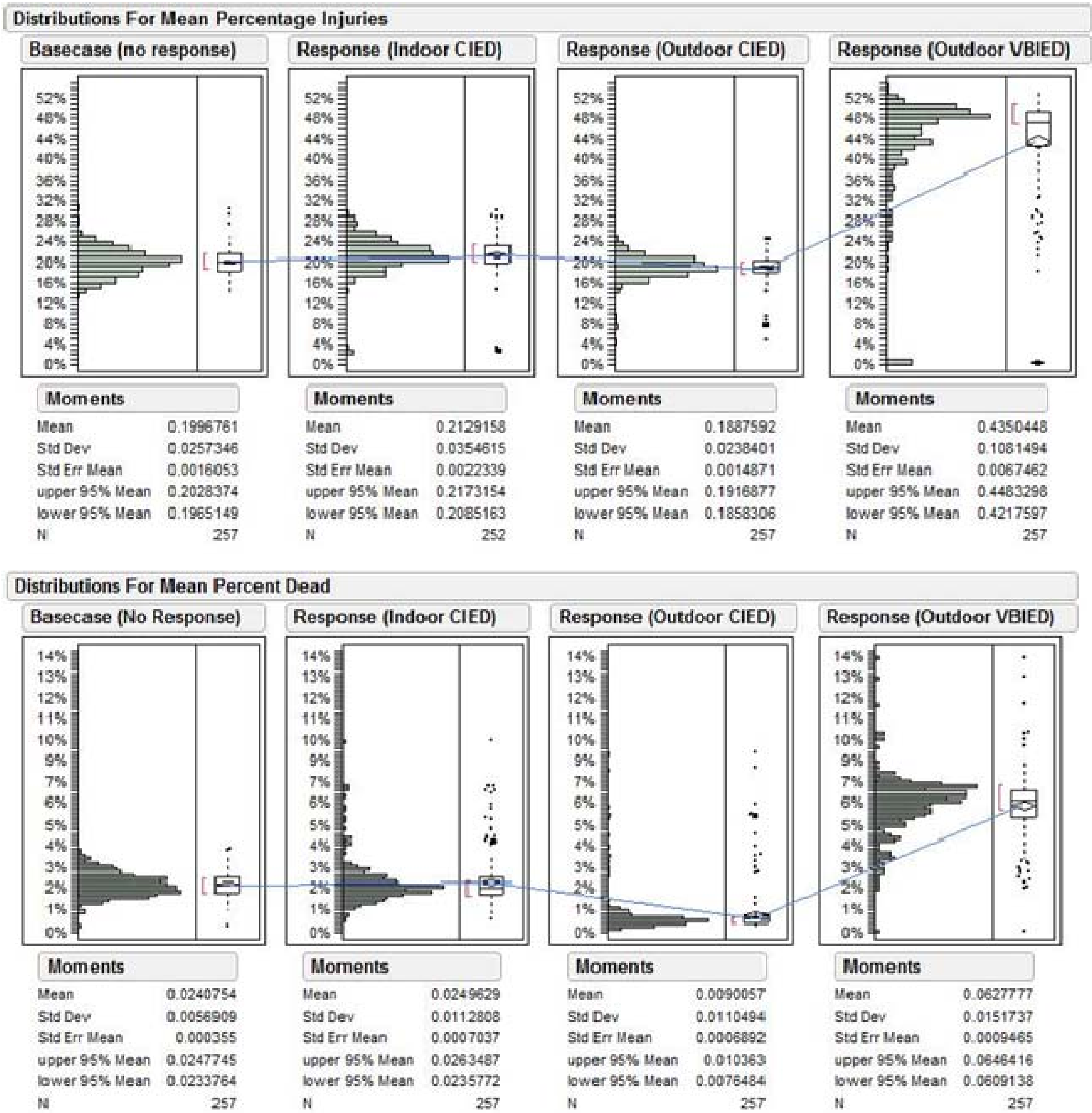


Figure 23. Histograms for all scenarios comparing percentage of injuries and deaths out of the affected population.

B. BASE CASE SCENARIO

Recall that the base case scenario allows us to compare the simulated impact of an incident in the absence of a response to a simulation inclusive of an activated emergency response. The analysis achieves this by analyzing the data set for both cases and then subsequently conducting a paired t-test to determine any significant difference between the responses obtained from both cases.

Partition (or regression) tree analysis partitions data recursively according to a relationship between the response and factors, creating a tree of partitions. Like a parametric regression, it finds a set of cuts or groupings of controllable factors that best predict the response. It does this by exhaustively searching all possible cuts or groupings. These splits (or partitions) of the data are done recursively forming a tree of decision rules until the desired fit is reached.

Regression tree analysis for the base case scenario revealed that the initial size of the population at the incident site influenced percentage survivorship the most. This corresponded with a parametric analysis of civilian survivorship versus the uncontrollable factors using Akaike Information Criterion (AIC) and a subsequent linear regression, shown in Figure 24.

Summary of Fit

RSquare	0.78719
RSquare Adj	0.775805
Root Mean Square Error	0.012185
Mean of Response	0.199676
Observations (or Sum Wgts)	257

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	13	0.13346116	0.010266	69.1434
Error	243	0.03608007	0.000148	Prob > F
C. Total	256	0.16954123		<.0001*

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
# Non-compliant Civilians	0.0023507	9.028e-5	26.04	<.0001*
# Neutral Civilians	-0.00082	9.047e-5	-9.07	<.0001*
(# Compliant Civilians-15.5019)*(# Compliant Civilians-15.5019)	6.1842e-5	0.000012	5.13	<.0001*
(# Compliant Civilians-15.5019)*(# Non-compliant Civilians-15.5019)	-4.053e-5	0.000011	-3.67	0.0003*
(# Neutral Civilians-15.5019)*(Compliant Civilian Range of Influence-25.5019)	-2.277e-5	6.499e-6	-3.50	0.0005*
(# Neutral Civilians-15.5019)*(Non-compliant Neutral Civilian-45.5019)	1.2266e-5	3.685e-6	3.33	0.0010*
(# Neutral Civilians-15.5019)*(# Non-compliant Civilians-15.5019)	-3.475e-5	0.000011	-3.16	0.0018*
(# Compliant Civilians-15.5019)*(# Neutral Civilians-15.5019)	2.8687e-5	1.042e-5	2.75	0.0064*
(# Compliant Civilians-15.5019)*(# Compliant Civilians-15.5019)*(# Compliant Civilians-15.5019)	-4.037e-6	1.622e-6	-2.49	0.0135*
Non-compliant Neutral Civilian	-0.000049	2.973e-5	-1.65	0.1006
Non-compliance Compliant Civilian	-3.921e-5	2.957e-5	-1.33	0.1861
Compliant Civilian Range of Influence	0.0000457	5.355e-5	0.85	0.3942
# Compliant Civilians	-4.286e-5	0.000226	-0.19	0.8500

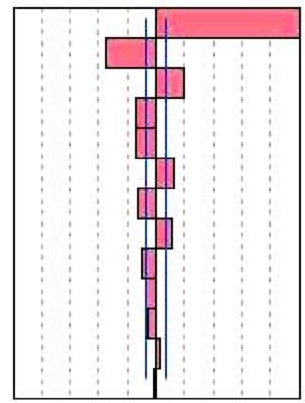


Figure 24. Regression Analysis results of mean percentage injured in base case scenario. Bar graph shows the t ratio, with blue line showing the 0.05 significance level.

Percentage combinations of neutral and non-compliant civilian numbers at the incident site explained the most variability in civilian survivorship and were the most statistically significant. Intuitively, more civilians in the target area would naturally mean more casualties and a higher possibility of injured and dead civilians.

To enable a robust assessment of the effect of the 21 selected controllable factors, civilian numbers would, based on our initial finding, be sufficient to complement them for the combined NOLH. The DOE continued to include eight uncontrollable factors into the design. The eight factors are, therefore, a combination of statistically-significant and interesting environmental factors in this study. As this study is more interested in understanding "civilian-responder" interactions, rather than "civilian-hazard" interactions, subsequent DOEs implementing the controllable factors excluded the factors "detectability of the chemical agent" and "sensitivity of human smell," and incorporated the factors corresponding to the intrinsic non-compliance of civilians, the influence of panicking individuals, and the influence of compliant individuals. The last two are of particular interest because they present the emergency responders and civil emergency planners with two options, both pertinent to the adequacy of emergency response procedures.

- Is it beneficial to incorporate into existing SOPs the task to apprehend and detain overly panicked individuals to stem the spread of panic?
- Is it beneficial to have compliant people that assist emergency-response efforts in the population?

Singapore's existing public education system for civil defense and emergency preparedness has the central objective of preparing the public to respond appropriately to an emergency incident. Civilian volunteers could be called upon to assist in emergencies affecting their communities, or simply support responders by behaving in a compliant manner and follow evacuation instructions.

C. SCENARIO #1: EMERGENCY RESPONSE TO INDOOR DEVICE

1. MOP 1: Comparison with Base Case Scenario

A paired t-test was conducted between the base case scenario and scenario #1 to determine if there was any significant difference, at 95% confidence, for the mean percentage of civilian injuries and deaths. Two hundred and forty-seven design points were compared. Five design points were lost in scenario #1 and five were removed from both sets as they lacked an operational basis. Results are shown in Figure 25. These suggest a statistically significant difference in the mean percentage of injuries sustained by the affected civilian population. Paired t-test results for mean percentage of deaths between base case and scenario #1 prove inconclusive; given only a 64.5% confidence achieved in disproving a difference.

t-test statistics	Mean Percent Injured (Scenario 1)	Mean Percent Injured (Base Case)	Mean Percent Dead (Scenario 1)	Mean Percent Dead (Base Case)
Mean	21.6	20.0	2.39	2.41
Variance	6.99×10^{-4}	6.69×10^{-4}	8.93×10^{-5}	3.82×10^{-5}
Observations	247	247	247	247
Pearson Correlation	0.302		0.0876	
Hypothesized Mean Difference	0		0	
Degrees of Freedom	246		246	
t Stat	**8.13**		**-0.373**	
P(T<= t) two-tail	$\mathbf{1.093 \times 10^{-14}}$		**0.355**	
t Critical two-tail	1.65		1.65	

Figure 25. Paired t-test results comparing percentage civilian injuries and deaths in the base case and scenario #1.

The t-test results suggest, rather counter-intuitively, that the conditions implemented by an emergency response might serve to increase the mean injured numbers in the affected population, albeit by only one percent. This leads to the question of why and how scenario #1 demonstrates this difference. To answer this, regression tree analysis was performed to determine which controllable factors, and at what values, were the most significant in influencing the mean deaths. The analysis disregarded the considerably low R-square value and kept in mind that the regression tree only considered controllable factors.

a. *Entry Time of Division Police Leader and SOC*

The entry time of the division police leader into the AO occupies the top-most tier of the regression tree—this is shown in Figure 26. An arrival time into the scenario map before time step 122 (approximately eight minutes) appears to correspond with fewer casualties, for both leaders. If both leaders take a longer time to arrive, then the next most significant factor in influencing the response is the maximum influence of the FRC patrol officers.

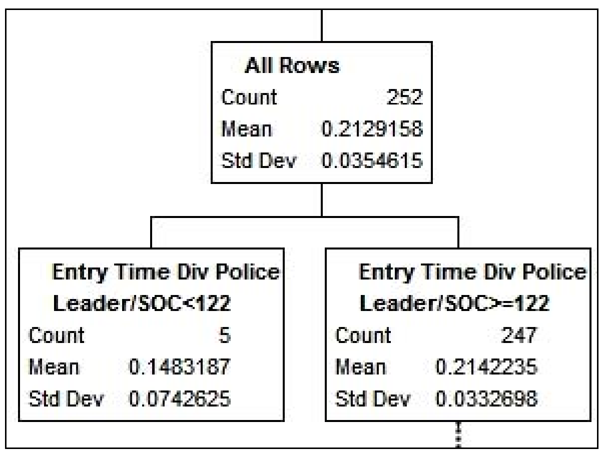


Figure 26. Scenario #1: Regression Tree of first statistically significant factor with mean percentage injured civilians as response, taking into account controllable factors (R-square = 0.142).

It is possible that the earlier arrival of the SOC allows for a more rapid clearance of civilians out of the incident site, leading to fewer casualties exposed to the sarin plume either in the incident building or within the vicinity of the origin of the plume. The entry time for the arrival of the division police leader and SOC to arrive on-site are surprising—122 time steps, corresponding to eight minutes. Operationally, this suggests that the arrival of the command group must occur almost as soon as the arrival of the FRC and patrol officers. Only five data points represent time step values below 122. This explains the small count on this “leaf.” Anecdotal reports of efficiency in response, particularly in exercise events, demonstrate such a finding (TODAY News Desk 2006). Nevertheless, what if this is not operationally feasible? One must look further down the regression tree.

b. Maximum Influence of FRC Patrol Officers

Figure 27 shows the branching of the regression tree continuing from Figure 26. If the patrol officers that arrive with the initial response (i.e., the FRC patrol officers) are able to influence at least 10 or more civilians, the mean percentage of injuries sustained by the civilian population can be improved by 3%. The data indicated suggests a large standard deviation, but the mean improvement is substantial, if coming from the viewpoint that a small improvement in civilian survival remains operationally useful. This effect translates into requiring the fast response force to control and communicate to civilians at a higher —not one or a few civilians, but *10* at a time! One feasible method would be to equip these first responders with loudspeakers. However, their use when in a protective posture would naturally be a technical complication. Thus, a suggestion would be to incorporate personal audio speaker systems that are compatible with existing individual protective equipment (IPE). This observation is not a new one—such devices exist and serve to reduce the difficulty of man-to-man communication in troops during gas mask use. Future research into procurement might consider loudspeaker functions as well.

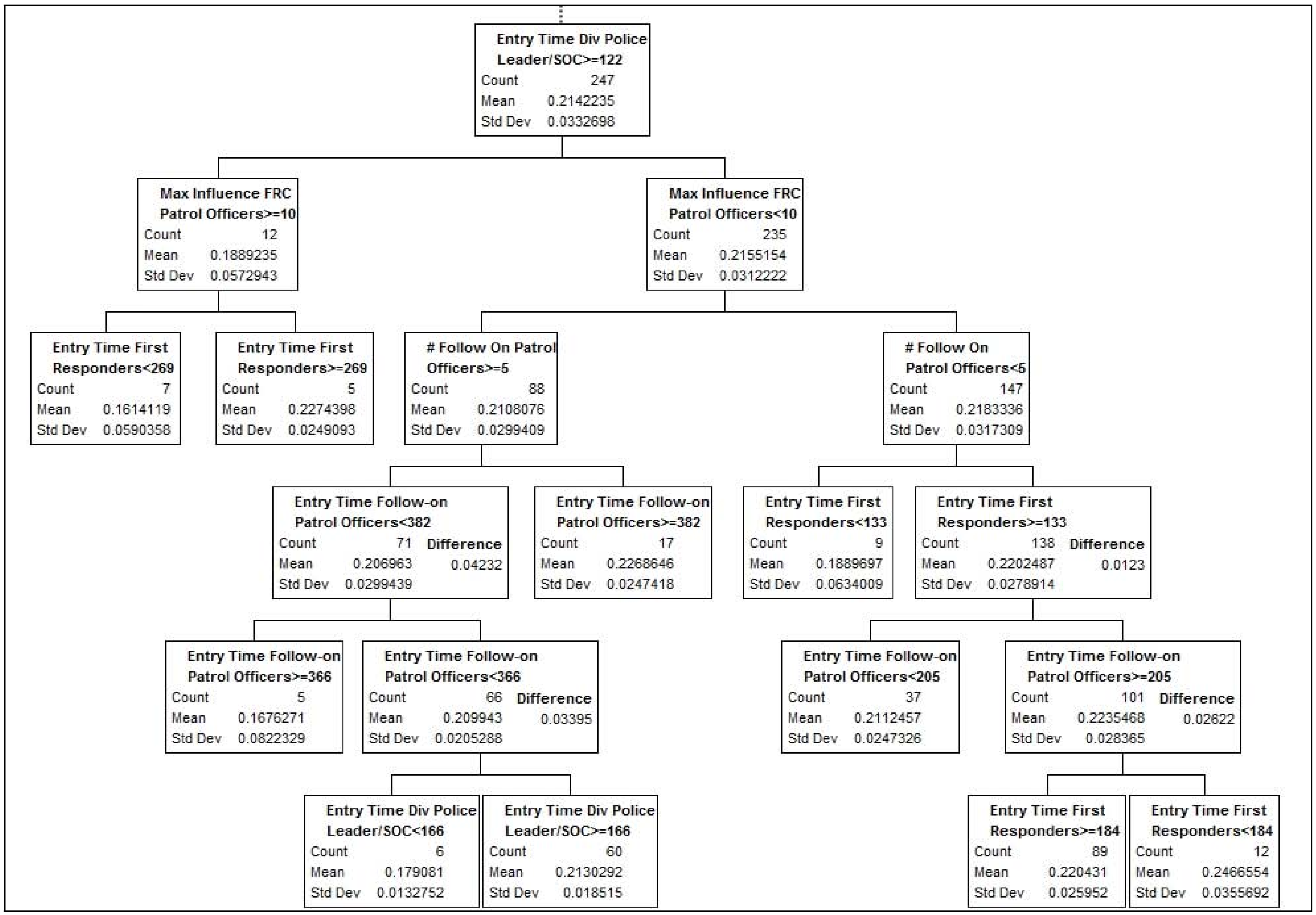


Figure 27. Scenario #1: Continuation of regression tree for MOP 1. Subsequent significant controllable factors given that the arrival of the division police leader and SOC units arrive after eight minutes (R-square 0.142).

Where influence over the civilian population by the FRC patrol officers can be achieved at 10 persons per responder, their earlier arrival will further reduce civilian injury rates by 4%, if arrival time occurs before 269 time steps (18 minutes). When the influence over the civilian population by the FRC patrol officers is less than 10, then the next significant factor would be to employ more than five follow-on patrol officers. If this is achievable and the entry time of these follow-on officers can occur within 24 to 25 minutes of the start of the incident, then the mean percentage of injured could be equivalent to that incurred when the FRC patrol officers are able to influence at least 10 civilians.

Conditions reducing the maximum influence by the FRC patrol officers would necessitate a larger follow-on force in several ways. For instance, a fast-degrading condition of public calm might reduce police influence on the public. The data analysis considers a linear regression for scenario #1 and generates the interaction plots for the controllable factors. Where it is not possible to have the follow-on force arrive with a sizable number of patrol officers (e.g., when available officers are engaged in other activities such as deliberate operations, or are too far away to respond in time), the response force's capacity to reduce civilian injuries then depends solely on how early the first responders arrive on site. An earlier arrival (within eight minutes) would improve the mean percentage of civilian injuries by 3 percent.

Given the low R-square values for the regression tree, a stepwise regression with all 29 controllable and uncontrollable factors determined which factors were most significant in estimating MOP 1. See Appendix F for the regression output form JMP 7.0. In general, the regression better accounted better for the variability, but showed the greater significance of the environmental factors in the process. The parametric expression of the regression fit resulted in the inclusion of 38 regressor terms, 21 of which are interaction and quadratic terms. While taking into account that the regression represents a multi-dimensional problem and that responses may not necessarily be directly associated with regressor values, the analysis investigated two regressor terms, as both involved controllable factors only. To analyze their influence on MOP 1, the contour plots shown in Figure 28 and Figure 29 were generated.

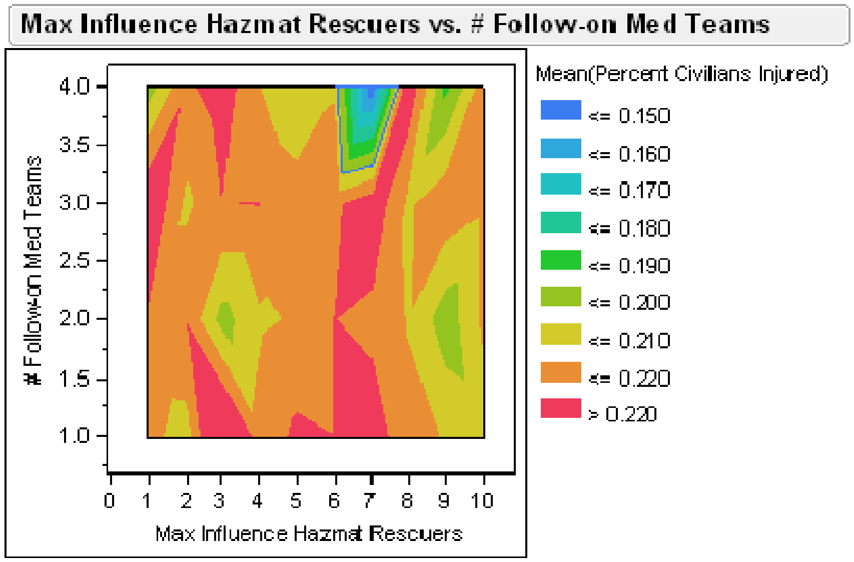


Figure 28. Contour plot for maximum influence hazmat rescuers vs. # follow-on medical teams.

From Figure 28, it becomes obvious that there is an optimum region associated with the two factors. The contour plot suggests that if the maximum influence of the hazmat rescuers is seven per rescuer and the number of follow-on medical teams stands at four, the MOP 1 value associated with it is 0.15 (15%) or less. This observation must be taken with some caution as a plot of the data points contributing to the contour plot (which is not shown here), indicate that this "ideal" contour area is represented by only one design point, which was found to have no representation of neutral civilians. Subsequent referencing in the data set revealed that the design point representing the response in the outlined area only has 29 persons at any single location—15 compliant, 14 non-compliant, and no neutrals. Similar trends surface in subsequent contour plots, all shown in Appendix F.

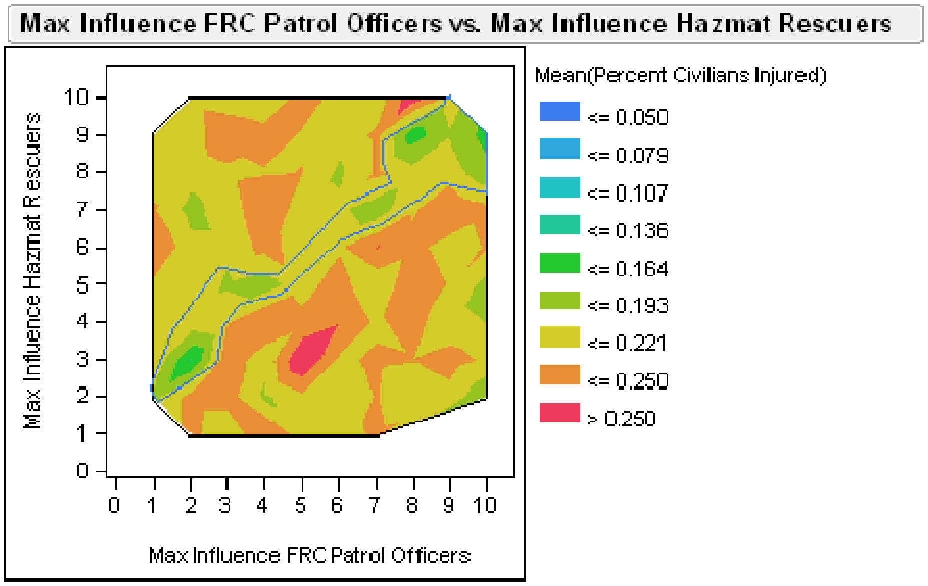


Figure 29. Contour plot for maximum influence of FRC patrol officers vs. maximum influence of hazmat rescuers.

From Figure 29, a "valley" of contours suggests a trend worth investigating. The outlined area suggests that if the maximum influence of the hazmat rescuers is slightly above par with the maximum influence of the FRC patrol officers, by one person, MOP 1 does not go beyond 0.221 (22%). As the contour plot only explores the data set in three dimensions (two factors and a response), where, in fact, the data set is for a multi-dimensional problem, the proof of any relationship would have to be done on separate runs focusing on these two factors.

2. MOP 2: Analysis and Categorical Regression Tree

MOP 2 for scenario #1 determines which controllable factors are significantly associated to a mean percentage injury rate of less than 20%, the overall mean civilian injuries observed from the base case. A histogram illustrating the classification of the design-point specific responses for MOP 2 is shown in Figure 30. Included is the corresponding histogram for the base case when scored on the same condition. Approximately one-third of the data set appears to support MOP 2 =1, indicating brevity of conditions that might potentially be studied to limit civilian injuries from being exacerbated by the response. Although the base case presents slightly more counts which qualify for MOP 2 =1, this stage of the analysis focuses on the controllable factors.

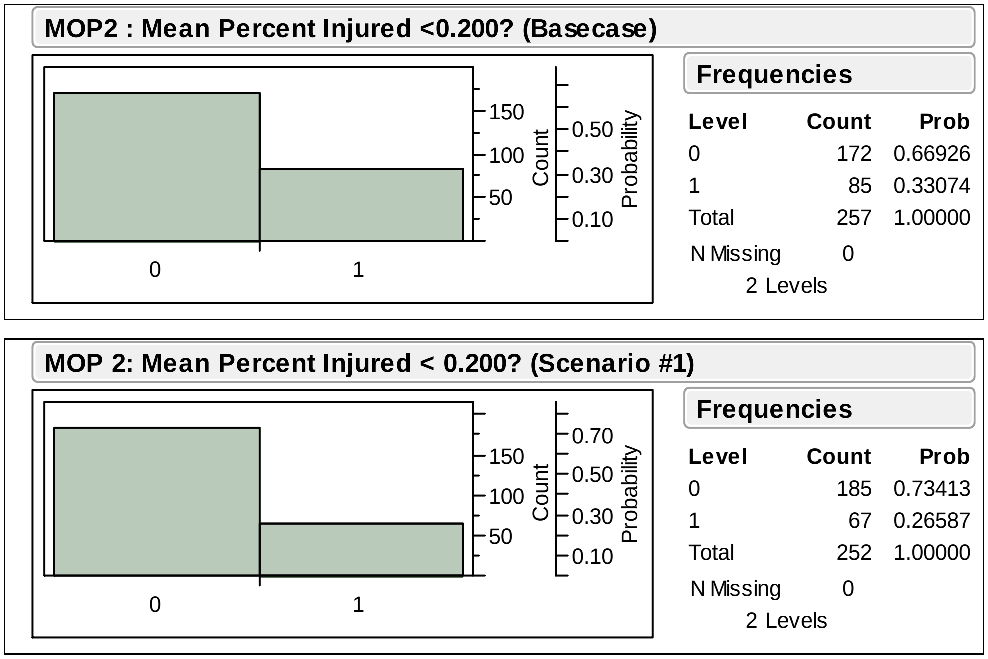


Figure 30. Base case and Scenario #1: Histogram for MOP 2 occurrence and probabilities.

This stage of the analysis uses a categorical regression tree to determine which factors best predict for a higher probability for MOP 2 = 1. The tree is shown in Figure 31.

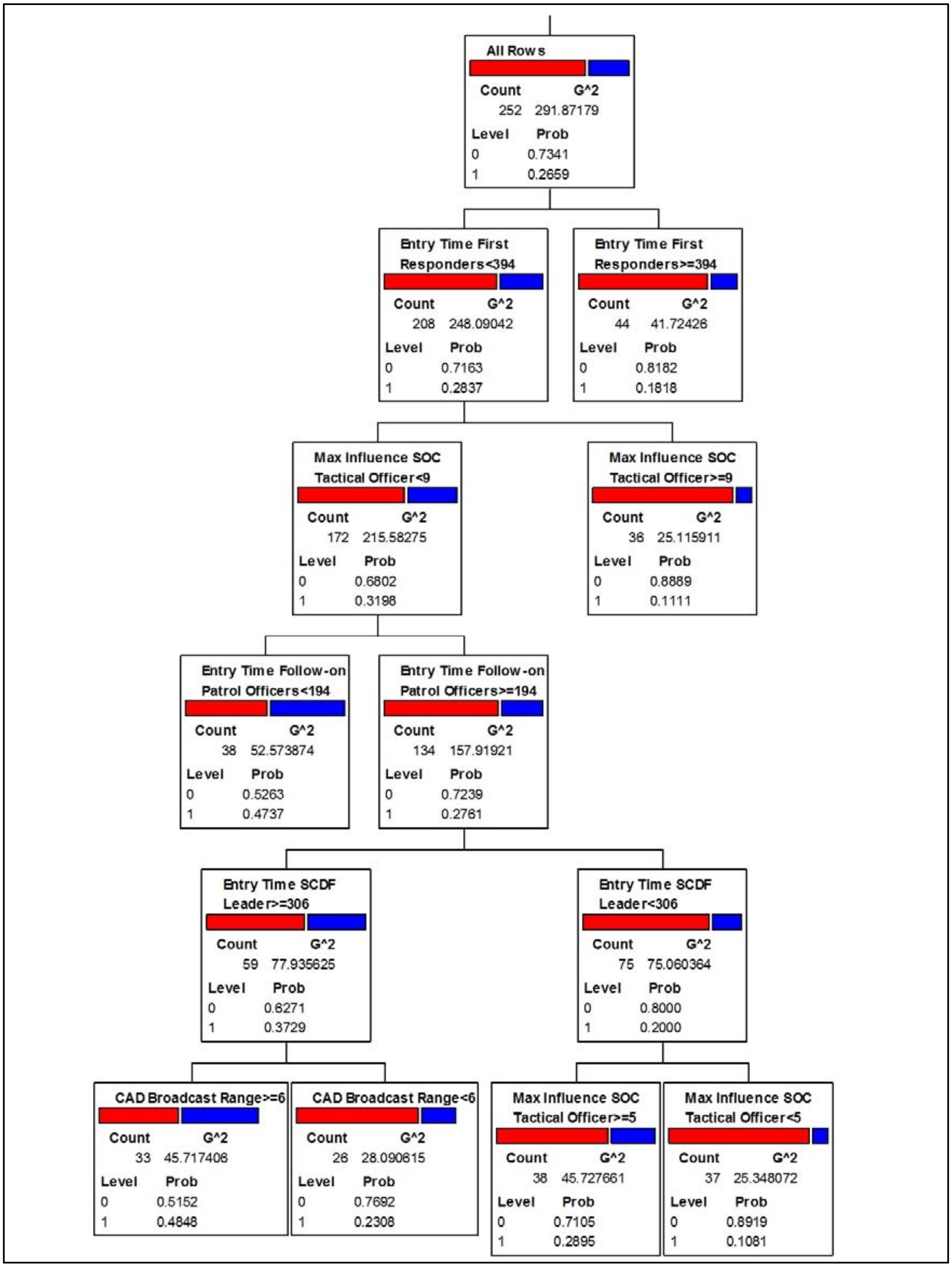


Figure 31. Scenario #1: Categorical regression tree for MOP 2 (R-square 0.094). The red bar represents the proportion of count above 20%. The blue bar represents the proportion below 20%.

Figure 31 suggests various conditions associated with a higher probability of the mean percentage of civilian injuries being lower than the benchmark. As the arrival of the first responders (inclusive of the FRC patrol officers) is often the first task on the response cascade, its influence is accounted for first. Interestingly, the most significant factors identified in the categorical regression tree differ from that shown in Figure 26 and Figure 27.

If SOC tactical officers influence fewer than nine persons, the probability of the response being below 20% is twice as much than if the officers influence more—0.326 compared to 0.106. If the entry time of the follow-on patrol officers occurs in less than 194 time steps (13 minutes), the probability improves to 0.487. If the entry time of the follow-on officers occurs in 13 minutes or longer, then the entry time of the SCDF leader is the next significant factor, whereby a later arrival is associated with a higher probability of mean injured being below 20%. Following this, a CAD broadcast range longer than six meters is favored over a shorter range.

3. Observations

a. There is No Direct Association of Medical Assets to Improving Civilian Survivorship

Surprisingly, the regression tree results for both MOP 1 and 2 do not indicate the involvement of any medical assets. This suggests that the improvement of civilian survival may not necessarily lie in changing the behavior or means for medical support elements committed to the response. Given the configuration of the scenarios and the emergency activation process, these elements may be indirectly associated with the SCDF leader's arrival and the entry time of the first responders.

b. Implementing an Emergency Response is Associated in a Marginal, but Significant Increase in Civilian Injury

With no real-life incidents ever indicating the effectiveness of an emergency response as opposed to no response, it is difficult to discern if an actual response truly translates to a reduction in the morbidity of injury in the affected population. The simulation results showed that the mean percentage of injuries associated with an emergency response to an indoor CIED was statistically higher than that associated with no response. The operational loss due to this difference is debatable, but the result is not far-fetched or inconceivable. Medical assets configured in the scenarios do not impart complete regeneration on civilians. Moreover, the continued retention of injured civilians at the incident site corresponds to the current SOPs for civilian decontamination. This suggests a reasonable representation of the real response. Focus should shift to eliminating conditions that exacerbate civilian injuries, and committing to actions and procedures that may present a higher probability of keeping mean percentage of injured civilians to a minimum.

c. The Effect of Entry Time on Civilian Injuries Varies with Different Response Elements.

Both Figure 27 and Figure 28 suggest that earlier arrival of response elements does not necessarily translate to improved civilian survivorship. When scored on MOP 1 (percent civilian injured), earlier entry times shown in Figure 27 are generally noted to be associated with a lower value for MOP 1. When scored based on MOP 2, the later arrival of the SCDF leader is associated with a higher, and thus preferred, probability for the mean percentage injured to be less than the benchmark. Two possible reasons account for this. The earlier arrival of the SCDF leader improves the currency of the leader’s information, allowing the earlier activation and arrival of hazmat, medical and decontamination elements. These forces may retain panicked but uninjured civilians (who would otherwise flee the incident site) to enable triage and medical decontamination while the threat is still active. Alternatively, the statistical significance of the regression tree splitting at SCDF leader time could possibly be happenstance and the entry times for the SCDF leader correspond with a more appropriate uncontrollable factor.

d. Varying the Influence of Security Elements is Associated with the Morbidity of Injury.

The association between responder influence over civilians and the corresponding MOPs is varied. If the FRC patrol officer can influence more than 10 civilians to move to the triage, a lower value for MOP 1 is associated. In the case of the SOC tactical officers, their capacity to influence fewer than nine civilians is associated with a higher probability that injured civilian proportions remain below 20%. Both responders carry weapons, give orders to civilians to move to the triage site, and operate in different locations on the incident site. No operational explanations can account for this result. Simulation settings for the interaction between SOC officers and any civilians allow for the calming of panicked civilians or the subversion of non-compliant individuals to compliancy. It may be possible that increased influence over the civilian population reduces further exposure to the chemical threat and prevents them from dying. This reduction in percentage dead would translate to an increase in percentage injured.

D. SCENARIO #2: EMERGENCY RESPONSE TO OUTDOOR DEVICE

As scenario #2 did not have a separate control case generated to analyze the impact of the outdoor emergency response (such as the base case and scenario #1), the data set is analyzed in isolation, but will draw some insight from the indoor case. A major point to note is that scenario #2 involves a different hazard zoning template. The location of emergency responders, less the security cordon elements (TP and SOC tactical team patrol routes) are shifted away from the department store at which the outdoor device is located.

1. MOP 1: Regression Tree and Linear Regression

The regression tree shown in Figure 33 was generated using MOP 1 results for scenario #2.

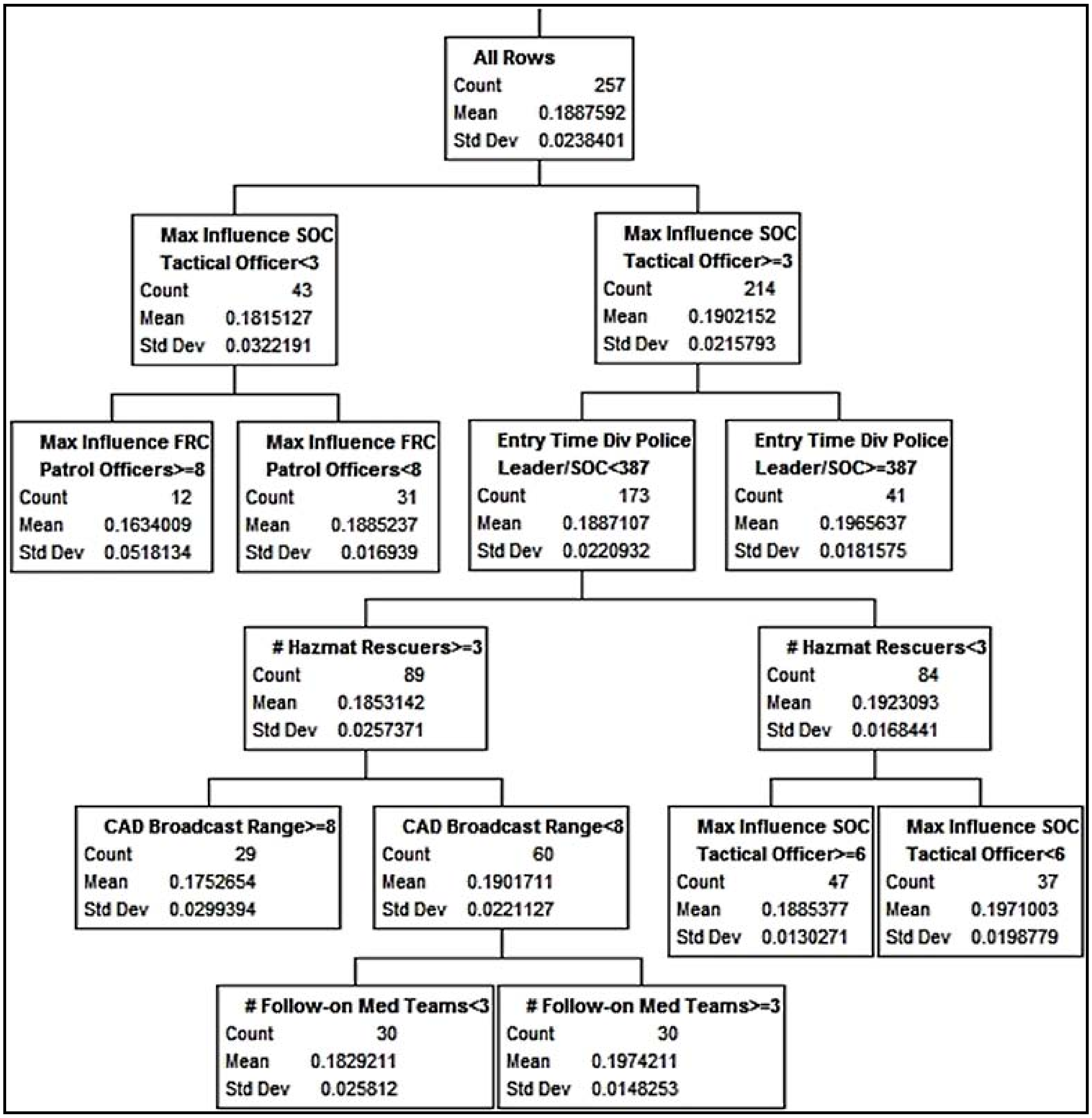


Figure 32. Scenario #2: regression tree (R-Square 0.109).

A lower mean value for MOP 1 was associated with a maximum influence of less than three civilians by the SOC officers. Following this branch, MOP 1 was significantly lower if FRC patrol officers were able to influence eight or more persons. If such a condition were achieved, then the associated value for MOP 1 (16.3%) would be 2% lower than the aggregate mean for the scenario (18.9%). When SOC tactical officers are able to influence more than three civilians, the next significant factor would be their entry time with the division police leader, in which case a lower value for MOP 1 is associated with an arrival time no later than 25.8 minutes. In this case, having three or more hazmat rescuers is associated with a lower MOP 1 value. After this, the operational significance of the change in MOP 1 diminishes and values fall between 17 and 18%.

Given the low R-square values for the regression tree, a linear regression with all 29 controllable and uncontrollable factors determined which factors were most significant in estimating MOP 1. Appendix E shows the results of the linear regression. The regression results are in agreement with the base case linear regression, that the numbers and non-compliance of civilians were dominant estimators for the percentage of civilians injured. In addition, two controllable factors—the number of pump engine rescuers and the entry time of first responders—were associated into the parametric equation, suggesting their significance in predicting MOP 1. Their coefficients are exceptionally small (0.002 and -1.625×10^{-5}), but comparable to the coefficients of other factors included in the fit. The negative polarity of the coefficient for the term corresponding to first responder entry time suggests an inverse relationship with the mean percentage of injuries. A shorter first responder entry time is therefore associated with a lower percentage of civilians injured.

2. MOP 2: Analysis and Regression Tree

For MOP 2, response values were scored on whether they were less than 18.9%, the aggregate mean percentage of injured for the whole data set. The number of design points that score “1” and “0” is shown in Figure 31. A close to equal proportion of design points score on both 1 and 0, suggesting that the NOLH design exhibits a good degree of conditions that may prevent the exacerbation of civilian injuries, or at the very least be associated with conditions supporting this.

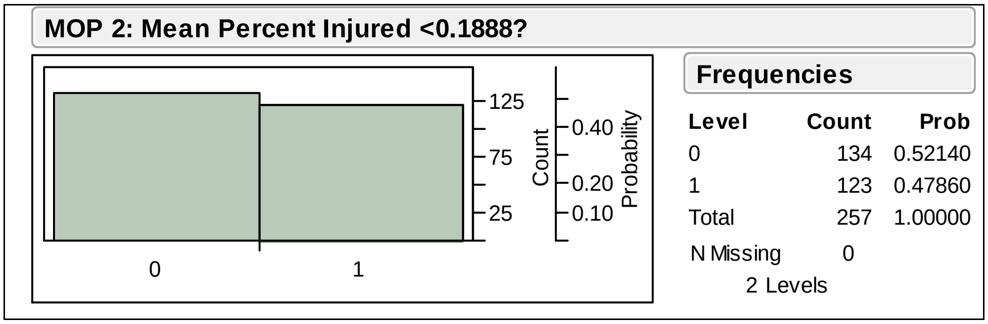


Figure 33. Scenario #2: Histogram for MOP 2 occurrence and probabilities.

Figure 34 shows the categorical regression for MOP 2. Like the analysis for scenario #1, the analysis takes into consideration that the significance of factors are assessed after the arrival of the first responders. If the conditions deemed significant on the leftmost branching of the regression tree are fulfilled, then the probability of MOP 2 associated with such conditions is 0.781, an improvement over the probability for the whole data set (0.4788). Entry time of the first responders appears to be most significant in predicting the probability of MOP 2 = 1. Like the MOP 2 analysis for scenario #1, the broadcast range of the CAD demonstrates itself to be significant in the categorical regression. The leftmost branch is partitioned along a CAD broadcast range greater than six meters, suggesting that this value is significant in predicting for both indoor and outdoor incidents.

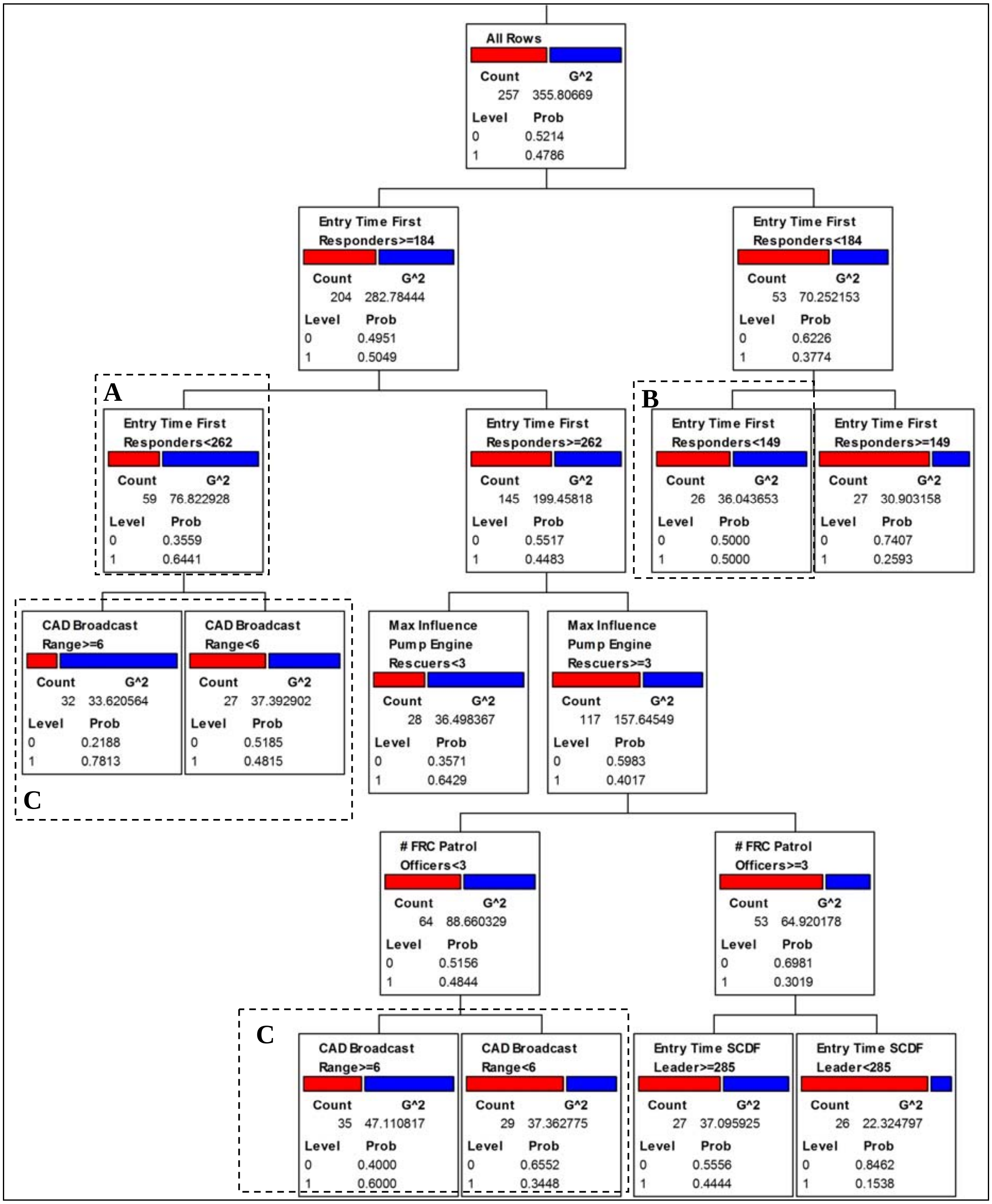


Figure 34. Scenario #2: Categorical regression tree for MOP 2 (R-square 0.105). The red bar represents the proportion of count above 18.9%. The blue bar represents the proportion below 18.9%.

a. *Reduced Influence of Pump Engine Rescuers and Fewer Patrol Officers is Associated with a Better Chance of Mean Percentage Injury > 18.9%.*

The reduced influence of the pump engine rescuers and more FRC patrol officers are associated with a higher probability for MOP 2 = 1. It is possible that increasing the influence of the rescuers actually allows them to better extract injured civilians before exposure to the CA causes them to die. A reasonable expectation when this occurs is when the proportion of civilian deaths decrease with the increase of civilian injuries.

b. *Earlier First Responder Entry Times are Associated with a Better Chance of Mean Percentage < 18.9%*

This observation can be noted in branches labeled box "A" and "B," as indicated in Figure 35. This is in agreement with the finding found from the linear regression fit described in Section D.1. In conjunction with the observations made for the scenario #1, it might be reasonable to say that the earlier arrival of the first responders is beneficial to limiting the exacerbation of civilian injuries in a CIED incident.

c. *Longer CAD Broadcast Range is Beneficial in Scenario #1 and #2.*

Interestingly, CAD broadcast range, which can be interpreted simply as the sound the device makes when it detects the chemical agent, is statistically significant in predicting civilian injury rates. There is no configured interaction between the civilians and the CAD; the CAD is a device used by the pump engine rescuers and the hazmat personnel. It is possible that the longer broadcast range allows for one rescuer to alert the others and primes them to adopt a "masked" condition. This masked condition improves their capacity to move about in the contaminated area and enhances the rescuers' capacity to extract civilians that are trapped in the contaminated area.

3. MOP 3: Panic

The mean values for MOP 3 are obtained and the controllable factors are determined that have the highest predictive value for compliant, neutral, and non-compliant civilian populations. The expectation was that these factors were likely to be different and the emergency response may or may not have the capacity to reduce the panic in either one or all three civilian sub-populations.

This stage of the analysis focuses on a single area to gain better clarity—in this case the pedestrian population moving outside the target shopping mall, codenamed ORLP. Figure 35 illustrates the histogram for the mean panic attribute values recorded for the three sub-populations.

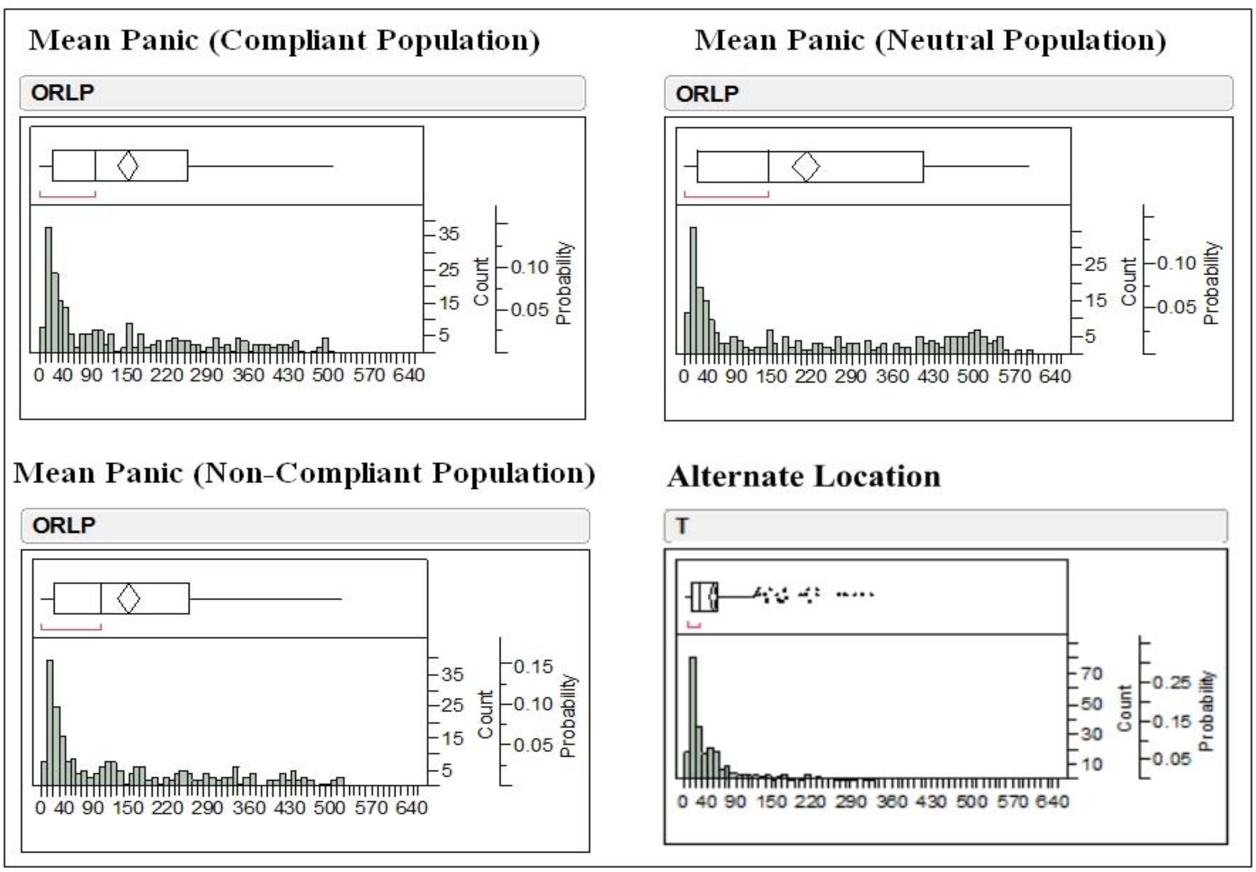


Figure 35. Scenario #2: Histograms for mean panic attribute values across compliant, neutral and non-compliant civilians.

At a glance, the histograms display a left-skewed distribution of counts. Civilians break the panic threshold once their panic attribute goes beyond 10. The numerical value for the panic attribute would thus describe the intensity of the panic that surrounds the location. As a counter-example, the diagram also shows the panic attribute histogram for location "T," the initial target location for scenario #1. Situated just adjacent to "ORLP," the neutral civilian population at "T" experiences a far narrower spread for panic attribute values, suggesting the population remains better sequestered from the incident site and its psychological effects. It is noted that a portion of the counts for "T" do exceed 10, indicating that on average the neutral population represented in "T" does engage in panic behavior. As such, comparison of the spread of panic by such means is proposed to be a reasonable way to appreciate the propagation of panic in a Pythagoras scenario.

Unfortunately, because of the diverse spread associated with the panic levels for affected civilians, regression analysis is not likely to derive any accurate results.

E. SCENARIO #3: EMERGENCY RESPONSE TO VBIED

Recall that the VBIED incident involves a large payload device, which does not have any CA associated with it. It is expected that mean percentage dead is likely to be determined by the VBIED, as the simulation does not allow for any other modes of damage to be caused by other agents. The VBIED scenario should, therefore reveal responder impact on the MOPs in the absence of a CA, which serves as a continual threat that can be mitigated. The expectation is that with an explosive device, the occurrence of deaths and injuries is likely to be harder to influence by an emergency response.

Ten data points had to be removed as they had zero results for mean percentage injured, but positive values for mean percentage dead. As this was operationally unlikely, the data points were removed to prevent skewing in the analysis. Two hundred and forty-seven data points remained for analysis.

1. MOP 1: Regression Tree

With reference to box "A" in Figure 36, a higher maximum influence by the SOC tactical officers serves as a significant indicator of a higher value for MOP 1.

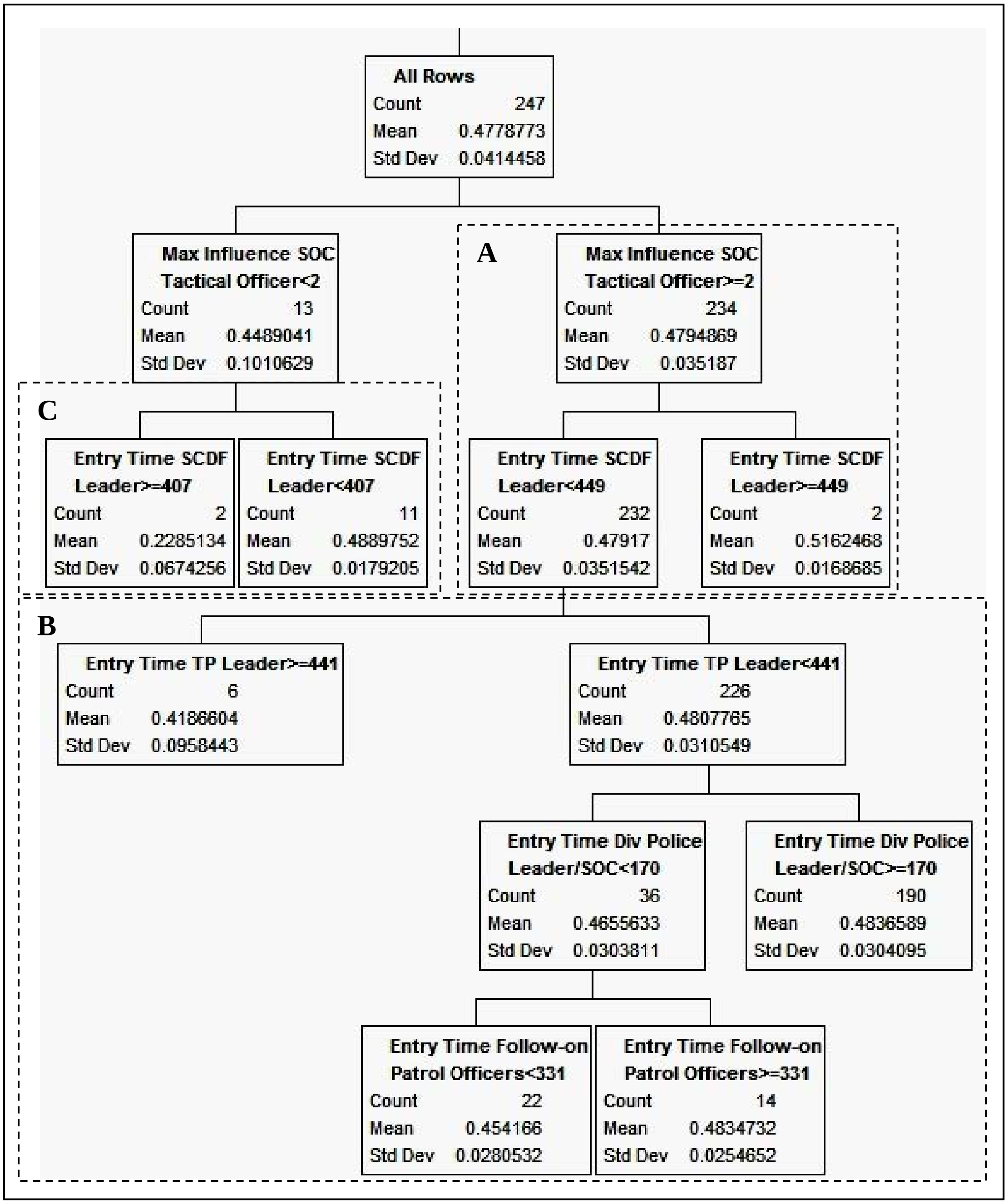


Figure 36. Scenario #3: Regression tree for MOP 1 (R-square 0.400).

Following this, if the entry time of the SCDF leader is kept within 449 times steps (30 minutes) or lower, then the next best predictor for limiting MOP 1 is the entry times of the security and cordon elements indicated in box “B,” all of which indicate significant times that do not precede 30 minutes. This suggests that in the case of VBIED incident, the arrivals of the TP and division police should precede the arrival of the SCDF leader and his associated elements. With this in mind, a suggestion would be to activate security elements and implement site control before medical, fire fighting, and mitigation assets are called to the incident site. In simulation, this would require the divisional follow-on patrol officers to support the FRC patrol officers in the clearance of the incident site. When civilians are diverted away from the site, it is possible that their exposure to any injury-causing elements in the scenario is reduced.

It is noteworthy that the branch in box “C” accounts for a high degree of variability as reflected by the change in R-square value for the regression tree. This branch has a small count, but a very distinct mean value for MOP 1. This is highly suggestive of outliers in the data set, which are identified using cluster and outlier analysis. This is described in Appendix I. The variability accounted for by this regression is also higher compared to the previous two scenarios, despite having a equal or fewer number of splits. This could be due to the smaller standard deviation relative to the larger mean response, which in turn could be a reflection of a more defined impact created by the VBIED, as compared to the combined effects of the sarin and IED for scenario 1 and 2.

2. MOP 2: Analysis and Regression Tree

Scenario #3 was scored for MOP 2 using the mean of the data set (0.468 or 46.8% of civilians injured). As shown in Figure 37, fewer design points score “1” on MOP 2.

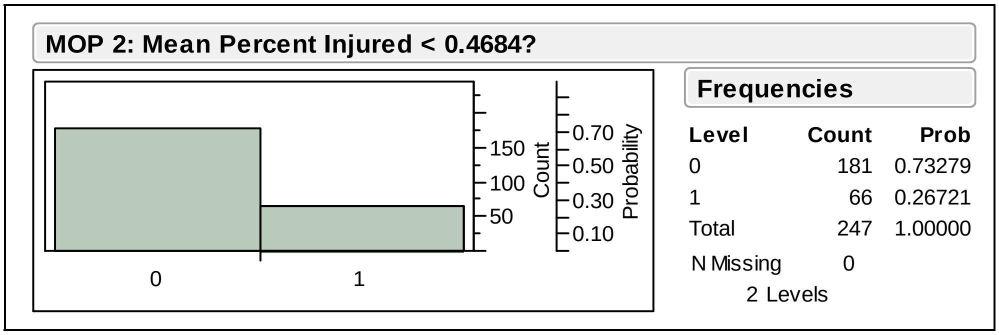


Figure 37. Scenario #3: Histogram for MOP 2 occurrence and probabilities.

Refer to Refer to Figure 38. When conditioned on the probability that MOP 2 =1, a categorical regression tree analysis indicates that the most significant group to branch along begins with the entry time of the division police leader/SOC teams (box "A"). When conditioned on the arrival of this group in 11 minutes or earlier (see box "B"), a higher maximum influence by follow-on patrol officers is associated with a higher probability for MOP 2 = 1. If the follow-on division police have the capacity to influence more than five civilians, the probability of MOP 2 = 1 is much higher (three times as much as was expected from the data set).

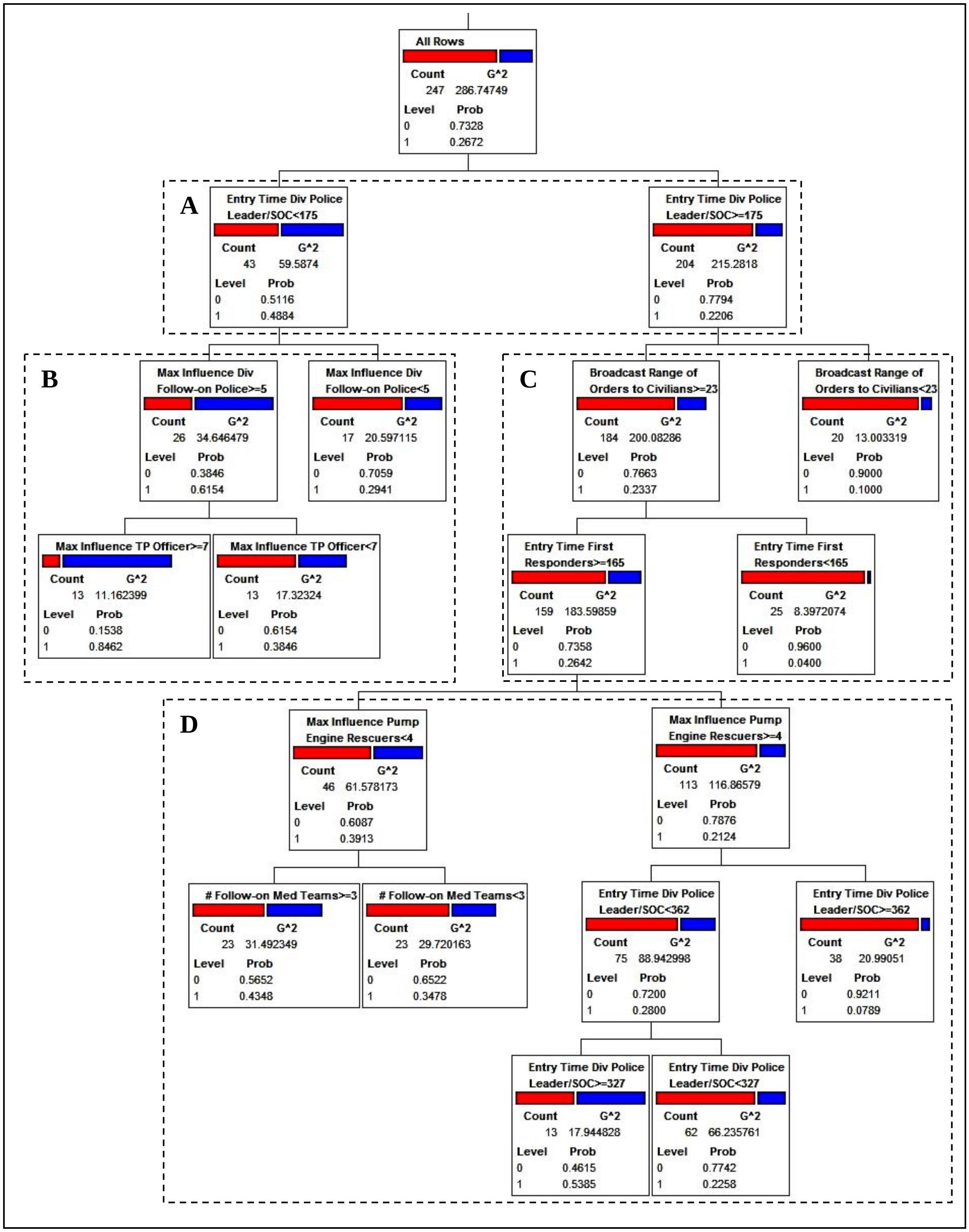


Figure 38. Scenario #3: Regression tree for MOP 2 (R-square 0.174).

If the division police leader and the SOC teams are not able to arrive within 11 minutes, then a higher probability for MOP 2 = 1 will occur when responders have the capacity to influence civilians within a 23 m radius (box "C"). Subject to this, the first responders can afford to arrive at 11 minutes or later. If this occurs, the maximum influence of the pump engine rescuers becomes significant in predicting the response (box "D"), after which, the entry time of the division police leader and SOC teams become dominant again in predicting MOP 1. If the pump engine rescuers have the capacity to influence more than four persons, then the division police leader/SOC teams should enter between 21.8 and 24 minutes. If the pump engine rescuers influence less than four civilians, the next best predictor condition requires the number of follow-on medical teams to be three or more to favor a higher probability for MOP 2 =1.

F. FURTHER ANALYSES AND OBSERVATIONS

To account for the variability in all the scenarios, stepwise regression and regression tree analysis, using both uncontrollable and controllable factors, was conducted. See Appendix F for the resulting diagrams. The number of civilians and their capacity for non-compliance accounts for much of the variability in all three scenarios. This supports the regression analysis conducted for the base case.

COADM was used to determine the existence of outliers of interest. Of the four data sets generated, COADM was only able to generate outputs for only two scenarios, scenario #1 and scenario #3. Errors in the compilation process of the cluster and outlier analysis occurred for the base case scenario and scenario #2. The majority of the outliers generated in both scenarios #1 and #3, while appearing to have desirable responses in terms of MOP 1 and MOP 2, occurred out of design point conditions that have few civilians or are lacking a sub-population entirely. The latter is due to the NOLH design and should be improved in future experiments. Nonetheless, the cluster analyses conducted with the other two scenario outputs are in general agreement with the regression analysis described in this chapter.

VI. RECOMMENDATIONS AND CONCLUSIONS

Given the sensitive nature of specific details regarding the TTPs used by the Singaporean military and paramilitary, as well as the limitations of the simulation, this study avoids proposing of operational revisions to the SOPs implemented by these forces, as this will require the need to reference sensitive material and will imply that existing measures fall short. Instead, the findings presented here should be taken in relation to the assumptions made and the nature and limitations of the simulation's design.

A. SUMMARY OF FINDINGS

From the data analysis, the following was determined:

- With respect to the percentage of civilians injured by an indoor CIED incident, there appears to be a statistically significant, but marginal increase associated with emergency response activation, versus a baseline reference of no response. What few actions associated with a statistically significant decrease in the percentage of civilians injured, only improve the percentage injured slightly by 1 to 4%.
- The follow-on force, particularly with respect to the patrol-officers who conduct much of the site clearance, must complement the efficiency of the initial FRC patrol officers. A less effective effort in the initial response by the FRC patrol officers, or an operational situation that impedes police influence, should necessitate more follow-on police officers to compensate. An increased maximum influence on the part of the patrol officers appears to be positively associated with a reduction in mean percentage injured, subject to a reduction in influence by the SOC tactical officers.
- To limit the potential increase incurred with an emergency response, factors that prevent the exacerbation of civilian injuries include the earlier entry time of first responders and follow-on police officers, the reduced maximum influence of SOC tactical officers, and potentially the later arrival of larger SCDF elements.
- The early arrival of response elements, particularly security cordon and decontamination elements may inhibit the civilian intentions for self-preservation. The data suggests the association of lower mean percentage injuries with the later arrival of such elements, and vice-versa. Interestingly, the earlier arrival of follow-on police officers is always associated with positive gains.
- No direct association of medical assets is observed in the statistical analysis for CIED incidents. If there is any influence, the possible response is likely to tend

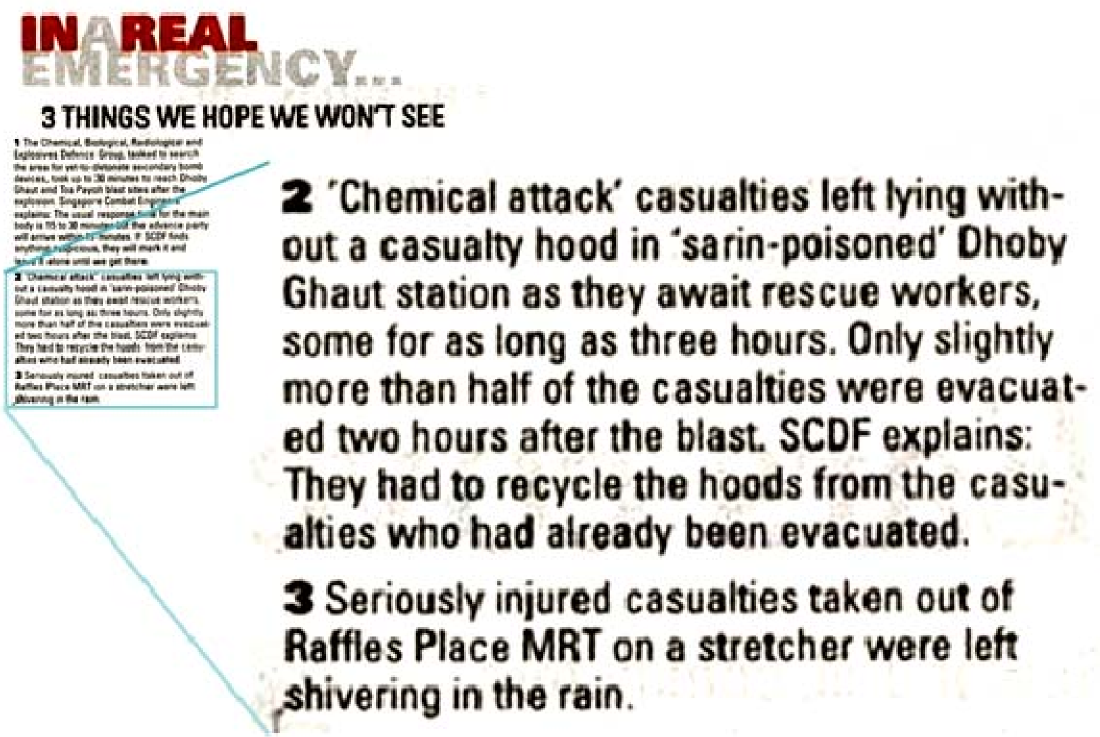
towards reducing mean percentage deaths and transferring the saving of civilian lives to an increase in the mean percentage injured. This is suggested based on the significance of the number of follow-on medical teams during the outdoor CIED incident, using regression tree analysis.

- Panic associated with the incident site demonstrates itself in varying degrees. In the context of the simulation, the representation of panic is subject to sequestering and proximity to the incident site.
- Increasing CAD broadcast range is beneficial in scenarios involving CA. This ranges from six to nine meters.
- For a VBIED incident, early arrival of security and cordon elements before the SCDF leader and his associated elements may be significant in limiting mean civilian injuries.

B. DISCUSSION AND RECOMMENDATIONS

1. Implication of Results

Assuming that the assumptions used in the design and generation of the simulation allow for a good approximation of the emergency response, there appears to be little that can be done to drastically improve the survival rates of the civilian population if attacked by either a CIED or a VBIED in indoor or outdoor environments. This would suggest that existing on-site emergency procedures do little to influence the survivorship of the affected population, and that the civilians themselves would have a far better chance of influencing their own survival rates. Recalling the observations made by the press during Exercise NorthStar V (shown in Figure 39), certain actions noted by the press did not appear to benefit the well-being of the casualties being evacuated (TODAY News Desk 2006). It is therefore interesting that the general impact of the standby response appears to be supported by these anecdotal accounts; however circumstantial. A bold claim would thus be that any action undertaken by the emergency response to interact with the civilian population might complicate their survival, particularly actions requiring the directing and influencing of civilians to remain on-site to be treated. Securing, cordoning, and decontamination of persons directly or indirectly affected by the incident site, might serve to complicate survival, not because of the quality of the treatment, but because the human instinct is far more effective in ensuring its own survival. This observation is not only counter-intuitive from the standpoint of the responder; it also runs against the grain of emergency response, that of the helpless victim and the emergency or medical professional who rushes to the rescue.


IN A REAL EMERGENCY...

3 THINGS WE HOPE WE WON'T SEE

1 The Chemical, Biological, Radiological and Explosives Defence Group, tasked to search the areas for yet-to-detonate secondary bomb devices, took up to 30 minutes to reach Dhoby Ghaut and Toa Payoh blast sites after the explosion. Singapore Combat Engineers explains: The usual response time for the main body is 15 to 30 minutes but the advance party will arrive within [illegible] minutes. If SCDF finds anything suspicious, they will mark it and leave it alone until we get there.

2 'Chemical attack' casualties left lying without a casualty hood in 'sarin-poisoned' Dhoby Ghaut station as they await rescue workers, some for as long as three hours. Only slightly more than half of the casualties were evacuated two hours after the blast. SCDF explains: They had to recycle the hoods from the casualties who had already been evacuated.

3 Seriously injured casualties taken out of Raffles Place MRT on a stretcher were left shivering in the rain.

Figure 39. Press observations for Exercise NorthStar V. From: TODAY News Desk (2006).

This study must therefore re-adjust its assumptions for the intent of the emergency response. A major issue of concern that supports the response in spite of a potential increase in casualties is to protect the national healthcare system. This comes as a layered approach towards protecting the rest of Singapore Island against a novel threat. With a small land mass and exceptionally porous urban environment, contamination from a chemical incident could have the capacity to spread beyond the incident site. The bulk of focus in any emergency response would therefore be towards *containment*. Whether this dimension is closely analyzed in a national exercise, or can be tested by means of an FTX, is unknown by this author.

2. On-site Medical Response versus Direct-Throughput to Hospitals

If responder actions might hurt instead of help, what can emergency responders do to reduce their impact? An existing debate exists on whether it is preferable to treat casualties from a CIED incident (or any CA incident) directly on or near the site of exposure, or whether it would be preferable to have these victims transported directly to a hospital specifically equipped to handle chemical casualties. The existing Singaporean model of on-scene decontamination and triage contains the chemical hazard to the immediate area of exposure (CBRNe World 2007). This study will not debate on the quality of the medical care administered to the civilian casualties, as the simulation's design cannot allow us to determine this. Rather, given the findings, the study will focus on issues regarding the containment of civilians to the incident site.

Countries that have the capacity to handle CA casualties at hospitals are typically equipped to manage combat casualties of war. A good example is Israel, which uses direct evacuation to a medical hospital given a chemical incident. Certainly, the expectations for medical hospitals in Israel vary from those in Singapore – the latter has only one hospital equipped to handle chemical casualties and highly infectious diseases. Equipping hospitals to be able to engage in chemical decontamination and medical treatment would mean that staff, infrastructure, and emergency protocols would have to be retrained, re-structured, and revised. Yet, when considering the instincts of the directly affected human population to escape any incident site, it is not hard to appreciate that individuals exposed to the CA may seek help at a public hospital without having gone through a whole gamut of medical decontamination and triage conducted on site. An example of this is the Tokyo subway attacks, when over 5,500 people were reported to have sought medical care, but emergency services on site transported only 688 patients (Kaplan 2000). The majority of these individuals were not contaminated, but no reference indicates if any of them were at the scene of the chemical release. In the Singaporean context, might it not be better to let fleeing civilians leave the incident site? Conversely, might it not be safer to detain all individuals in the affected area for decontamination? If given the limited capacity of the emergency response to improve survivorship, would it be preferable to allow such people out of the secured area?

If a reasonable decision is to be made, the consequences that come with these civilians potentially affecting the public health system have to be balanced with the potential impact the emergency responders might have on their survival. Two options for mitigating such a complication would be to:

- Define clear ROEs for the TP and the SOC. Both elements fulfill specific tasks. In the case of the simulation, their roles are to ensure law and order, neutralize hostile threats and take on the control of the escaping civilian population, if necessary. Train police forces to identify strange and panicked behavior, and equipped them with CADs to enable them to discern whether a panicking civilian moving out of the warm zone is chemically contaminated or merely part of the "worried well" who can physically manage on their own. Costs incurred would be in terms of the total cost of ownership of CADs and related equipment, as well as the person-hours spent training forces to use CADs.
- Put in place "aid stations" outside the warm zone of the incident site, that fleeing civilians are able to approach for help once they return to a rational state of mind. Assuming that the natural tendency for a person that senses danger would be to distance himself from the source of the threat, civilians might seek immediate help once they feel safe enough to return to a non-escaping state of mind. Aid stations might be stand-alone tents or ambulances stationed outside the security zone and have clear signs indicating their presence. The arrival of these aid stations would possibly have to occur at the start of the acute phase of the emergency activation.

FTXs and a simulation-based analysis could be used to assess the feasibility of these two options.

3. Analyzing Civilian Response to the Terrorist Threat

If an emergency response were likely to be geared towards protecting the unaffected population rather than the affected, it would therefore be logical to analyze the behavior of the civilians in simulation as they behave accordingly to the threat. The present scope of this study focuses on what can be done on the part of the emergency responder. The results, however, suggest that the best course of action in improving the chances of civilian survival might lie in the measures influencing the environment, and hence the civilian population instead. The old adage of “prevention is better than the cure” would be valid in this case—that civil authorities have the capacity to reduce the vulnerability of the population by implementing preventive measures, rather than responsive measures. Such measures could include public education and better human factor engineering for the built environment. The focus of one particular research effort at the Nanyang Technological University (NTU) in Singapore involves finding high-performance means to analyze such human intangibles. Future efforts can use the data generated for this study to validate common assumptions used here and in the NTU effort.

B. OTHER LIMITATIONS

It was initially the author’s intent to study how the emergency response can influence the panic experienced by the population. The complexities involved in this measure, however, such as the impact of civilian movement, sequestering, civilian-on-civilian influence, as well as the limitations of the simulation platform and design, makes any statistical analysis with the existing data difficult to do. In addition, as panic is abstracted as a numerical attribute, it can be argued that such a representation is invalid.

One limitation involves the absence of vehicular traffic in the scenario. Urban traffic conditions will result in the extended arrival times of emergency responders. Civilian road users may also form collective sub-populations varying in degrees of compliancy, in this case to give way to emergency vehicles en route to the incident site. The implication of this limitation is that the preferable times of entry as indicated by the regression tree analysis in Chapter V may be difficult to achieve.

A limitation concerning the civilian population is that the distribution of the civilians may not be entirely representative of the distribution of pedestrians in the actual location. Pedestrian distribution at the incident site is dependent on traffic density, time of day and even the day of the week. These factors will influence the locations of civilians, their exposure to the blast, and fragmentation zones of the IEDs. The results presented here may raise several interesting questions, but they should supported by more in-depth assessments on the behavior of civilians in the simulation. The transience of crowd build-up along the interior of buildings and along pedestrian walkways, in itself, can be treated as a separate study that focuses more on characterizing behavior than analyzing the response operation.

Another major limitation in the design of the simulation pertains to the adequacy of the medical response as characterized by Pythagoras. In this study, the role of the medical elements was noted to have very little impact on either MOPs. Casualties were not classified by the degree of injury they had sustained. The data generated could not be used to assess how well the medical personnel administered to the casualties. As such, the analysis loses resolution on whether the medical elements are able to limit the number of injured civilians dying while waiting for treatment. The study, therefore cannot comment on the performance of the medical elements. Moreover, to achieve this, there needs to be an assessment of the change in civilians injured and dead, scoped specifically to determine the number that transition from injury *to* death. Data would have to be collected over successive time steps (in the case of Pythagoras, which is a discrete time simulation).

C. CONCLUSIONS TO THE EXPERIMENTATION

The data presented in this study suggest that an emergency response has many more complicated issues than both the media and the civil authorities are keen on making known during an exercise. An objective analysis of the simulation results compared and contrasted to the open-source reports on the lessons learned and observations made on Exercise NorthStar V, suggests similar trends in observation. This study revisits the research questions again to place our findings in context:

- How feasible are existing operational templates, TTPs, and information making processes?
- How robust are current procedures in containing civilians exposed to chemical agents?
- What factors influence the efficiency of emergency response procedures?
- To what degree does civilian compliancy affect the performance of casualty treatment?

With respect to the research questions:

- Assessment of the feasibility of the response gave counter-intuitive results. When focused on improving civilian survivorship, simulation results prove inconclusive in showing that civilian deaths incurred from an indoor CIED incident and subsequent an emergency response, vis-à-vis no response. The percentage of civilians injured associated with the emergency response to the same device prove significantly higher than would be expected with no response. Key actions associated with the response, however, are inversely associated with a decrease in civilian casualties. In general, earlier arrival of the first responders improves civilian survivorship, while increased influence over the population by security forces serves to increase civilian injury.

- The robustness of current procedures should be deemed reasonable as the flexibility of the initial and follow-on configurations allow IMs and response force leaders to manage the consequences of complications, in the time and compliancy domains. If a direct relationship is assumed between the responses and the experimental factors, then several follow-on actions can be implemented to compensate for problems reducing responder arrival time and civilian compliance. The entry time of the first responders composing the initial response is a significant factor in limiting the exacerbation of casualties at the incident site. The maximum influence that each response force exerts on the affected population should vary in relation to the impact it has on the civilians. Security and cordon elements should be careful in limiting their control of the population. Rescuer influence should be slightly greater than that of patrol officers.

- Assuming that the civilian behavioral model is valid, the intrinsic compliancy of civilians is not as dominant a deciding factor of civilian casualties, as much as the size of the population is. This suggests that irrespective of his compliance towards an emergency response, the civilian is likely to be able to find a way to escape the hazard. Public compliancy towards an emergency response should therefore not be a major concern to emergency planners, who should focus instead on the proper identification of persons affected by the incident.

D. ON THE SUITABILITY OF PYTHAGORAS ABM

A major aspect of the M&S work was conducted to determine if Pythagoras had enough function and flexibility to allow for the design of a terrorist attack scenario, with the eventuality that a computer-based simulation could be used to augment the learning and developmental value of a mass FTX. During use, the researcher encountered several technical problems that required direct correspondence with the developers. Appendix J describes two of these issues. Nonetheless, Pythagoras does lend itself well to generating a complex scenario such as a terrorist incident. Major issues encountered in the course of this research that can reduce the feasibility of a Pythagoras-based simulation used in conjunction with a mass FTX include the following:

- The time taken to run a single replicate becomes longer as the number of agent instances increase. This will impact the capability of Pythagoras to simulate large crowds. The current study has been able to generate scenarios with approximately 900 agent instances on a single scenario map without issue, given the use of an HPC cluster.
- The co-ordinate-based design of terrain features requires point by point creation of individual elements in the Pythagoras scenario. Increasing the number of terrain features and achieving a high fidelity in terms of terrain features is both time and labor intensive. Future efforts with respect to "after-market" software supporting Pythagoras 2.0.3, could focus on a terrain generator tool that can render terrain in terms of an XY grid co-ordinate system and save the data in an XML format that can be "spliced" into the scenario file in XML format.
- The decision-making process for an agent instance of movement is based on deciding which direction, relative to its center line, it should turn (left or right), based on the immediate obstacles, agent preferences to avoid or prefer specific terrain, and its intended waypoints and destinations. Curved features, such as roads and interior passages, may cause agent instances to "stick." This is a major problem if the instance is unique and vital the process. An easy solution would to be to script its movement, but in doing so, the simulation becomes more deterministic in behavior—the scripted behavior that works for one scenario will not work for another.

E. FUTURE WORK

The following is a list of related follow-up research that could branch off from this work.

- Simulation and analysis of the effectiveness of medical decontamination and support during an emergency response. Both processes are essentially queues with multiple service-providers. How these two functions work together in unison with the rest of the emergency response force would be interesting to research and will complement the findings from this study.
- Simulation and analysis of a secondary device search during an emergency response. As the simulation in this study only represents the first hour of the emergency response, the function of a secondary device search is not captured

within the simulation. It would be interesting to study this process while it occurs in conjunction with an emergency response. Various analytical search models exist in operational research. It would therefore be intriguing to implement an extension of the Pythagoras simulation to capture this operational function and compare the results with an analytical model.

- Analysis of human intangibles via low-resolution simulation. The reality of utilizing physics-based simulations to analyze a crowd is that they are intensive and require a high degree of computing power to observe behavior. Pythagoras may be a low-resolution option that is accessible to both operational planners and defense scientists alike.

- Command, Control and Communications (C3) analysis for emergency response. This research does not touch on the impact of various C3 architectures on the emergency response. An interesting study would be to address the impact of this on the emergency response, particularly when responders are forced into consequence management, i.e., when a secondary device is activated, or when responders are attacked by harassing forces.

- Scenario: multi-pronged terrorist incident. The expanse of the scenario map in Pythagoras now allows a sizable area to be designed. A good application would be to use this new improvement to analyze multi-pronged attacks, which are quickly becoming a new terrorist mode of operation. The impetus is as current and evident as the recent Mumbai terror attacks (Sengupta & Bradsher 2008), which both protracted and complicated emergency response operations over four days in November 2008, and demonstrates the capacity for terrorist actions to occur as a multi-pronged effort.

This study represents a combined analysis of emergency response procedures, crowd behavior, and a non-physics-based simulation of chemical release and IED effects. Granted, the findings found here are controversial and prompt more questions than this study can currently answer. The insights, data, and calculations performed, however, provide a good foundation for planning and analyzing effective response from an operational research point of view.

APPENDIX A. CALIBRATION OF BOMB EFFECTS

A. CONCEALED INDOOR/OUTDOOR CIED: EXPLOSIVE PAYLOAD

- 5300 m/s (17,384 fps) → modelled as instantaneous effect
- Relative Effectiveness Factor = 0.83 (TNT = 1.0)
- Bowen Impulse Pressure for 1% Probability of Survival = 90 PSI = 10^5 Pa
- Lethal Range assuming relative effectiveness is true = 15 meters lethal radius
- Considering Casing Factor of 5 kg Drum, by Proctor Equation:

  C = 0.47 + 0.53/(1+5/(7.07) = 0.78

  C = 0.47 + 0.53/(1+5/(8.5) = 0.803

B. VEHICLE-BORNE IMPROVISED EXPLOSIVE DEVICE (VBIED)

- For the VBIED, the hypothetical casing factor and scaled distance for the charge is determined:

Casing Factor = 0.47 + 0.53/ (1 + casing weight/payload weight in TNT)

= 0.47 + 0.53/ (1 + (3610/3334 kg)) = 0.724

Q = 2415.3754

Scaled Distance = R / $Q^{1/3}$ = 13.41684

For an overpressure of 10^5 Pa, R, the blast radius, must be from 53.667 to 107.335 meters. This value does not deviate from that used in Roginski's analysis. As such, the design of scenario #3 does not deviate from the simulation design implemented by him.

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APPENDIX B. WEAPONS, INFLUENCE TOOLS AND RESTORATIVE CAPABILITIES

Max Terrain Dimension	4816896	sq. meters	1.000	sq. meters/grid
# CELLs in max dimension	4816896	# GRIDS	1.094	Yds/grid
Steps per Minute	15	Steps	3.282	Feet/grid
Steps per Second	0.25	Steps		

General Characteristics of Weapons, Influence Tools and Restorative Capabiltiies

	Type	Effect-iveness	FireRate per Min	Pythag FireRate	Max Engage Range(m)	Pythag Max Range	Basic load	Random Damage Degree*	Suppress Duration	WpnTGT	Direct Fire
AMSAA Data	M4 (5.56 mm)	1	15	1.00	336	336	300	1.00	0	E	Y
	M9 (9 mm)	1	5	0.33	50	50	45	0.25	0	E	Y
	IED (Carleton)	1	15	1.00	2	2	1	0.50	0	F, E, N	N
	IED (Cookie Cutter)	1	15	1.00	2	2	1	0.75	0	F, E, N	N
	IED (Eyes and Ears)	0	15	1.00	2	2	1	0.00	0	F, E, N	N
	Decontaminant (casualty)	1	15	1.00	2	2	0	0.00	0	F, N	Y
	Detection Alert	1	15	1.00	100	100	10000	0.00	0	F	Y
	Lethal Chem	1	15	1.00	1	1	10000	1.00	20	E, N	N
	Miosis Chem	1	15	1.00	1	1	10000	0.00	20	E, N	N
	Medical Kit	0.75	3	0.20	2	2	20	0.20	0	U, F, N	Y
	Orders - to Civilian	1	7.5	0.50	31	31	500	0.00	0	F, N	Y
	Orders from Compliant Civ	1	7.5	0.50	31	31	500	0.00	0	F, N	Y
	Panic Shouting	1	7.5	0.50	31	31	500	0.00	0	F, N	Y

Table 10. Characteristics of weapons, influence tools, and restorative capabilities related to Pythagoras input data (From: Roginski 2006).

Attribute Changer Settings For Weapons

	Sidedness			Psychological			Physiological		
Type	Red	Green	Blue	Alpha	Beta	Gamma	a	b	c
M4 (5.56 mm)	-	-	-	-	-	-	-	-	-
M9 (9 mm)	-	-	-	-	-	-	-	-	-
IED (Carleton)	-	-	-	20	-	-	-	-	-
IED (Cookie Cutter)	-	-	-	20	-	-	-	-	-
IED (Eyes and Ears)	-	-	-	10	-	-	-	-	-
Decontaminant (casualty)	-	-	-	-5	-	-	-1	-11	-1
Detection Alert	-	-	-	-10	-	-	-	-	-
Lethal Chem	+5	-	-	-10	-	-	1	-	-
Miosis Chem	+1	-	-	-10	-	-	-	-	1
Medical Kit	-	-	-	-10	-	-	-	-	-
Orders - to Civilian	-5	-	-	-10	-	-	-	-	-
Orders from Compliant Civ	-	-	-	-8	-	-5	-	-	-
Panic Shouting	-	-	-	10	-	-	-	-	-

Table 11. Attribute changer settings for weapons, influence tools, and restorative capabilities (From: Roginski, 2006).

Probability of Hit

	Type		RANGE											
		Pyth*	0	1	6	12	25	50	75	100	125	150	175	200
		Real**	**0.30**	**1**	**6**	**12**	**25**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
AMSAA Data	M4(5.56 mm)	pHit	1.00	1.00	0.75	0.63	0.47	0.30	0.22	0.15	0.11	0.00	0.00	0.00
	M9(9 mm)		1.00	1.00	0.50	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Agitator		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Bomb (Carleton)		See probability of kill data											
	Bomb (Cookie Cutter)		See probability of kill data											
	Medical Kit		0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Orders - From Firemen		1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
	Orders - From Medics		1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
	Orders - From Police		1.00	1.00	1.00	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50

*Units of measurement for Pythagoras distances are pixels

**Units of measurment for Real distances are in meters

Table 12. Working agent pair-wise color comparisons, showing relationship among pairs of agents (From: Roginski, 2006).

Probability of Effectiveness Given Hit

	Type		RANGE											
		Pyth*	0	1	6	12	25	50	75	100	125	150	175	200
		Real**	**0.30**	**1**	**6**	**12**	**25**	**50**	**75**	**100**	**125**	**150**	**175**	**200**
AMSAA Data	M4(5.56 mm)	Pkill	1.00	0.90	0.52	0.52	0.51	0.49	0.46	0.44	0.42	0.40	0.36	0.32
	M9(9 mm)		1.00	0.95	0.71	0.50	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	AK47		1.00	0.90	0.58	0.58	0.57	0.55	0.54	0.53	0.53	0.53	0.49	0.47
	Agitator		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Bomb (Carleton)		1.00	1.00	1.00	1.00	0.99	0.97	0.94	0.89	0.84	0.78	0.71	0.64
	Bomb (Cookie Cutter)		0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.00	0.00
	Medical Kit		0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Orders - From Firemen		1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Orders - From Medics		1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Orders - From Police		1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

*Units of measurement for Pythagoras distances are pixels

**Units of measurment for Real distances are in meters

Table 13. Probability of effectiveness given hit (From: Roginski, 2006).

APPENDIX C. SIDEDNESS SETTINGS

				Unit				Friendly				Enemy			
Agent Name	Red	Green	Blue	Color Radius	Use Red	Use Green	Use Blue	Color Radius	Use Red	Use Green	Use Blue	Color Radius	Use Red	Use Green	Use Blue
Blue	0	0	255	0	0	0	1	10	0	0	1	20	1	0	0
Chemical Agent	255	0	0	0	1	0	0	10	1	0	0	20	0	1	1
Civilian	0	255	250	0	0	1	0	10	0	0	1	20	1	0	0
Division Police	0	0	255	0	0	0	1	10	0	0	1	20	1	0	0
Division Police FRC Patrol Officer	0	0	255	0	0	0	1	10	0	0	1	20	1	0	0
Red	255	0	0	0	1	0	0	10	1	0	0	20	0	0	1
SAF-CBRE	0	0	255	0	0	0	1	10	0	0	1	20	1	0	0
SAF-EOD	0	0	255	0	0	0	1	10	0	0	1	20	1	0	0
SCDF-hazmat	0	0	255	0	0	0	1	10	0	0	1	20	1	0	0
SCDF-EMT	0	0	255	0	0	0	1	10	0	0	1	20	1	0	0
Traffic Police	0	0	255	0	0	0	1	10	0	0	1	20	1	0	0

Table 14. Color sidedness settings for agents configured in Pythagoras simulation. (From: Bitinas, Henscheid & Truong, 2003).

	Blue	Chemical Agent	Civilian	Division Police	Police FRC Patrol	Red	SAF-CBRE	SAF-EOD	SCDF-hazmat	SCDF-EMT	Traffic Police
Blue	--	ENEMY	FRIEND	UNIT FRIEND	UNIT FRIEND	ENEMY	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND
Chemical Agent	ENEMY	--	ENEMY	ENEMY	ENEMY	UNIT FRIEND	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY
Civilian	FRIEND	ENEMY	--	FRIEND	FRIEND	ENEMY	FRIEND	FRIEND	FRIEND	FRIEND	FRIEND
Division Police	UNIT FRIEND	ENEMY	FRIEND	--	UNIT FRIEND	ENEMY	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND
Division Police FRC Patrol Officer	UNIT FRIEND	ENEMY	FRIEND	UNIT FRIEND	--	ENEMY	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND
Red	ENEMY	UNIT FRIEND	ENEMY	ENEMY	ENEMY	--	ENEMY	ENEMY	ENEMY	ENEMY	ENEMY
SAF-CBRE	UNIT FRIEND	ENEMY	FRIEND	UNIT FRIEND	UNIT FRIEND	ENEMY	--	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND
SAF-EOD	UNIT FRIEND	ENEMY	FRIEND	UNIT FRIEND	UNIT FRIEND	ENEMY	UNIT FRIEND	--	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND
SCDF-hazmat	UNIT FRIEND	ENEMY	FRIEND	UNIT FRIEND	UNIT FRIEND	ENEMY	UNIT FRIEND	UNIT FRIEND	--	UNIT FRIEND	UNIT FRIEND
SCDF-EMT	UNIT FRIEND	ENEMY	FRIEND	UNIT FRIEND	UNIT FRIEND	ENEMY	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND	--	UNIT FRIEND
Traffic Police	UNIT FRIEND	ENEMY	FRIEND	UNIT FRIEND	UNIT FRIEND	ENEMY	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND	UNIT FRIEND	--

Table 15. Working agent pair-wise color comparisons, showing relationship among pairs of agents (From: Bitinas, Henscheid & Truong, 2003).

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APPENDIX D. AGENT BEHAVIORS

The following event state diagrams attempt to implement a universal method of recording and display alternate behavior routines that are configured in Pythagoras. The absence of such a format delays the learning curve of Pythagoras, as a visual representation is useful for drafting alternate behaviors and the related conditions necessary for transition.

The following graphs are based loosely on the drawing of discrete event simulation (DES) methodology (Schruben 1983). This does not mean that Pythagoras implements DES. Rather, the use of this drawing scheme is preferred as it associates alternate behaviors (loosely associated with the "state") and trigger conditions (required transition "event"), allowing the user to visualize the flow of functions for each agent type. One must keep in mind that for every agent instance in Pythagoras, a reference of an instance's characteristics is kept in memory. Thus, as an agent instance transits from one behavior to another, and its prior characteristics may be switched or remain the same. These can be related to the variables of a DES.

While every effort has been made to include as much of the critical modeling details as possible, the following diagrams do not show all the configuration details of the agents. Figure descriptions will indicate which agents have the same scheme of alternate behavior changes.

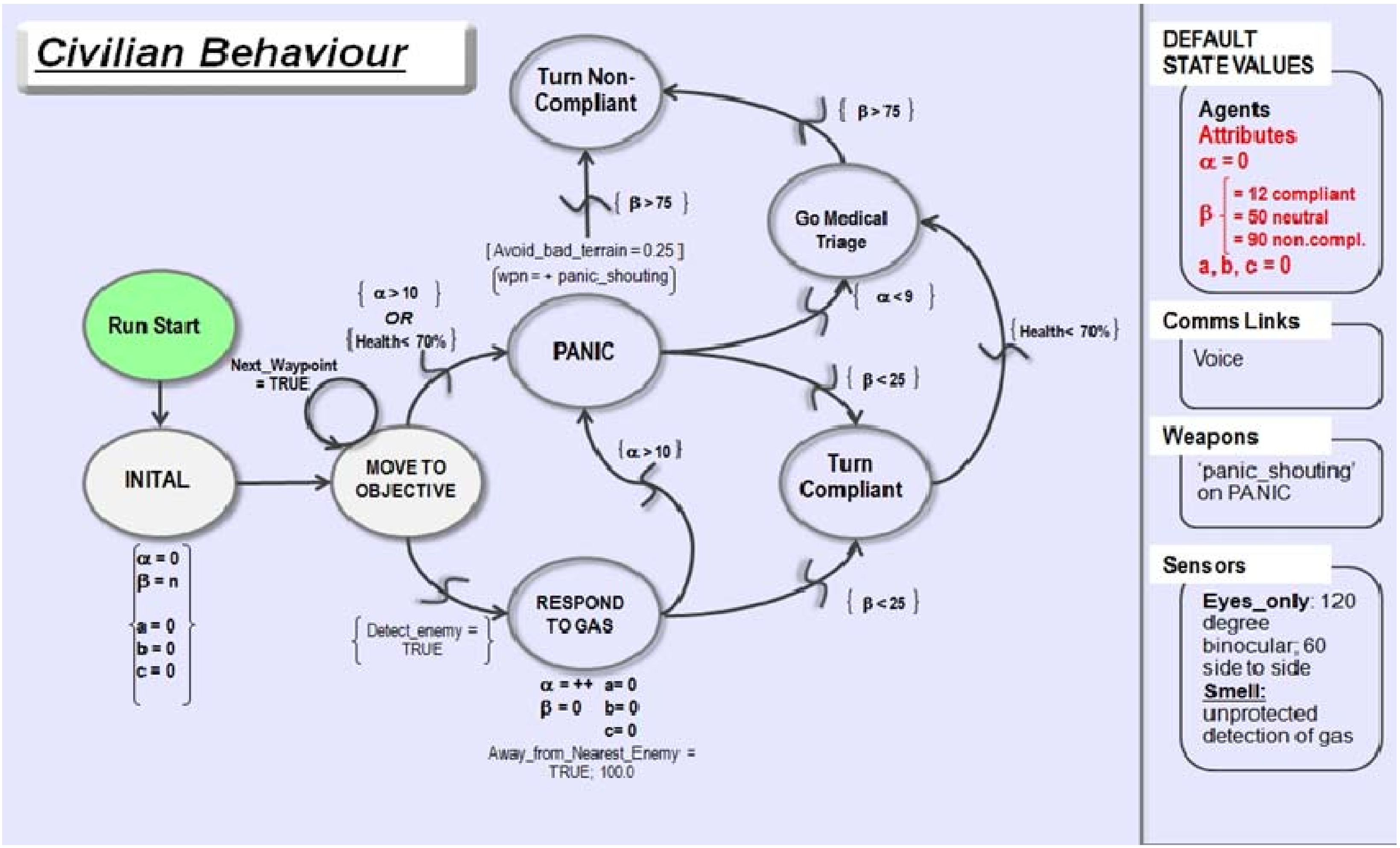


Figure 40. Graph for civilian behavior.

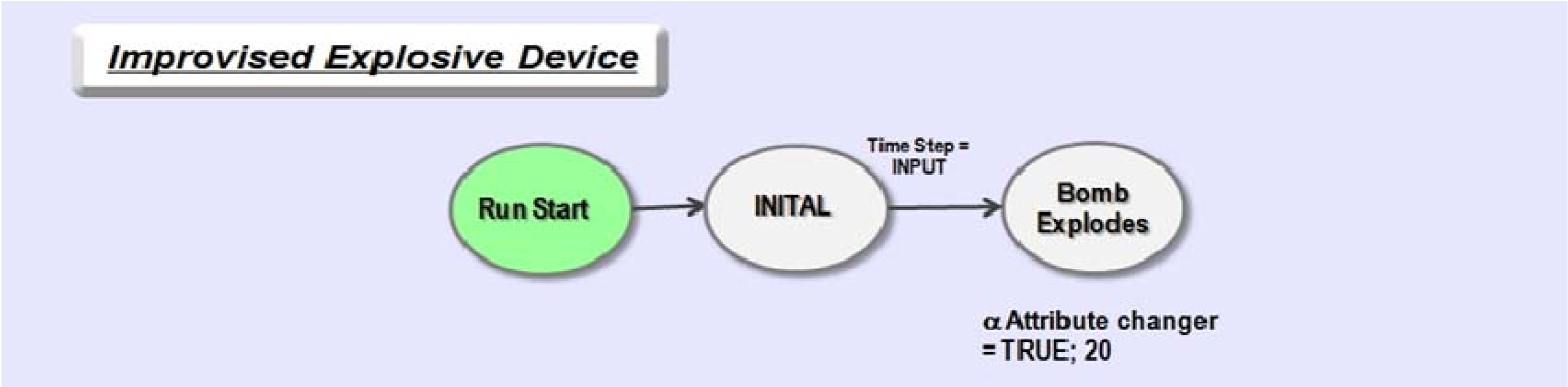


Figure 41. Graph for Improvised explosive device behavior.

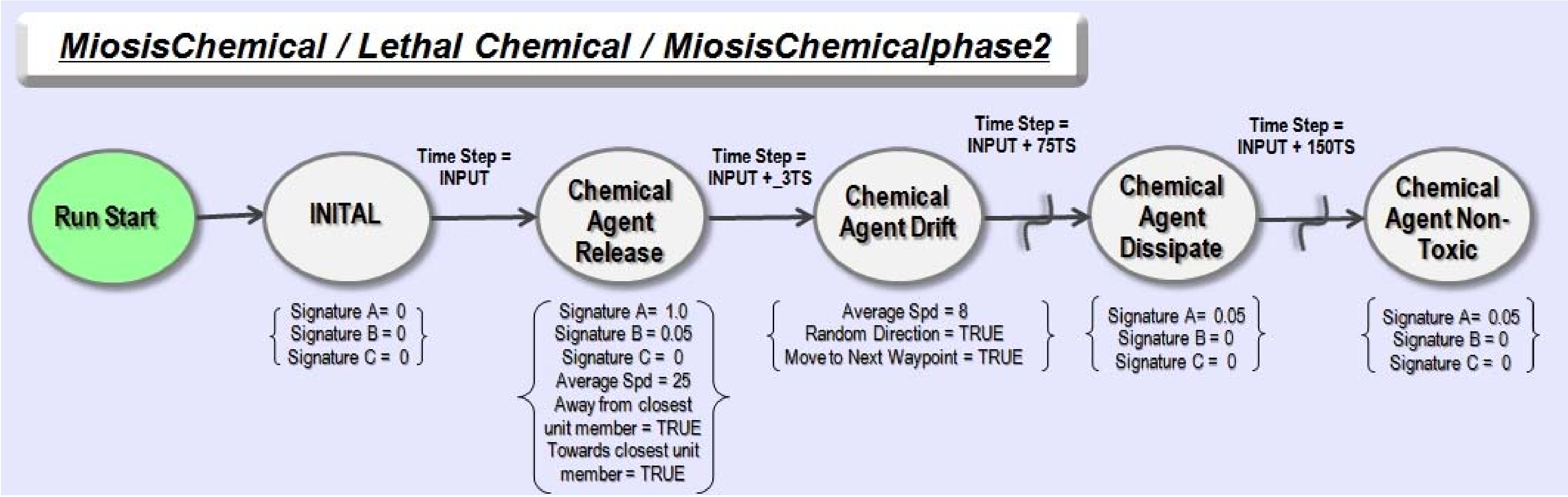


Figure 42. Graph for sarin gas and plume behavior.

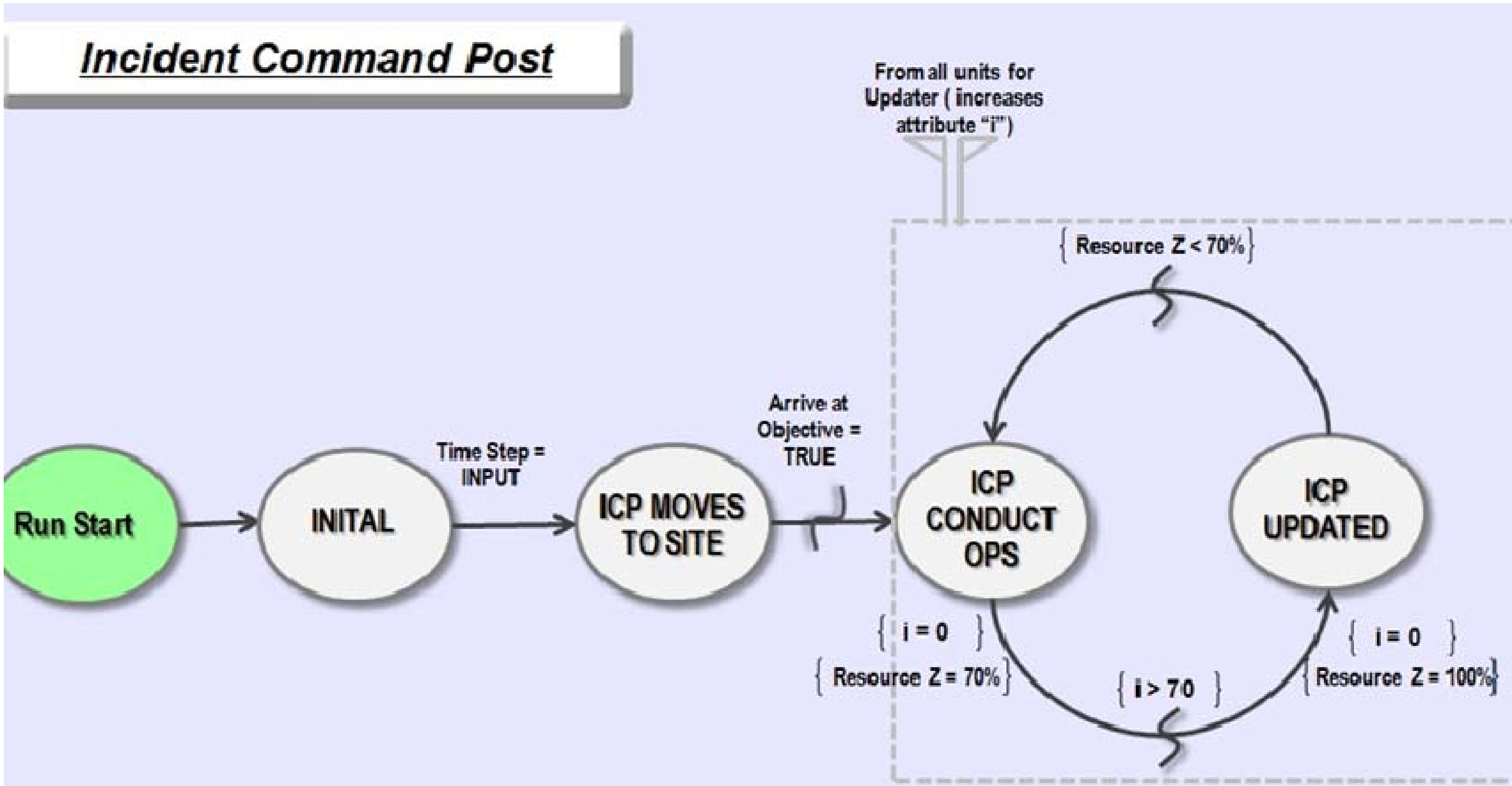


Figure 43. Graph for Incident Command Post behavior.

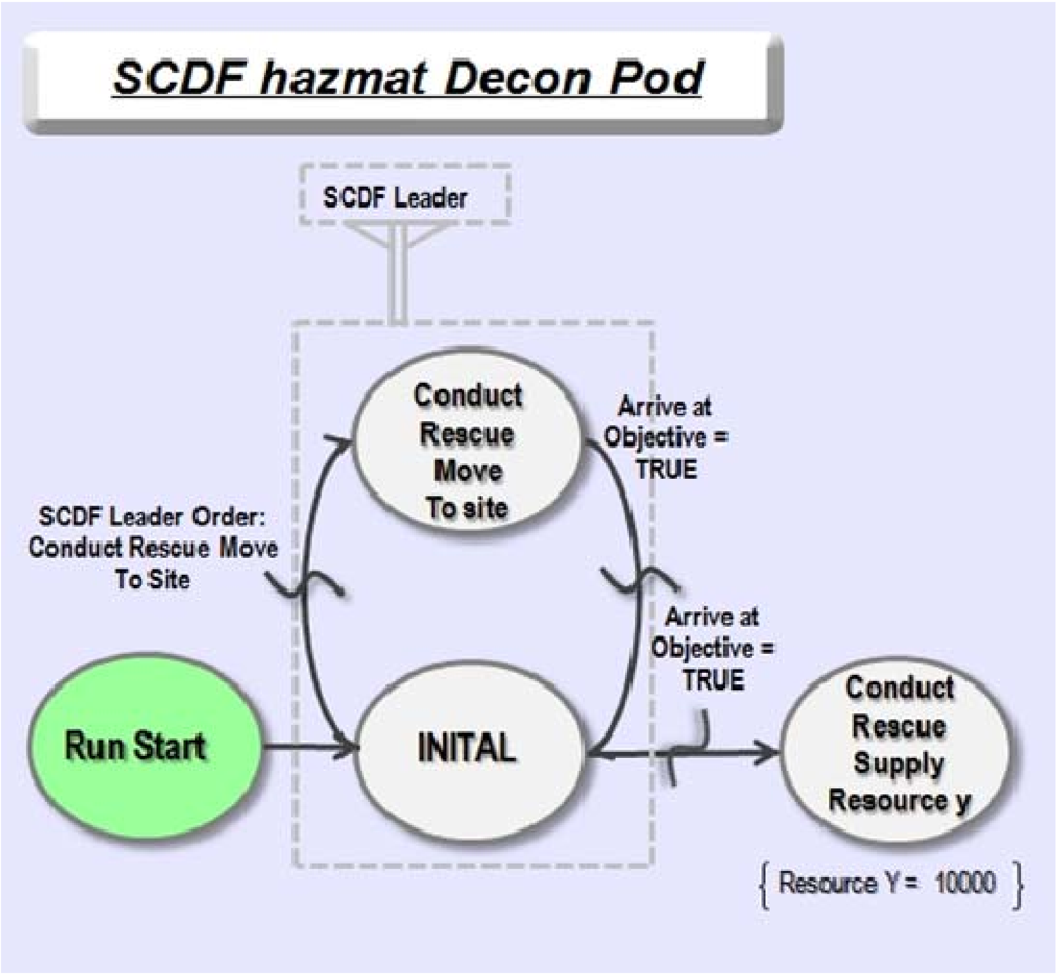


Figure 44. Graph for SCDF hazmat decontamination pod behavior. The SCDF Pump Engine Agent follows the same design.

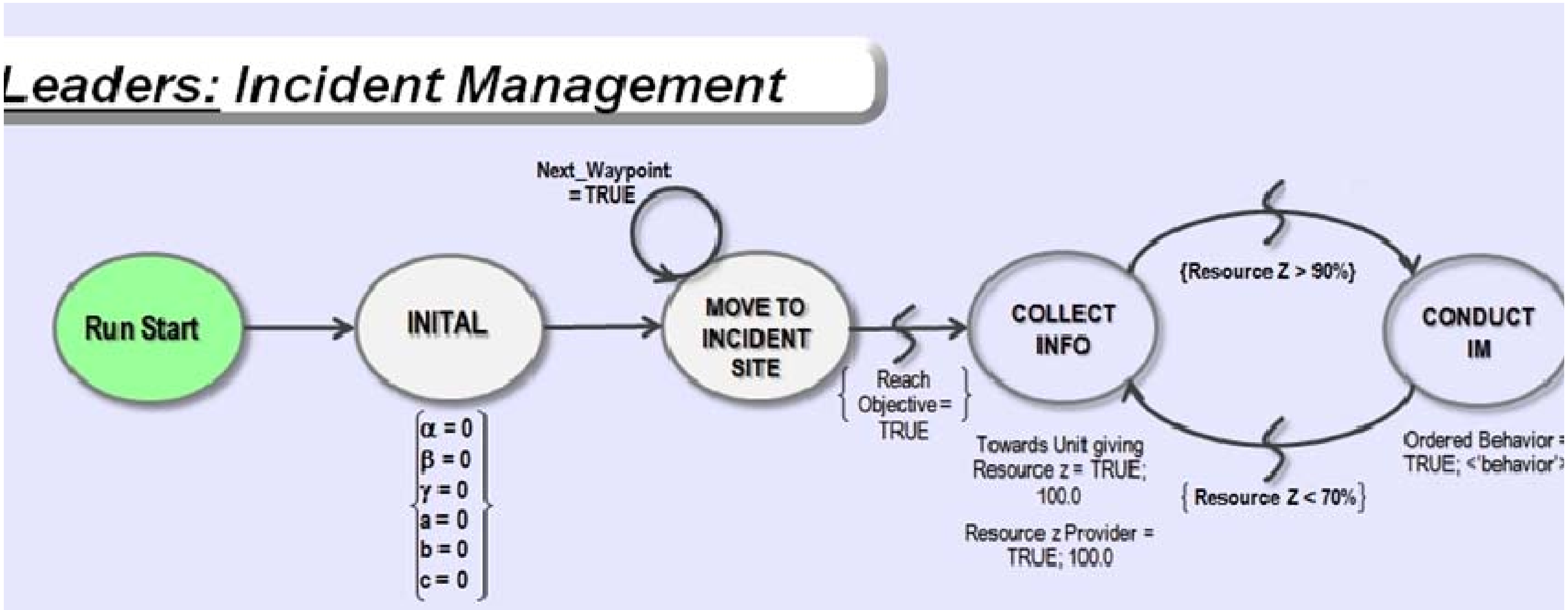


Figure 45. Generic graph for incident management behavior for force leaders. This represents a generic form for information collection by the force leaders.

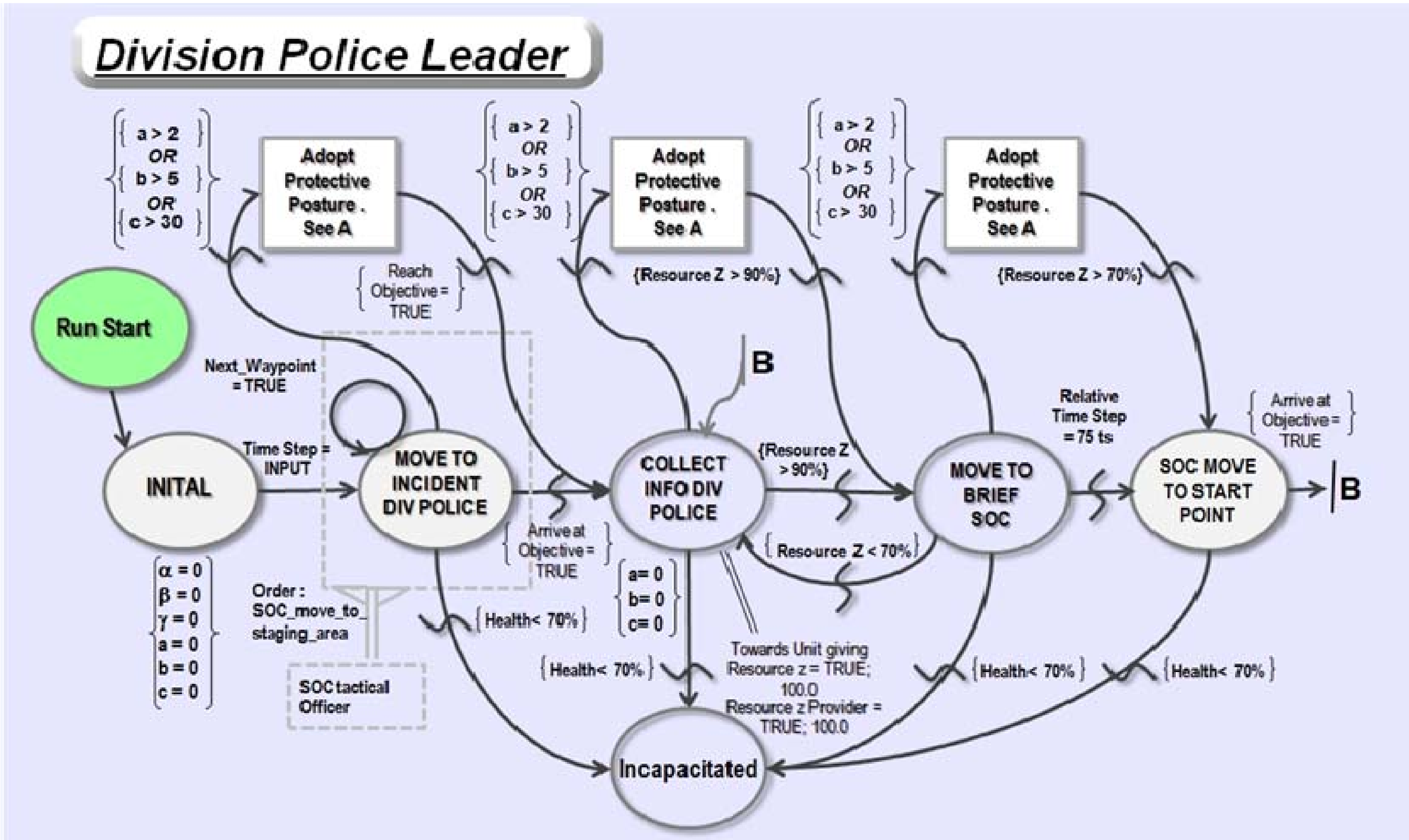


Figure 46. Graph for division police leader behavior. The “listener” box indicates that friendly units that belong to the same side and have either have communications with the leader, or always know about the leader, are aware of the ordered behavior from the leader.

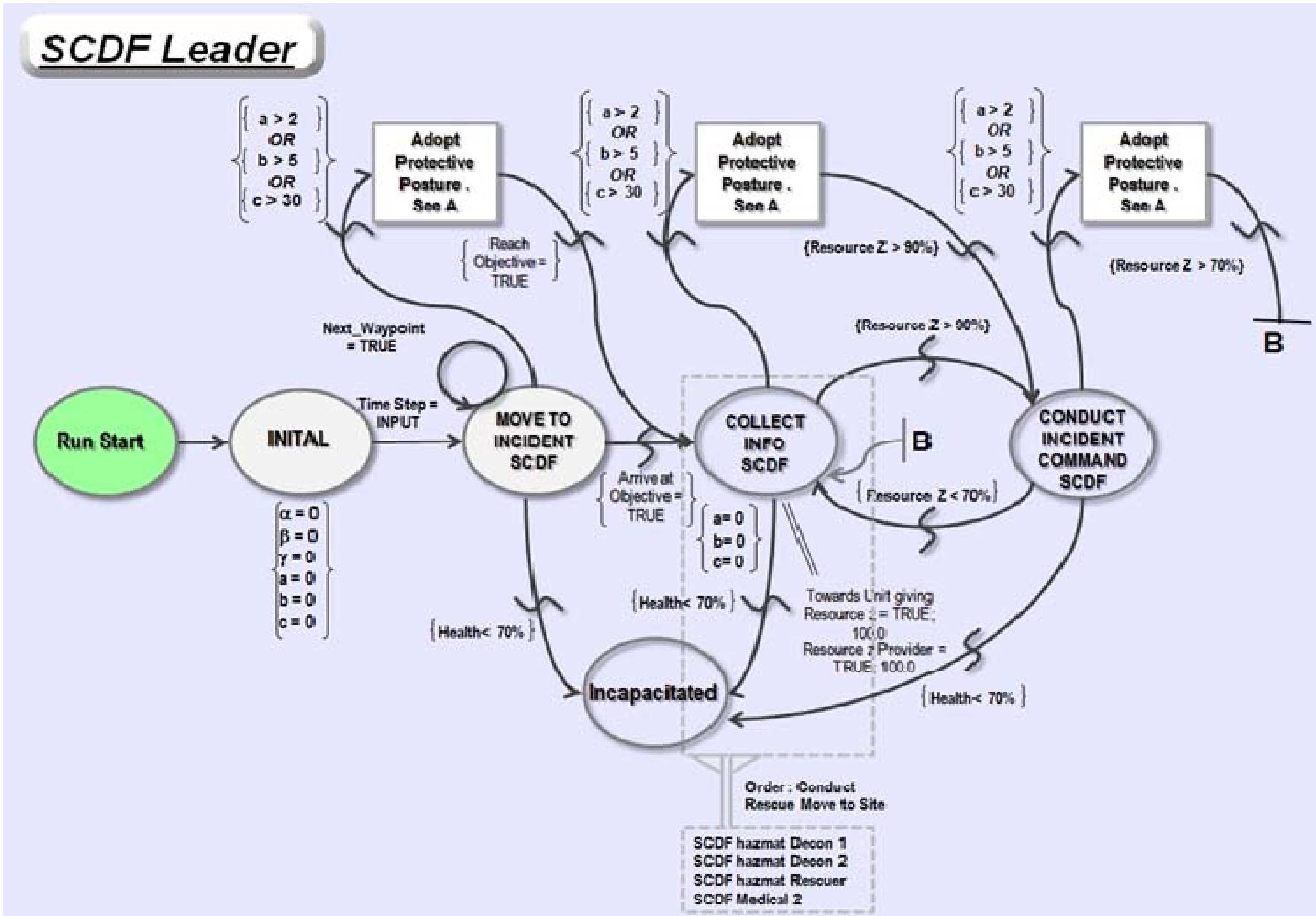


Figure 47. Graph for SCDF leader behavior.

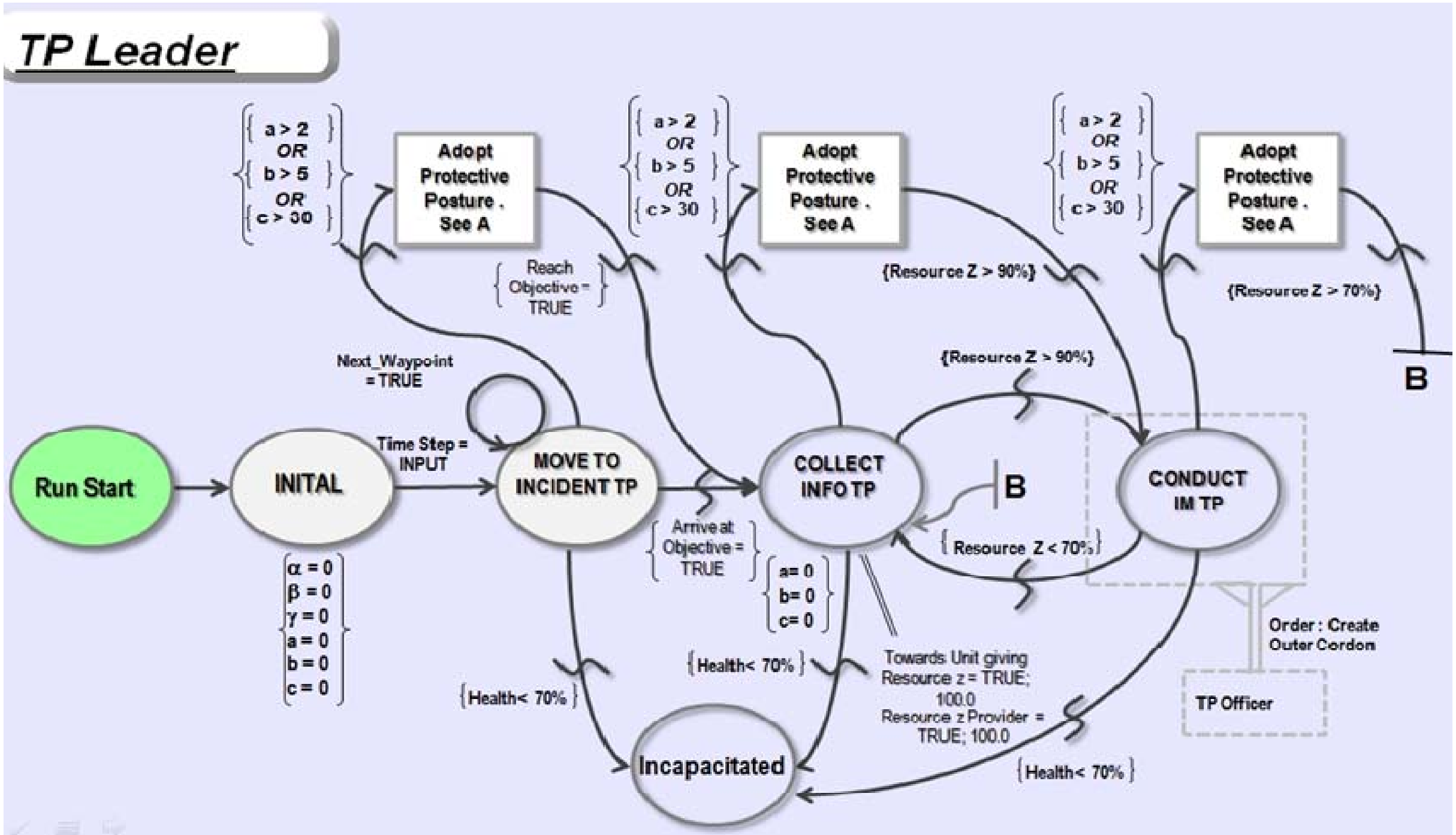


Figure 48. Graph for TP leader behavior.

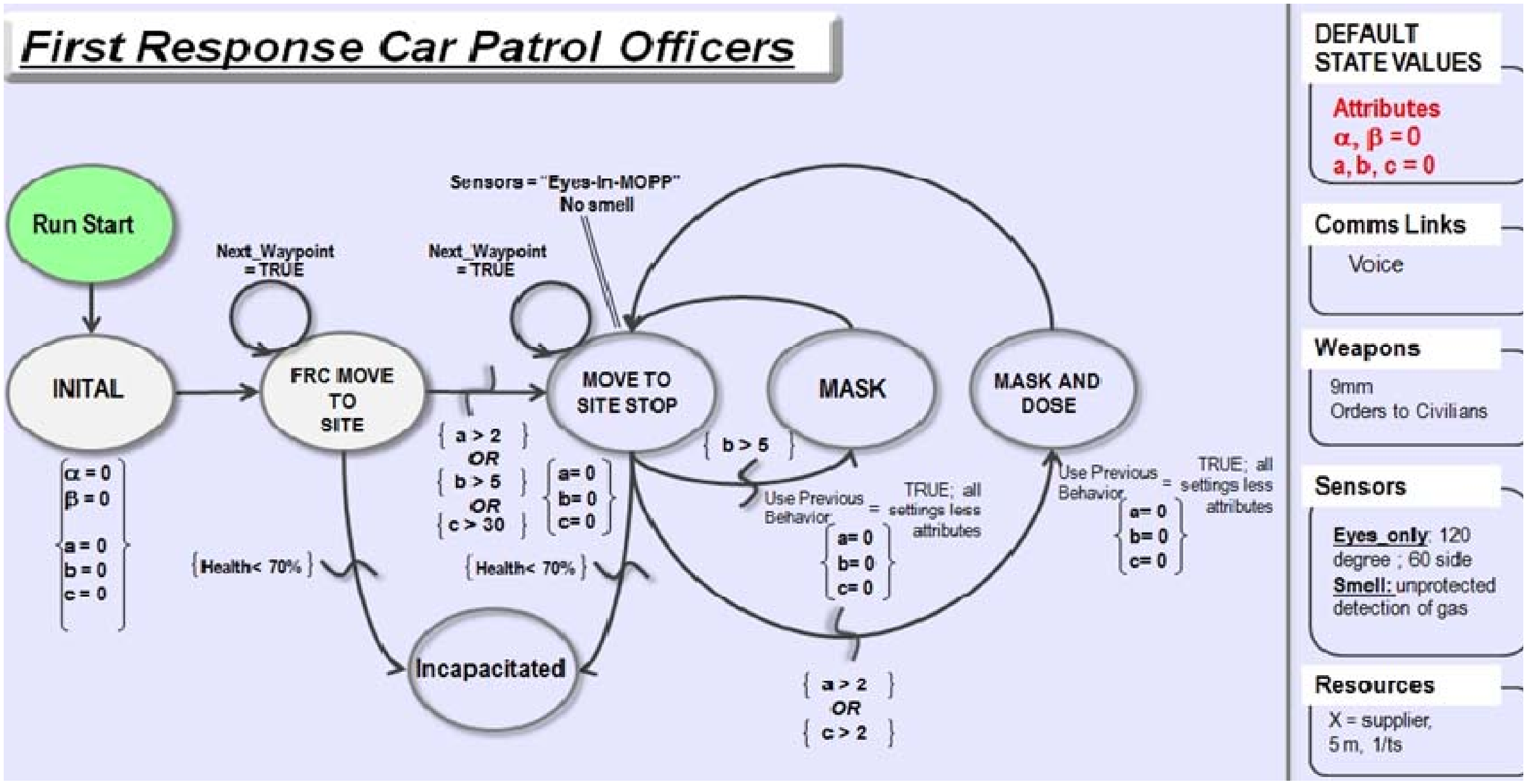


Figure 49. Graph for FRC patrol officer behavior. "MOVE TO SITE STOP,""MASK," and "MASK AND DOSE" use previous behavior settings of "FRC MOVE TO SITE." "MOVE TO SITE STOP" is a "clone" of "FRC MOVE TO SITE,"necessary to retain the triggers unique to "FRC MOVE TO SITE." This is replicated in subsequent graphs.

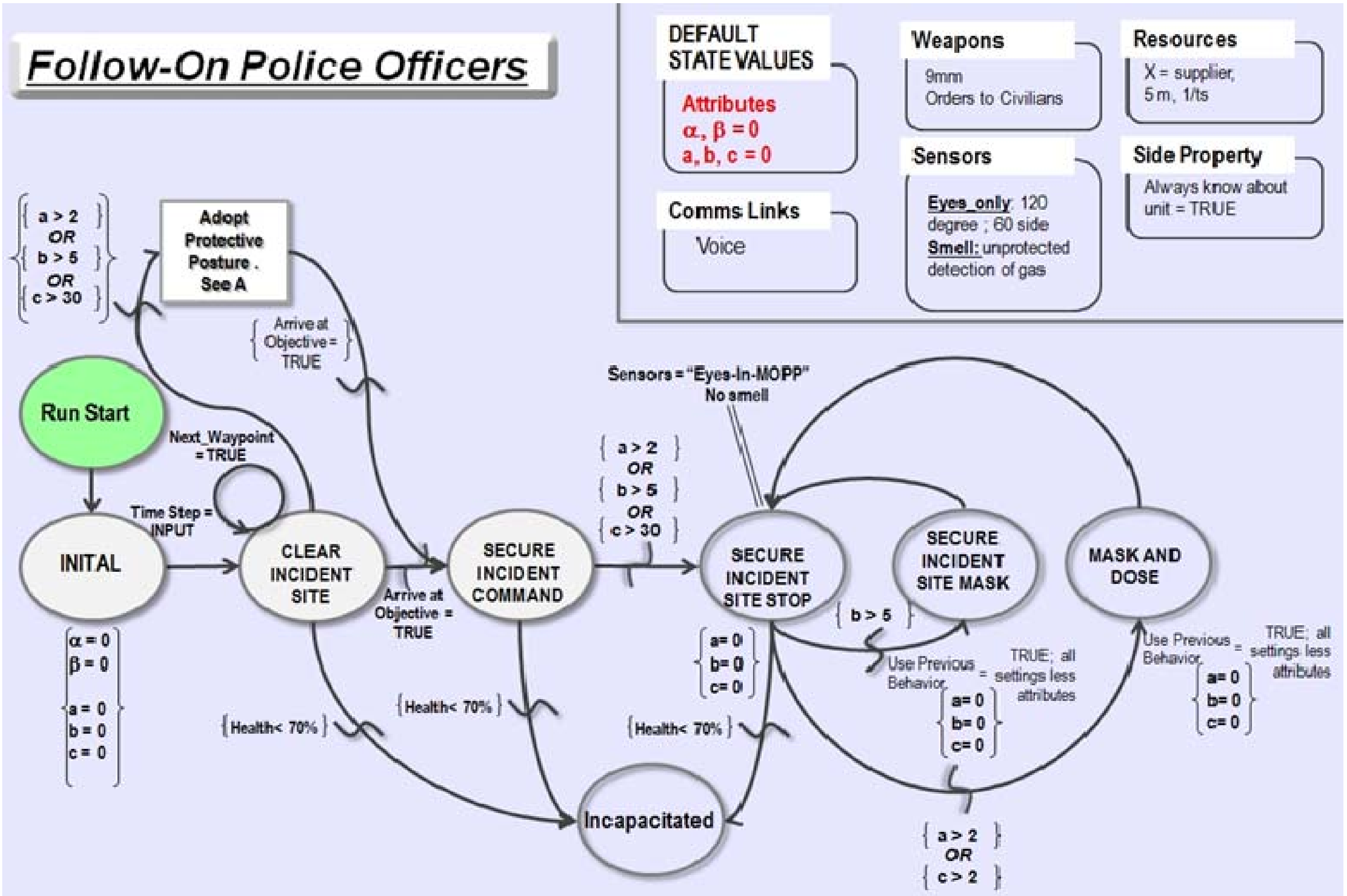


Figure 50. Graph for follow-on police officer behavior.

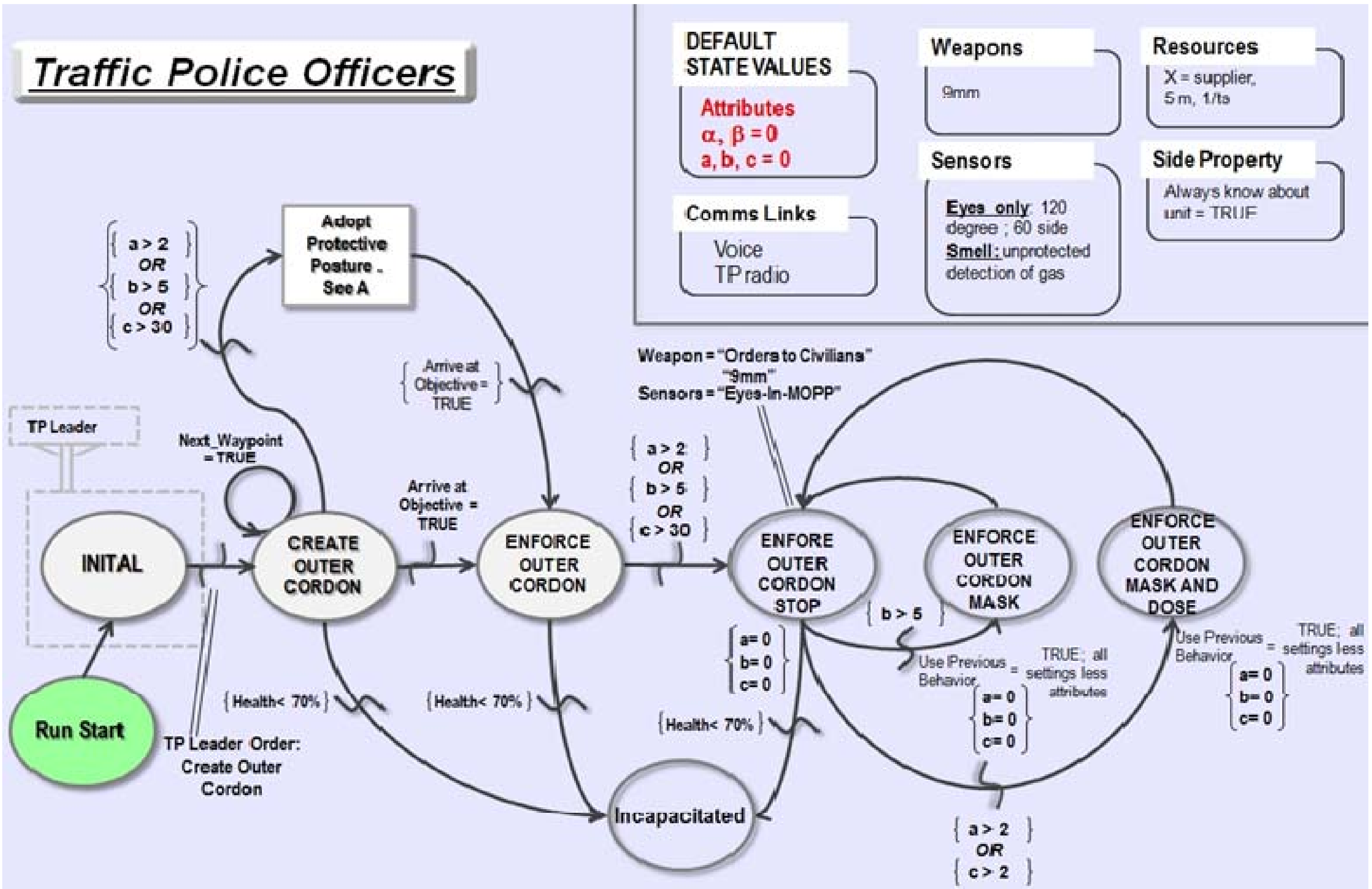


Figure 51. Graph for traffic police officer behavior.

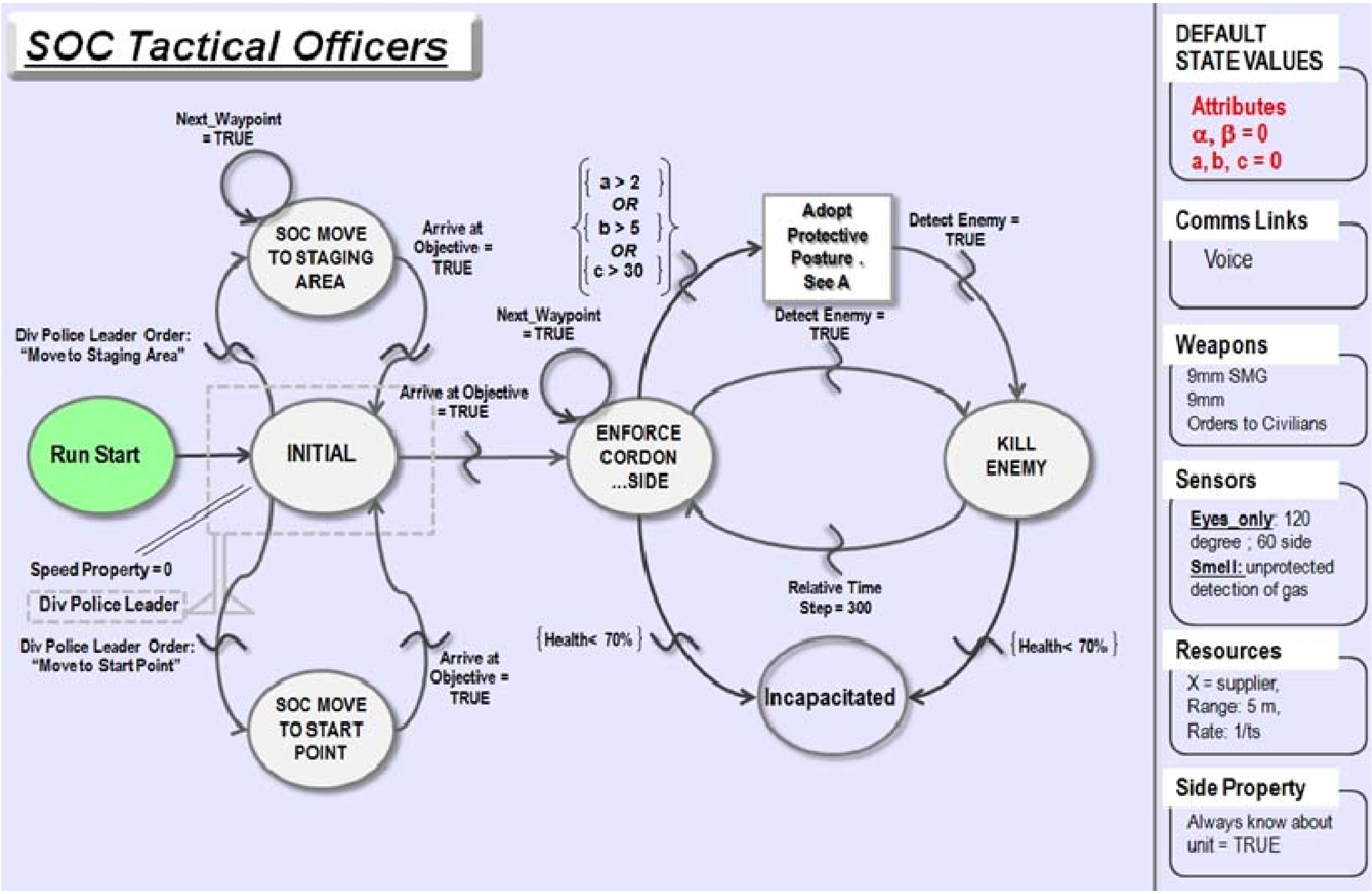


Figure 52. Graph for SOC tactical officer behavior. "ENFORCE CORDON …SIDE" indicates that two different routes exist.

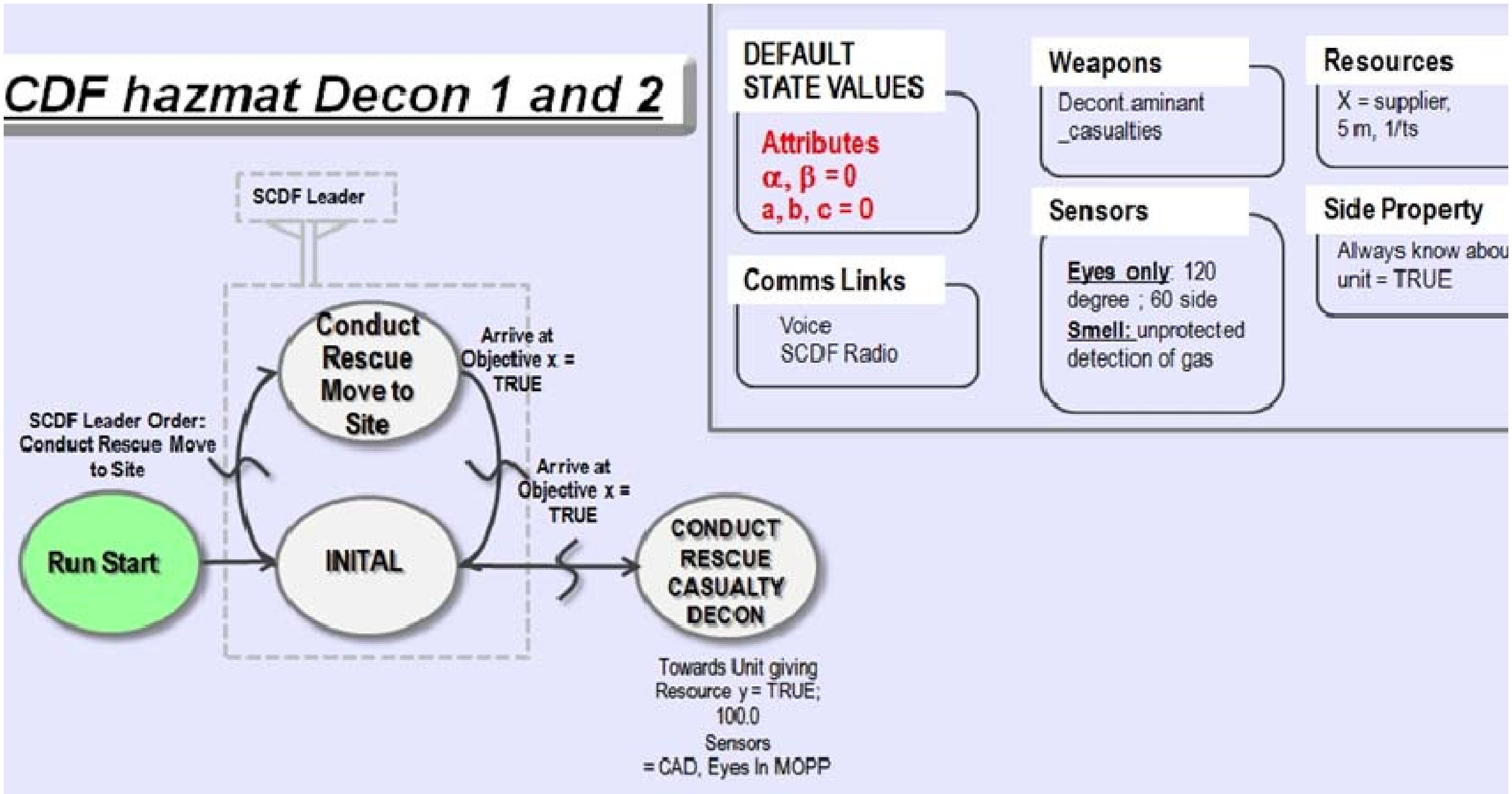


Figure 53. Graph for SCDF hazmat decontamination team behavior. The SCDF hazmat rescuers are configured to perform the casualty extraction operation from the incident site in the same format as above.

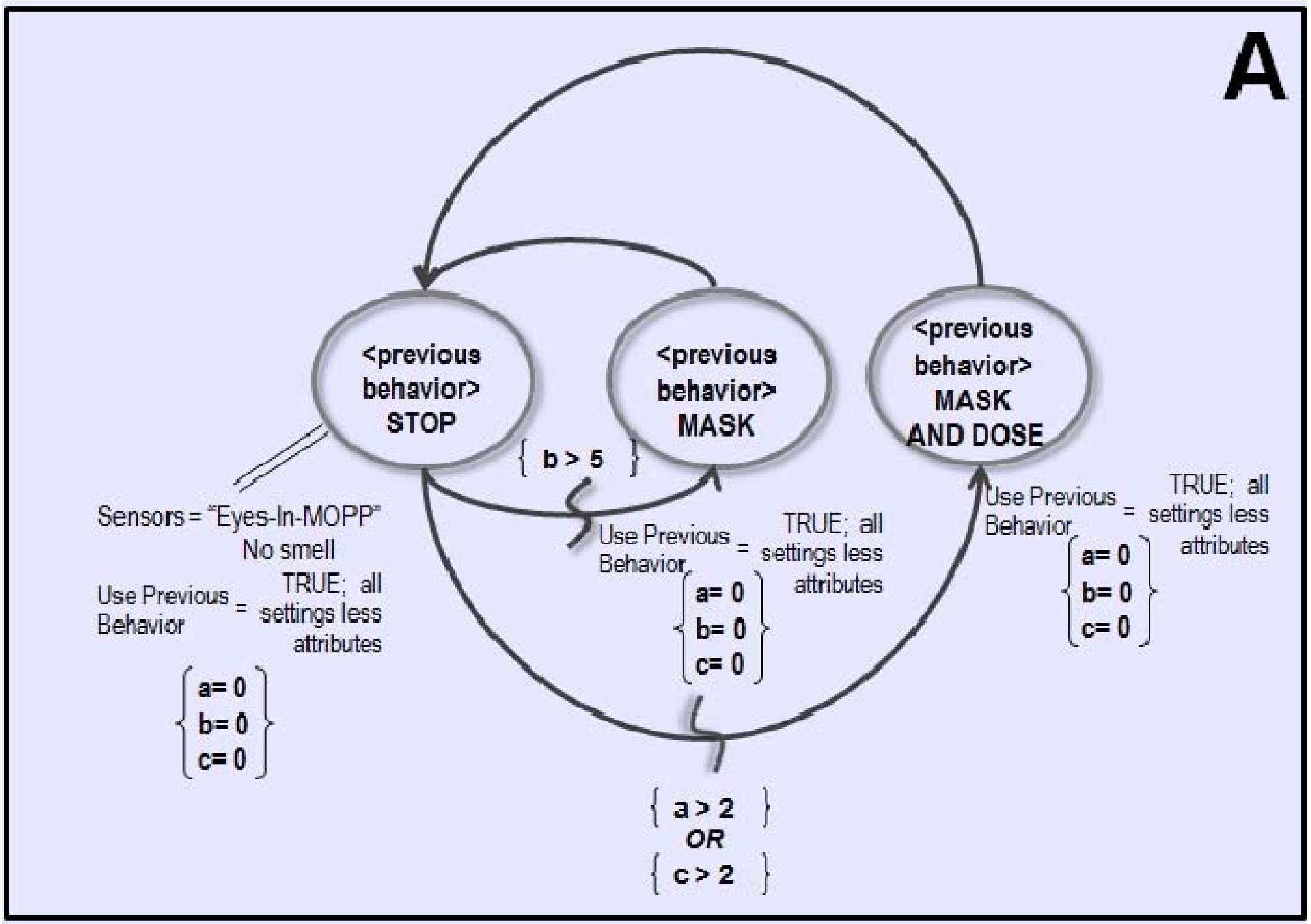
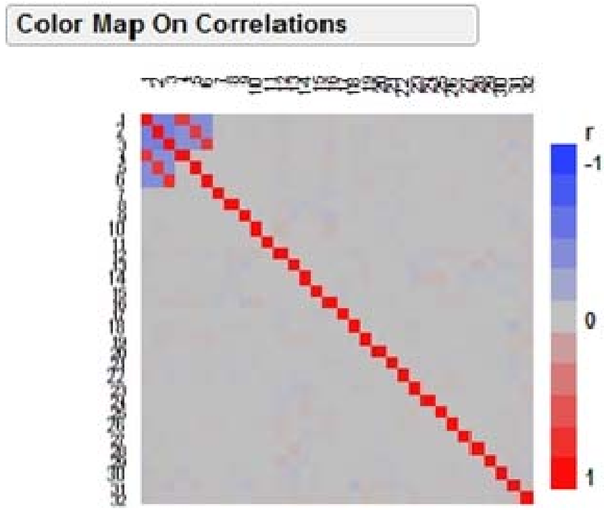


Figure 54. Sub-graph for immediate action drill against a chemical vapor hazard (Kent 2007).

APPENDIX E. ANALYSIS OF CORRELATION IN PARAMETERS

Prior to running the full experiment, the study analyzed the correlation between the chosen factors. The study used JMP 7.0 to generate a matrix of correlation coefficients that summarizes the strength of the linear relationships between each pair of response variables (Y). Figure 54 summarizes this analysis in the form of a color matrix, showing the correlations among variables on a scale from red (+1) to blue (-1). Numerically, the maximum correlation coefficient between any two factors is 0.0786. As most of the factors chosen for this study involve a combination of both physical and intangible characteristics (such as abstractions of psychological and social factors), the study deems this value acceptable for our purposes. The following numbered key corresponds to the factors in color matrix. As counter-examples, note that factors one through six are highly correlated in the positive and negative range. This is because they are interpretations of the total number of compliant, neutral, and non-compliant civilians in each area. The calculations for values 1 through 3 are based on values 4 through 6. As such, the study avoids using the percentage values for our regression when analyzing the uncontrollable (environmental) factors.



1. Percent Affected Popn. Compliant
2. Percent Affected Popn.Neutral
3. Percent Affected Popn.Non-compliant
4. # Compliant Civilians
5. # Neutral Civilians
6. # Non-compliant Civilians
7. Non-compliance Compliant Civilians
8. Non-compliance Neutral Civilians
9. Non-compliance Non-compliant Civilians
10. P(Influence) by Compliant Civilians
11. P(Influence) Panicking Civilians
12. # FRC Patrol Officers
13. # FR Medical Teams
14. # Follow-on Med Teams
15. # Hazmat Rescuers
16. # Pump Engine Rescuers
17. Broadcast Range of Orders to Civilians
18. Max Influence FRC Patrol Officers
19. Max Influence Div Follow-on Police
20. Max Influence Hazmat Rescuers
21. Max Influence Pump Engine Rescuers
22. Max Influence SOC Tactical Officers
23. Max Influence TP Officers
24. Entry Time First Responders
25. Entry Time SCDF Leader
26. Entry Time TP Leader
27. Entry Time Div Police Leader/SOC
28. Entry Time Follow-on Patrol Officers
29. Chem Detection Range
30. CAD Broadcast Range
31. # Follow On Patrol Officers
32. # Decon Pods and Teams

Figure 55. Color map summarizing the degree of correlation of 29 factors (controllable and uncontrollable) used in the experiments.

APPENDIX F. LINEAR REGRESSION FOR SCENARIO OUTPUTS

JMP 7.0 allows the user to generate a "best-fit" parametric model to estimate the chosen response, using the scoring characteristics of a step-wise regression, followed by a "least-squares" fit to generate a regression model that best plots an estimator line through the data set of observations. Stepwise regression is an approach for selecting variables for a regression model and is used when there is little theory to guide the selection of terms for a model and when the intent is to determine what can potentially provide a good fit.

In this study, the responses are MOP 1 and MOP 2. The analysis scopes the regression to estimates for MOP 1. In all four scenarios, the linear plot of the estimate generated by the parametric equation does not fit perfectly with the scatter plot of the data. This is expected given the high variability in scatter, the less than perfect R-square values for the regression, and the possibility that the relationships between the regressor and the response are poorly defined. As such, the study attaches a lower priority to the estimative capabilities of the regression, and focuses on the regressor term selection, which determines what factors prove (statistically) significant to estimating the response and what interactions exist among factors that are strongly associated with the outcome.

StepAIC allows the user to configure selection criteria to include or exclude any factor or combination of factors desired by the user. For this study, interaction terms and polynomial terms up to 3 orders (i.e., cubic terms and triple factor interaction terms) were allows. The probability for terms to enter selection was set to 0.001. The probability for terms to be excluded was set to 0.1.

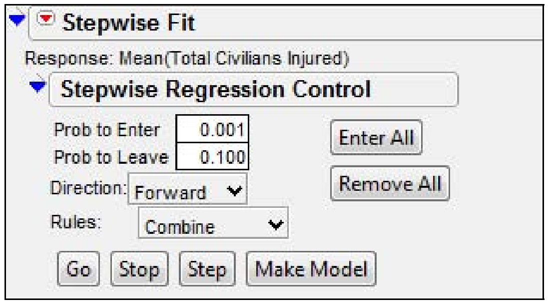
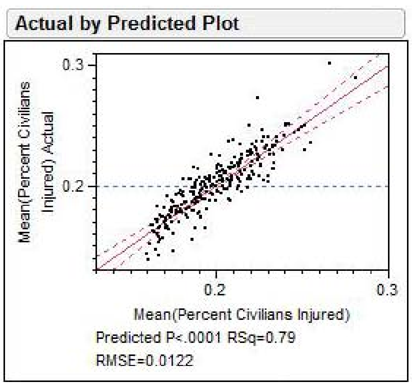


Figure 56. Entry prompt showing control settings for stepwise regression

As the analyses are interested in the relationships between the controllable factors with respect to how they influence MOP 1, interaction terms with two controllable factors were analyzed as contoured plots using MOP 1 as the response. The only exception is the base case, where contour plots were used instead to analyze the relationship among the most significant environmental factors.

A. BASE CASE



Summary of Fit

RSquare	0.78719
RSquare Adj	0.775805
Root Mean Square Error	0.012185
Mean of Response	0.199676
Observations (or Sum Wgts)	257

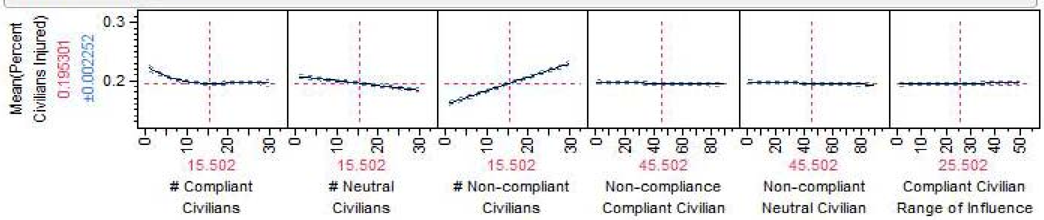
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	13	0.13346116	0.010266	69.1434
Error	243	0.03608007	0.000148	Prob > F
C. Total	256	0.16954123		<.0001*

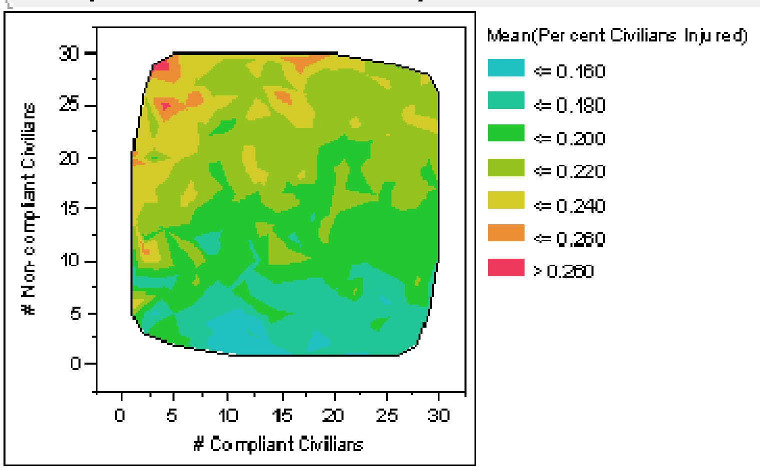
Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
# Non-compliant Civilians	0.0023507	9.028e-5	26.04	<.0001*
# Neutral Civilians	-0.00082	9.047e-5	-9.07	<.0001*
(# Compliant Civilians-15.5019)*(# Compliant Civilians-15.5019)	6.1842e-5	0.000012	5.13	<.0001*
(# Compliant Civilians-15.5019)*(# Non-compliant Civilians-15.5019)	-4.053e-5	0.000011	-3.67	0.0003*
(# Neutral Civilians-15.5019)*(Compliant Civilian Range of Influence-25.5019)	-2.277e-5	6.499e-6	-3.50	0.0005*
(# Neutral Civilians-15.5019)*(Non-compliant Neutral Civilian-45.5019)	1.2266e-5	3.685e-6	3.33	0.0010*
(# Neutral Civilians-15.5019)*(# Non-compliant Civilians-15.5019)	-3.475e-5	0.000011	-3.16	0.0018*
(# Compliant Civilians-15.5019)*(# Neutral Civilians-15.5019)	2.8687e-5	1.042e-5	2.75	0.0064*
(# Compliant Civilians-15.5019)*(# Compliant Civilians-15.5019)*(# Compliant Civilians-15.5019)	-4.037e-6	1.622e-6	-2.49	0.0135*
Non-compliant Neutral Civilian	-0.000049	2.973e-5	-1.65	0.1006
Non-compliance Compliant Civilian	-3.921e-5	2.957e-5	-1.33	0.1861
Compliant Civilian Range of Influence	0.0000457	5.355e-5	0.85	0.3942
# Compliant Civilians	-4.286e-5	0.000226	-0.19	0.8500

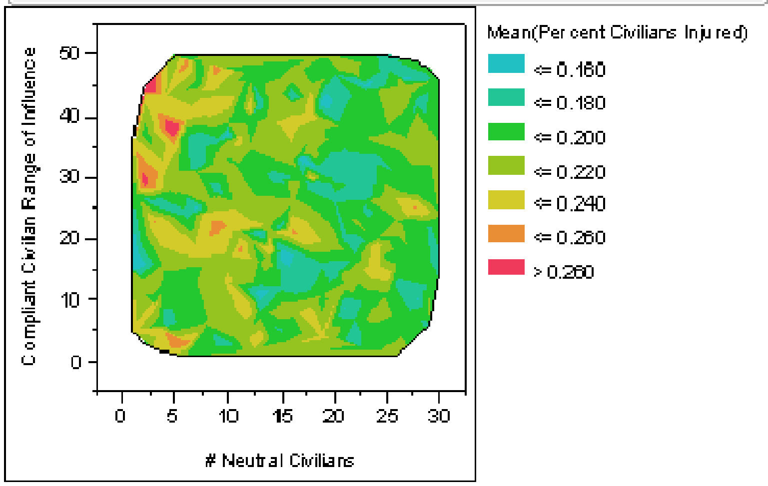
Prediction Profiler



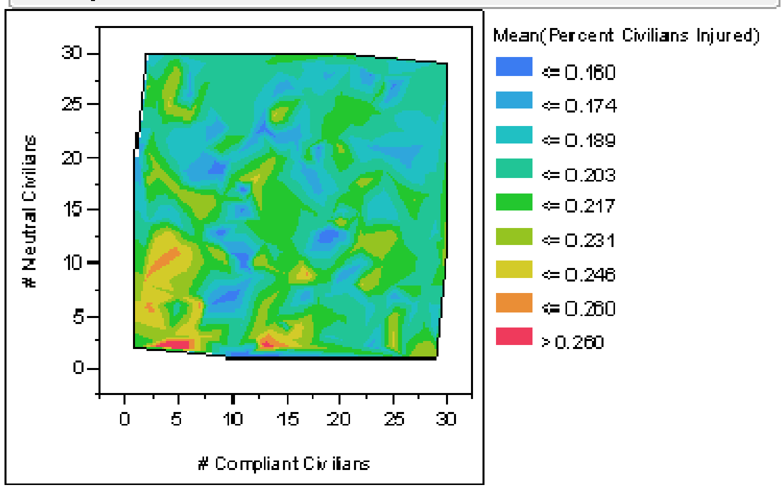
Compliant Civilians vs. # Non-compliant Civilians



 # Neutral Civilians vs. Compliant Civilian Range of Influence



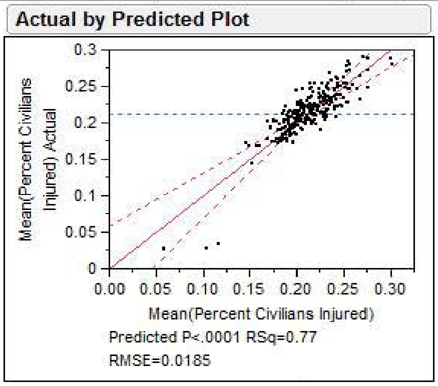
 # Compliant Civilians vs. # Neutral Civilians



B. SCENARIO #1: INDOOR CIED

Response Mean(Percent Civilians Injured)

Actual by Predicted Plot



Summary of Fit

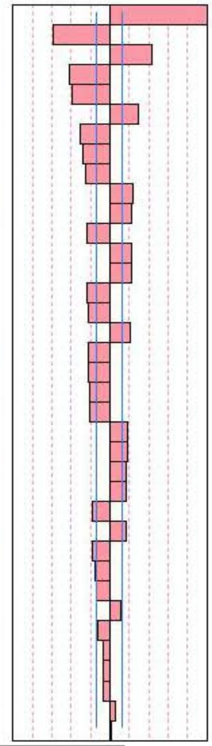
RSquare	0.769026
RSquare Adj	0.729091
Root Mean Square Error	0.018457
Mean of Response	0.212916
Observations (or Sum Wgts)	252

Analysis of Variance

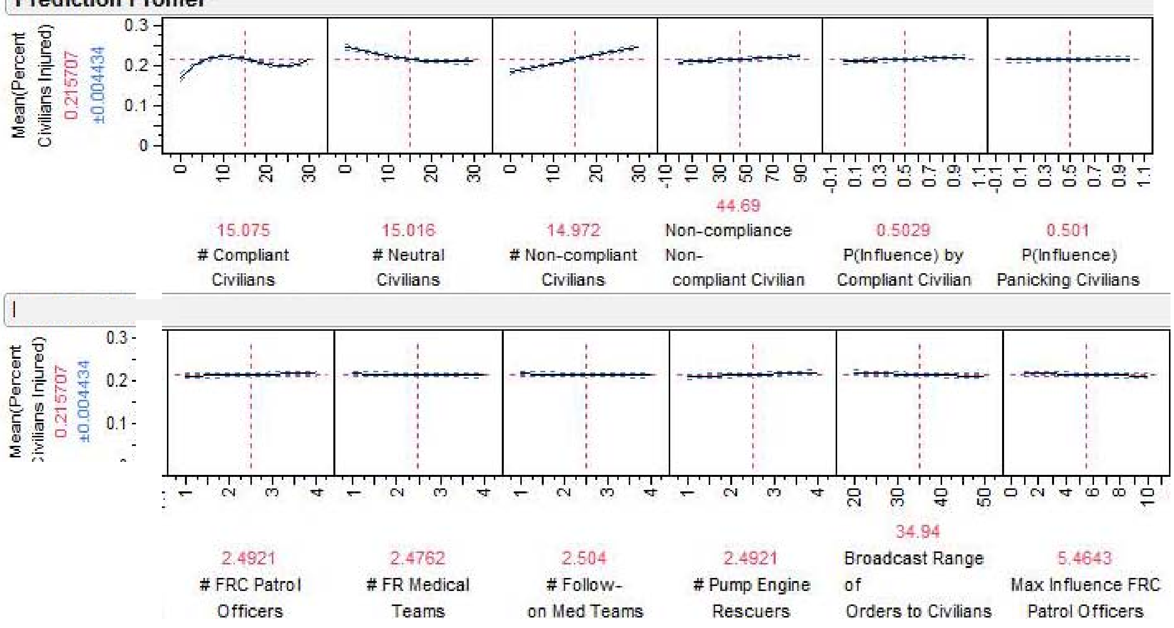
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	37	0.24273363	0.006560	19.2570
Error	214	0.07290424	0.000341	**Prob > F**
C. Total	251	0.31563787		<.0001*

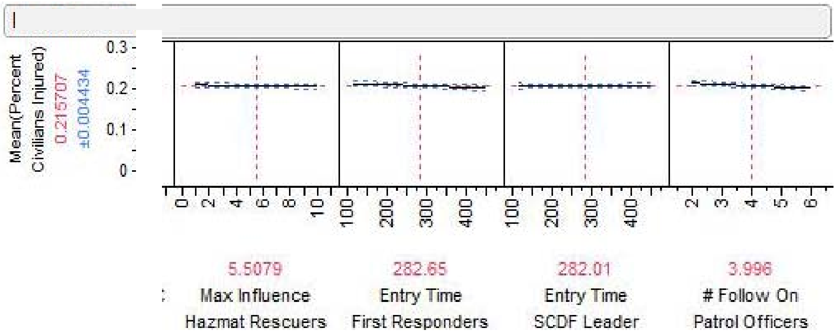
Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
# Non-compliant Civilians	0.002085	0.000139	14.97	<.0001*
# Neutral Civilians	-0.001156	0.000134	-8.60	<.0001*
(# Compliant Civilians-15.0754)*(# Compliant Civilians-15.0754)*(# Compliant Civilians-15.0754)	1.6347e-5	2.512e-6	6.51	<.0001*
# Compliant Civilians	-0.002228	0.000364	-6.11	<.0001*
(# Compliant Civilians-15.0754)*(# Compliant Civilians-15.0754)	-0.000102	0.000018	-5.67	<.0001*
(# Compliant Civilians-15.0754)*(Non-compliance Non-compliant Civilian-44.6905)*(Entry Time First Responders-282.655)	2.9705e-7	6.729e-8	4.41	<.0001*
(# Compliant Civilians-15.0754)*(Non-compliance Non-compliant Civilian-44.6905)	-0.000025	5.716e-6	-4.36	<.0001*
(# Compliant Civilians-15.0754)*(# Pump Engine Rescuers-2.49206)*(Broadcast Range of Orders to Civilians-34.9405)	-6.42e-5	0.000016	-4.00	<.0001*
(# Compliant Civilians-15.0754)*(P(Influence) by Compliant Civilian-0.50286)	-0.001806	0.000494	-3.65	0.0003*
(P(Influence) Panicking Civilians-0.50099)*(# FRC Patrol Officers-2.49206)	0.0146721	0.004212	3.48	0.0006*
(# Neutral Civilians-15.0159)*(# Neutral Civilians-15.0159)	0.0000619	1.817e-5	3.41	0.0008*
(P(Influence) by Compliant Civilian-0.50286)*(# Follow-on Med Teams-2.50397)	-0.014845	0.004411	-3.37	0.0009*
(# Compliant Civilians-15.0754)*(# Follow-on Med Teams-2.50397)	0.0005333	0.000159	3.35	0.0009*
(# Pump Engine Rescuers-2.49206)*(Broadcast Range of Orders to Civilians-34.9405)	0.0004891	0.000146	3.35	0.0010*
(# Compliant Civilians-15.0754)*(# Non-compliant Civilians-14.9722)	-4.869e-5	0.000015	-3.26	0.0013*
(# Compliant Civilians-15.0754)*(Entry Time SCDF Leader-282.008)	-4.684e-6	1.473e-6	-3.18	0.0017*
Non-compliance Non-compliant Civilian	0.0001452	4.587e-5	3.16	0.0018*
# Follow On Patrol Officers	-0.003051	0.000969	-3.15	0.0019*
(# Neutral Civilians-15.0159)*(# Non-compliant Civilians-14.9722)	-5.159e-5	1.649e-5	-3.13	0.0020*
(Non-compliance Non-compliant Civilian-44.6905)*(Entry Time First Responders-282.655)	-1.598e-6	5.388e-7	-2.97	0.0034*
(Max Influence FRC Patrol Officers-5.46429)*(Max Influence Hazmat Rescuers-5.50794)	-0.000545	0.000188	-2.90	0.0041*
(# Compliant Civilians-15.0754)*(# Neutral Civilians-15.0159)*(Entry Time SCDF Leader-282.008)	5.727e-7	2.105e-7	2.72	0.0071*
(# Compliant Civilians-15.0754)*(P(Influence) by Compliant Civilian-0.50286)*(# Follow-on Med Teams-2.50397)	0.0017727	0.000653	2.71	0.0072*
# Pump Engine Rescuers	0.0031849	0.001241	2.57	0.0110*
(# Compliant Civilians-15.0754)*(Broadcast Range of Orders to Civilians-34.9405)	4.3173e-5	1.685e-5	2.56	0.0111*
(Max Influence Hazmat Rescuers-5.50794)*(# Follow On Patrol Officers-3.99603)	-0.000866	0.000343	-2.52	0.0123*
P(Influence) by Compliant Civilian	0.0099572	0.004042	2.46	0.0145*
(# Compliant Civilians-15.0754)*(# Pump Engine Rescuers-2.49206)	-0.000332	0.000136	-2.45	0.0152*
Entry Time First Responders	-3.214e-5	1.535e-5	-2.09	0.0374*
Broadcast Range of Orders to Civilians	-0.000253	0.000135	-1.87	0.0627
# FRC Patrol Officers	0.0021377	0.001226	1.74	0.0827
Max Influence FRC Patrol Officers	-0.000735	0.000457	-1.61	0.1093
# Follow-on Med Teams	-0.001213	0.00122	-0.99	0.3212
Max Influence Hazmat Rescuers	-0.000443	0.000446	-0.99	0.3219
# FR Medical Teams	-0.001209	0.001262	-0.96	0.3391
P(Influence) Panicking Civilians	0.0032572	0.00405	0.80	0.4222
Entry Time SCDF Leader	3.0689e-6	1.219e-5	0.25	0.8014

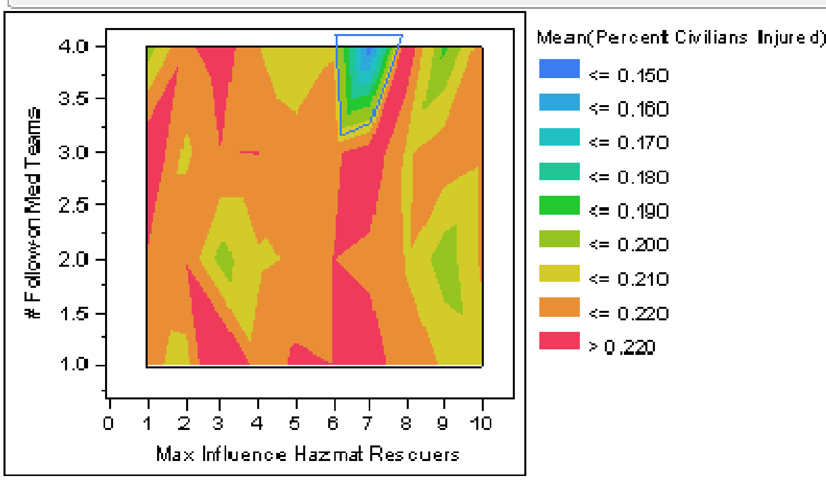


Prediction Profiler

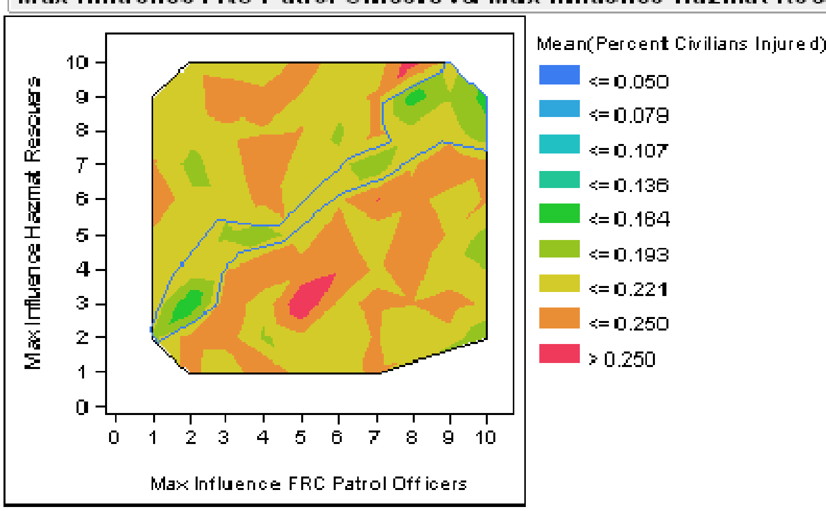




Max Influence Hazmat Rescuers vs. # Follow-on Med Teams



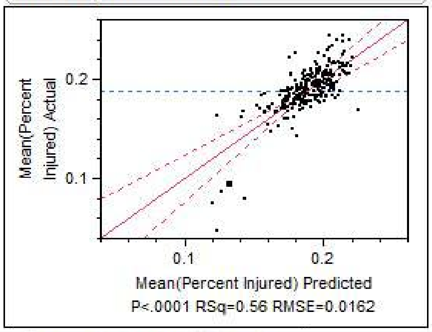
Max Influence FRC Patrol Officers vs. Max Influence Hazmat Rescuers



C. SCENARIO #2: OUTDOOR CIED

Response Mean(Percent Injured)

Actual by Predicted Plot



Summary of Fit

RSquare	0.561804
RSquare Adj	0.540253
Root Mean Square Error	0.016165
Mean of Response	0.188759
Observations (or Sum Wgts)	257

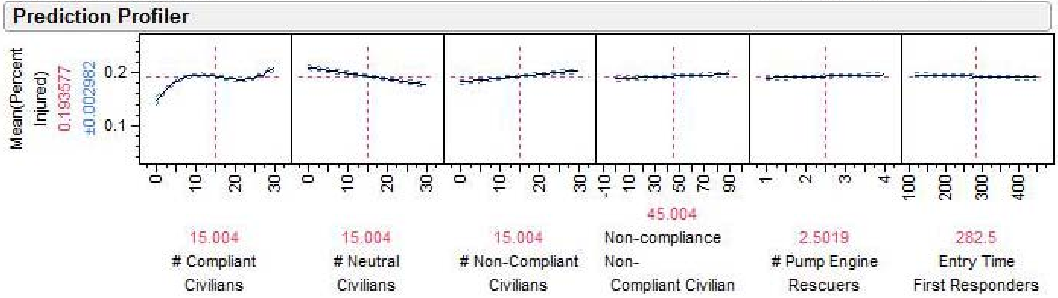
Analysis of Variance

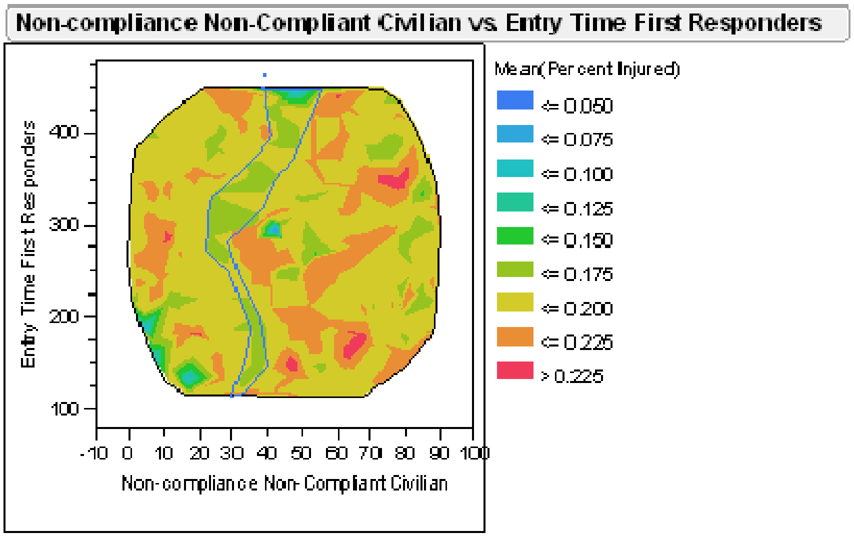
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	12	0.08174088	0.006812	26.0690
Error	244	0.06375639	0.000261	Prob > F
C. Total	256	0.14549727		<.0001*

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
# Neutral Civilians	-0.001071	0.000116	-9.24	<.0001*
(# Compliant Civilians-15.0039)*(# Compliant Civilians-15.0039)*(# Compliant Civilians-15.0039)	1.5012e-5	1.942e-6	7.73	<.0001*
# Non-Compliant Civilians	0.000733	0.000116	6.32	<.0001*
(# Compliant Civilians-15.0039)*(# Compliant Civilians-15.0039)	-0.000062	0.000015	-4.15	<.0001*
# Compliant Civilians	-0.001172	0.00029	-4.05	<.0001*
(Non-compliance Non-Compliant Civilian-45.0039)*(Entry Time First Responders-282.502)	-1.688e-6	4.632e-7	-3.64	0.0003*
(# Compliant Civilians-15.0039)*(# Pump Engine Rescuers-2.50195)	-0.000359	0.000113	-3.18	0.0016*
(# Compliant Civilians-15.0039)*(# Non-Compliant Civilians-15.0039)	-3.771e-5	1.219e-5	-3.09	0.0022*
(# Compliant Civilians-15.0039)*(Non-compliance Non-Compliant Civilian-45.0039)	-1.172e-5	4.745e-6	-2.47	0.0142*
Non-compliance Non-Compliant Civilian	9.3541e-5	3.879e-5	2.41	0.0166*
# Pump Engine Rescuers	0.0020002	0.001055	1.90	0.0592
Entry Time First Responders	-1.625e-5	1.048e-5	-1.55	0.1221

Prediction Profiler

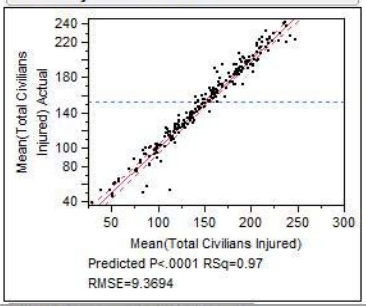



Non-compliance Non-Compliant Civilian vs. Entry Time First Responders
Entry Time First Responders
100
200
300
400
-10
0
10
20
30
40
50
60
70
80
90
100
Non-compliance Non-Compliant Civilian
Mean(Percent Injured)
<= 0.050
<= 0.075
<= 0.100
<= 0.125
<= 0.150
<= 0.175
<= 0.200
<= 0.225
> 0.225

D. SCENARIO #3: OUTDOOR VBIED

Response Mean(Total Civilians Injured)

Actual by Predicted Plot



Summary of Fit

RSquare	0.971811
RSquare Adj	0.969316
Root Mean Square Error	9.369378
Mean of Response	151.9715
Observations (or Sum Wgts)	247

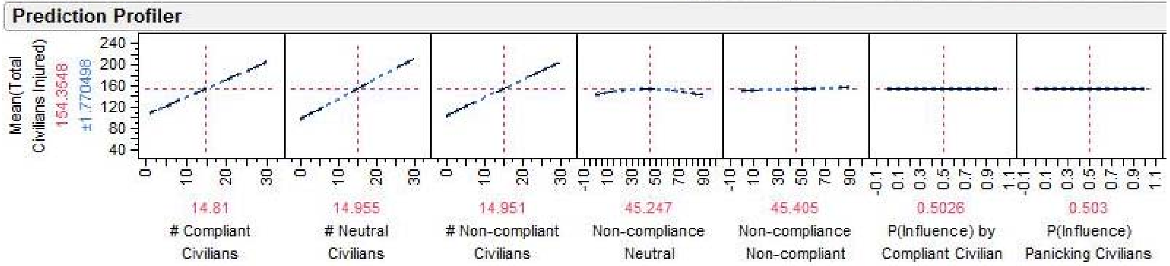
Analysis of Variance

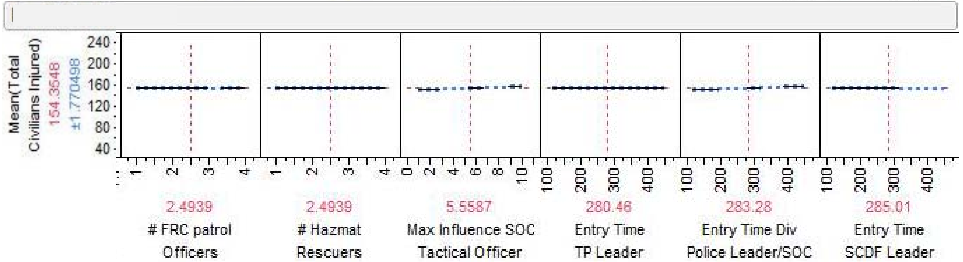
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	20	683957.39	34197.9	389.5629
Error	226	19839.46	87.8	Prob > F
C. Total	246	703796.86		<.0001*

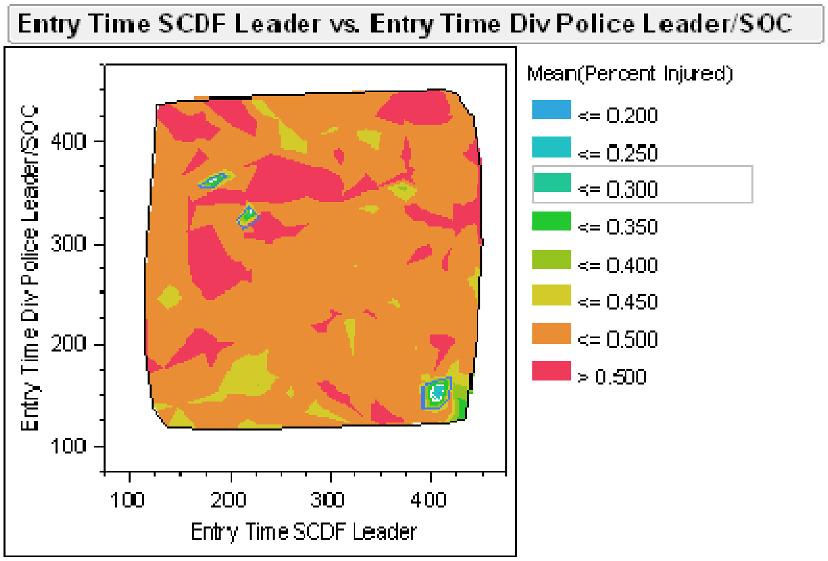
Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
# Neutral Civilians	3.7833713	0.068829	54.97	<.0001*
# Non-compliant Civilians	3.3254084	0.068572	48.50	<.0001*
# Compliant Civilians	3.3368114	0.070283	47.48	<.0001*
(Non-compliance Neutral-45.247)*(Non-compliance Neutral-45.247)	-0.005804	0.000986	-5.89	<.0001*
(Non-compliance Neutral-45.247)*(Entry Time TP Leader-280.462)	0.0008664	0.000249	3.48	0.0006*
Entry Time Div Police Leader/SOC	0.0204651	0.006182	3.31	0.0011*
(P(Influence) Panicking Civilians-0.50304)*(# FRC patrol Officers-2.49393)	6.8137412	2.116733	3.22	0.0015*
(P(Influence) by Compliant Civilian-0.50263)*(P(Influence) Panicking Civilians-0.50304)	-21.59223	7.253915	-2.98	0.0032*
(Entry Time SCDF Leader-285.008)*(Entry Time Div Police Leader/SOC-283.283)	0.0001893	6.764e-5	2.80	0.0056*
Max Influence SOC Tactical Officer	0.6122568	0.227293	2.69	0.0076*
(# FRC patrol Officers-2.49393)*(Entry Time Div Police Leader/SOC-283.283)	0.016453	0.006284	2.62	0.0094*
(# Hazmat Rescuers-2.49393)*(Entry Time Div Police Leader/SOC-283.283)	0.0153761	0.006691	2.30	0.0225*
Non-compliance Non-compliant	0.0488288	0.023097	2.11	0.0356*
Non-compliance Neutral	-0.030552	0.022911	-1.33	0.1837
Entry Time SCDF Leader	-0.007352	0.006173	-1.19	0.2349
# FRC patrol Officers	-0.534476	0.621288	-0.86	0.3906
P(Influence) Panicking Civilians	-0.958597	2.05859	-0.47	0.6419
# Hazmat Rescuers	0.1348167	0.623402	0.22	0.8290
P(Influence) by Compliant Civilian	0.4437051	2.056926	0.22	0.8294
Entry Time TP Leader	-0.000158	0.006096	-0.03	0.9793

Prediction Profiler






Entry Time SCDF Leader vs. Entry Time Div Police Leader/SOC
Entry Time Div Police Leader/SOC
400
300
200
100
100
200
300
400
Entry Time SCDF Leader
Mean(Percent Injured)
<= 0.200
<= 0.250
<= 0.300
<= 0.350
<= 0.400
<= 0.450
<= 0.500
> 0.500

APPENDIX G. MOP 3: HISTOGRAMS FOR PANIC ATTRIBUTES

The panic attribute is a numerical attribute that accumulates under the influence of effects that are expected to induce panic. Civilians will have their panic attributes altered depending on where they are located and how exposed they are to panic inducing agents. The location of the civilians will influence how much panic they display. The CIED explosive and SA effects both induce panic on whatever civilian is present. As Pythagoras records the panic of the civilian agents as an average value across the instance for each civilian agent type, it is impossible to determine the proportions to which each sub-population develops. Nonetheless, a mean panic value for a sub-population over multiple replicates can serve as an average indication of level of exposure experienced by this crowd. From the histograms below, it is observed that sub-populations at ORWM, ORLP, PRGN, WM, and TKA experience a more intense display of panic, compared to sub-populations at T, FE, and SHW. Scenario #2 results in a chemical plume migrating downwind from T in the direction of PRGN and TKA. Thus, this flow of hazard results in an expected response from population.

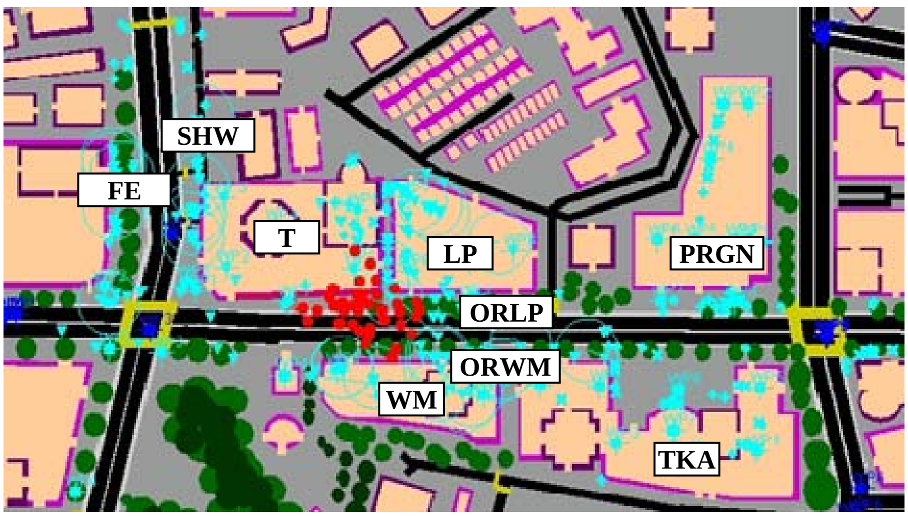
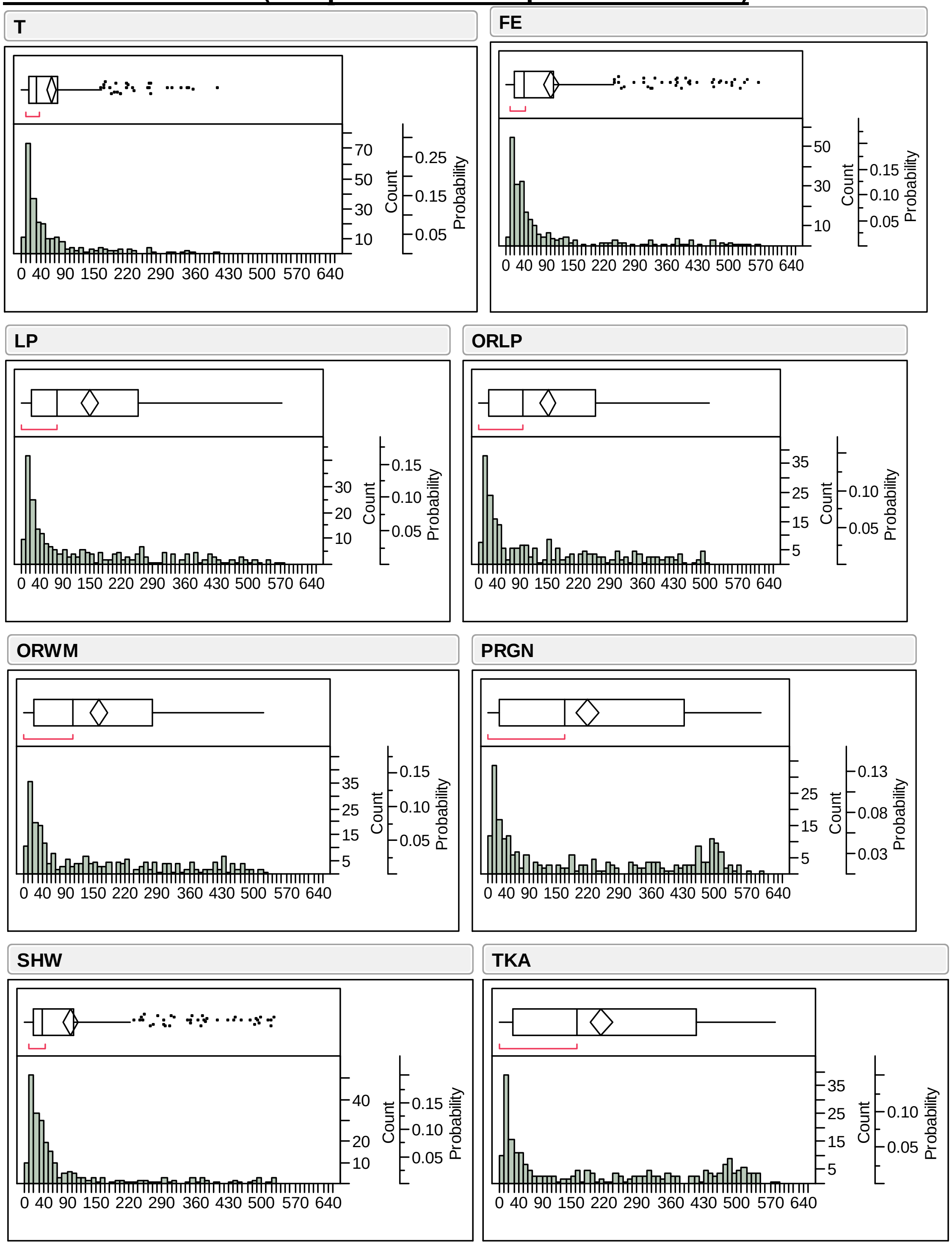
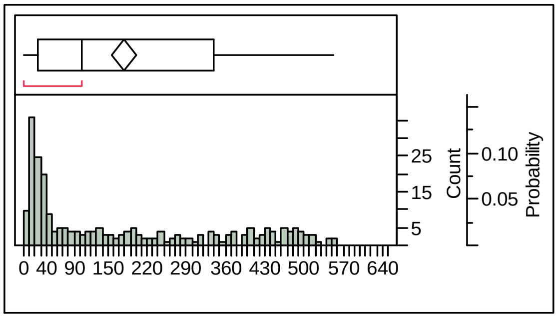


Figure 57. Scenario #2: Locations of sub-populations of civilians in coded names.

Mean Panic Attribute (Compliant Civilians Specific to Location)

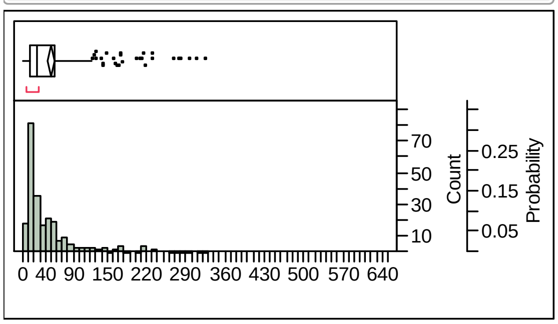


WM

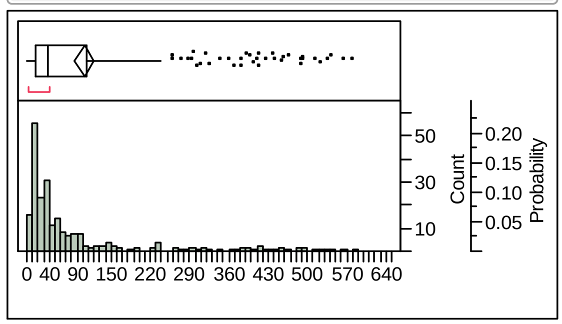


Mean Panic Attribute (Neutral Civilians Specific to Location)

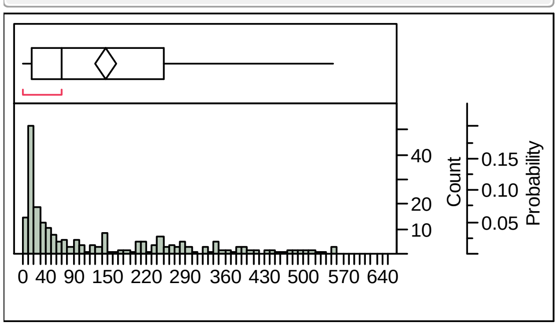
T



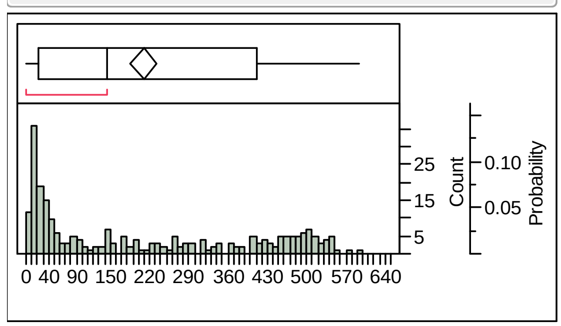
FE



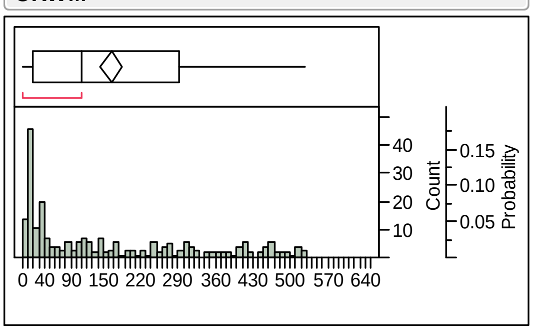
LP



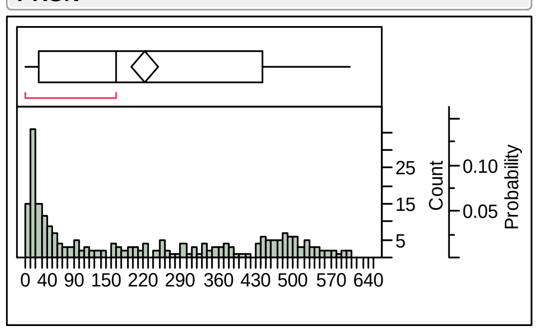
ORLP



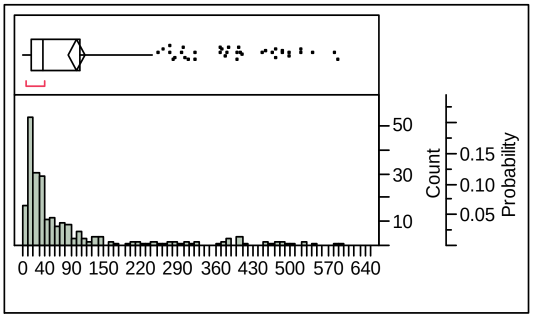
ORWM



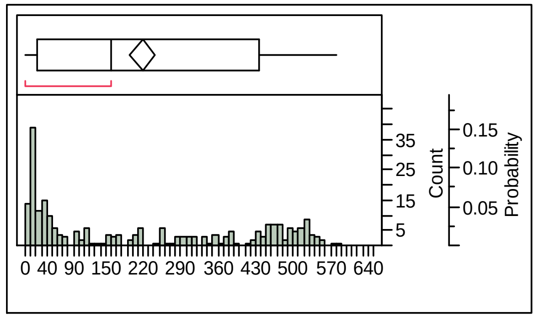
PRGN



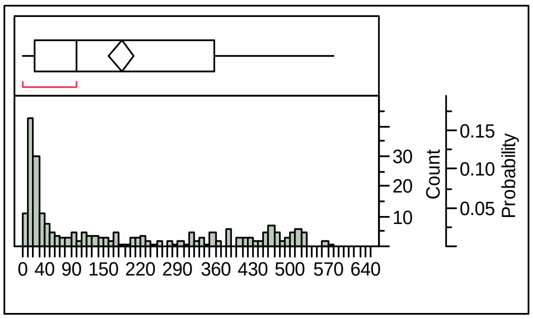
SHW



TKA

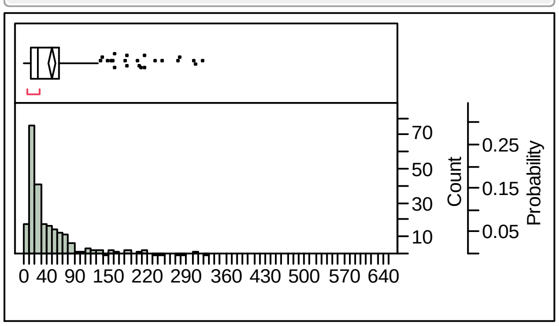


WM

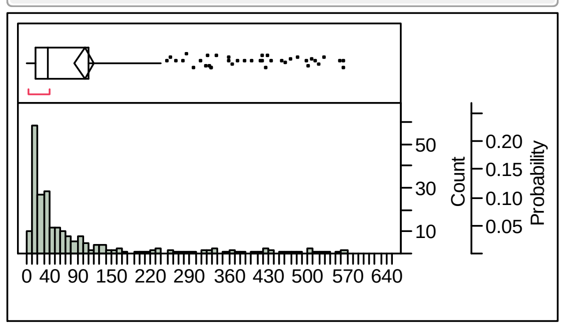


Mean Panic Attribute (Non-compliant Civilians Specific to Location)

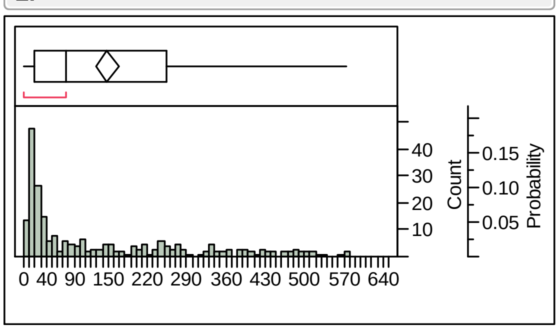
T



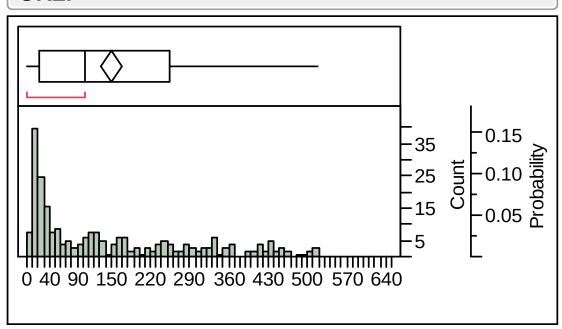
FE



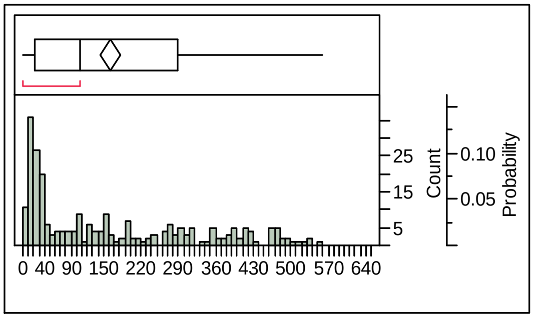
LP



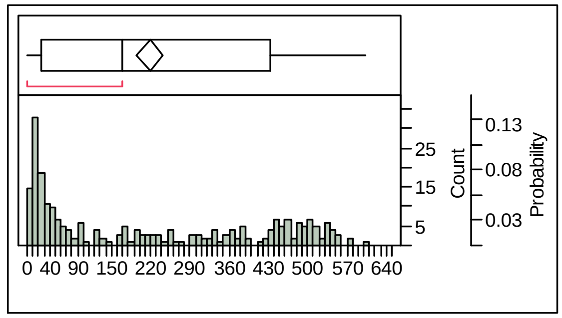
ORLP



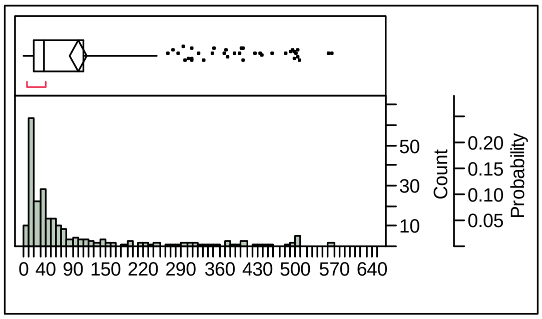
ORWM



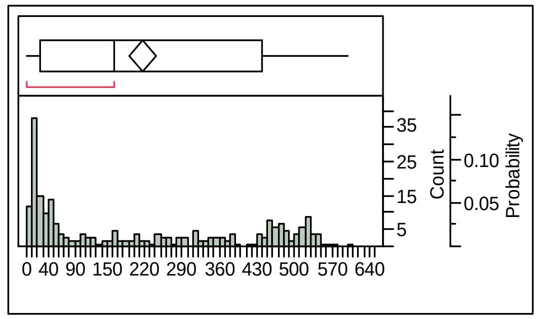
PRGN



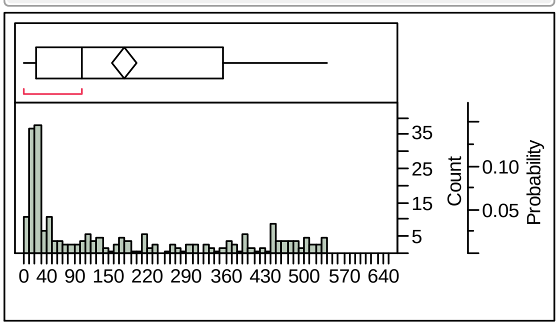
SHW



TKA



WM



APPENDIX H. SUPPLEMENTARY REGRESSION TREES FOR SCENARIOS

The following regression trees were conducted using all 29 factors to determine which types of factors were most significant in predicting the mean percentage of injury. In general, uncontrollable factors demonstrated the most significance, in particular the number of compliant, neutral, and non-compliant civilians located at each populated area, and the intrinsic non-compliance of civilians are the most significant. The variability of the regression trees is also best explained by these factors. Regression trees shown here are spilt to the point of diminishing returns in the form of improved explanation of variability (in terms of R-square value).

A. REGRESSION TREE FOR SCENARIO #1

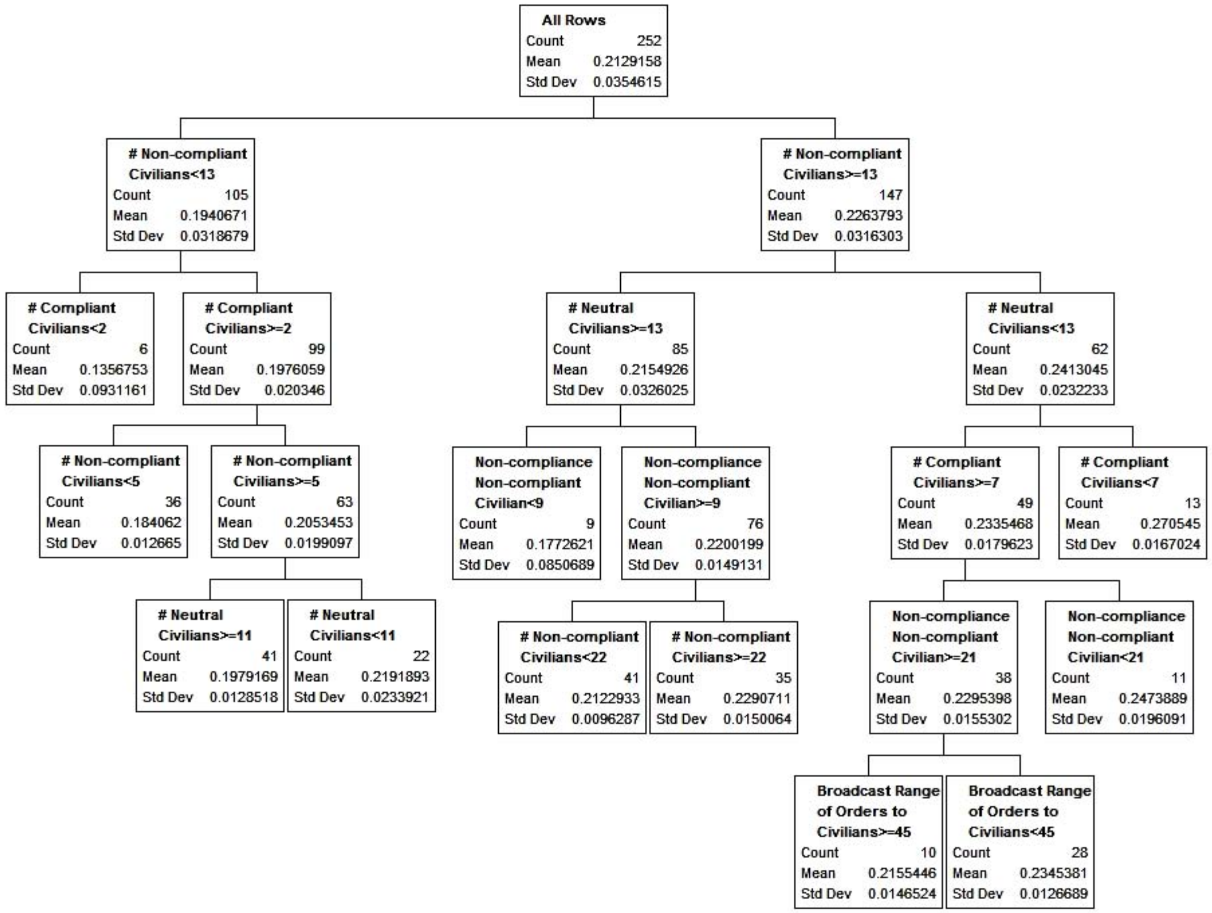


Figure 58. Regression Tree for mean percentage civilian injuries (R-square = 0.525; Splits = 10).

B. REGRESSION TREE FOR SCENARIO #2

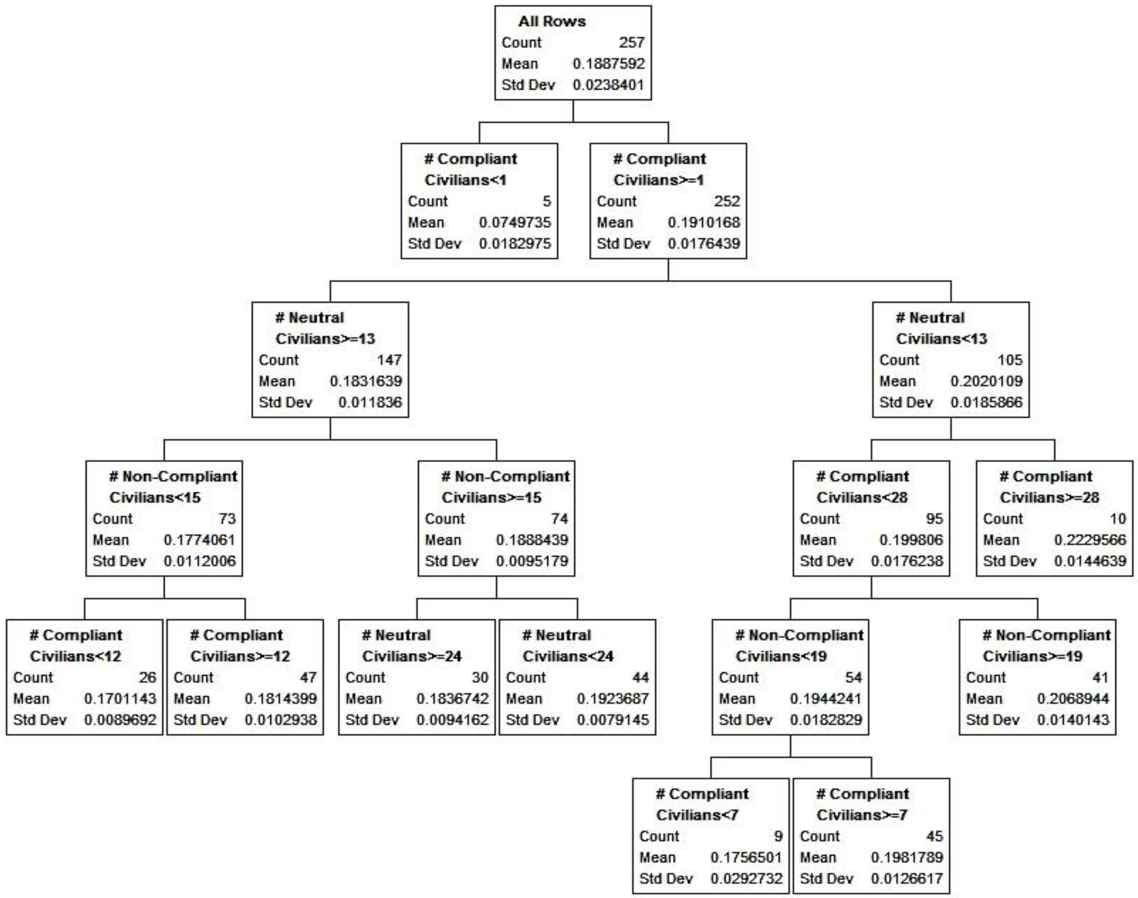


Figure 59. Regression Tree for mean percentage civilian injuries in scenario #2 (R-square = 0.745; Splits = 9).

C. REGRESSION TREE FOR SCENARIO #3

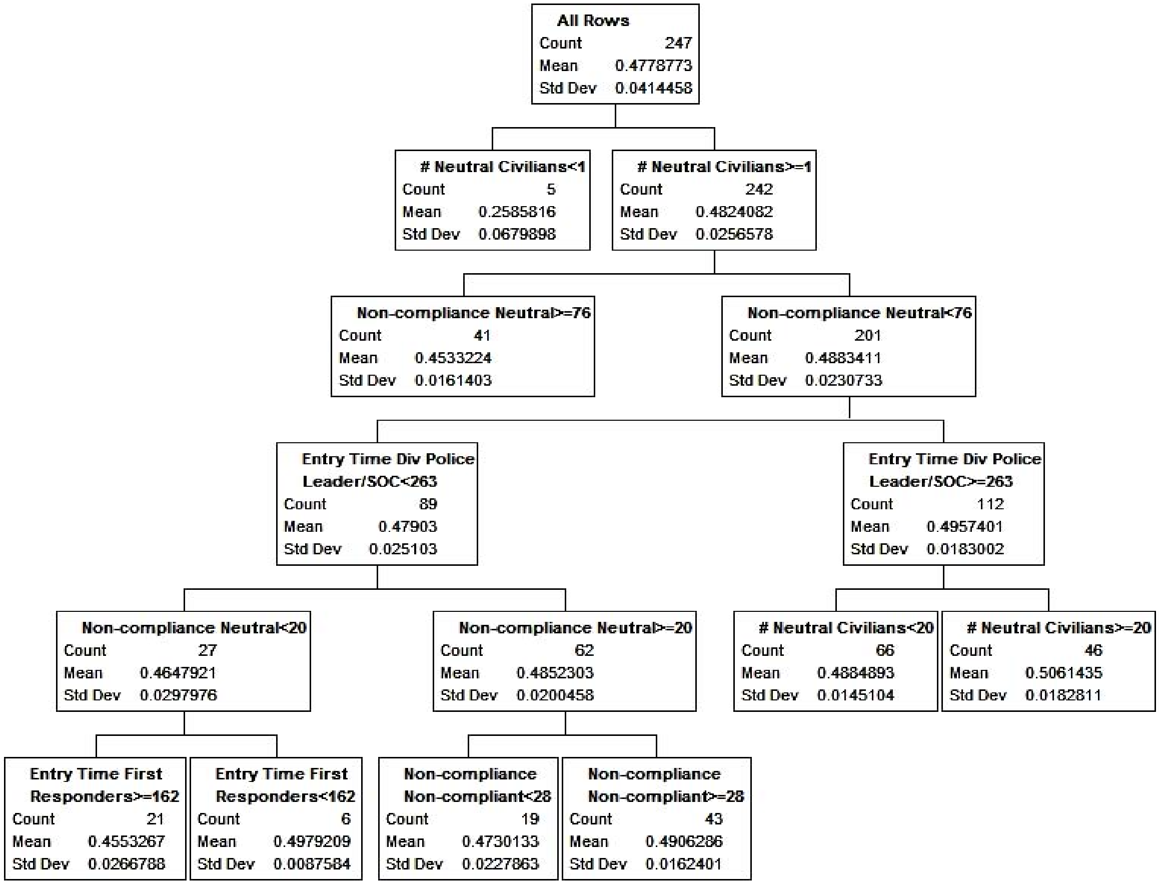


Figure 60. Regression Tree for mean percentage civilian injuries in scenario #3 (R-square = 0.781; splits = 7).

APPENDIX I. CLUSTERING AND OUTLIER ANALYSIS

A. INTRODUCTION

The analysis shown here supplements the statistical analysis conducted in Chapter V, and implements the software package, COADM written by DSO National Laboratories, Singapore.

B. OBJECTIVE

Cluster analysis allows the user to create a global view of the data set in terms of the commons traits shared among each data point. This allows for the quick identification of general trends of factor settings that attribute to "good" and "bad" performances in terms of the defined MOEs. By the virtue of this "clustering" effect, the researcher can identify small groups or individual outliers representing observations of interest. Parameters contributing to this "bad" performance can subsequently be input back into the simulation to examine why such conditions were unsatisfactory.

C. CORRELATION PLOTS FOR SCENARIO #1: INDOOR CIED

Figure 60 shows the overview of the factor settings used as inputs for the Pythagoras scenario run for an indoor CIED incident. As can be expected, the input parameters for the scenario demonstrate no apparent correlation in their cluster patterns. With respect to the cluster pattern of MOP 1 (boxed "MOP 1"), it is noted that the cluster patterns for the percentage affected population that is non-compliant (box "A") and non-compliant civilian numbers (box "B") appear very similar to that of MOP 1. As established in Chapter V, the non-compliant population number and the associated percentage value out of the affected population serves best to predict the value of MOP 1 in the base case. Given the cluster pattern shown here, it is likely to be the same for scenario #1 as well. As expected, the cluster diagrams for MOP 1 and MOP 2 appear to be correlated. Overall, it appears that the controllable factors implemented do not correspond well with the cluster pattern of MOP 1. This seems to agree with the poor explanation of variability when regressing solely on the controllable factors.

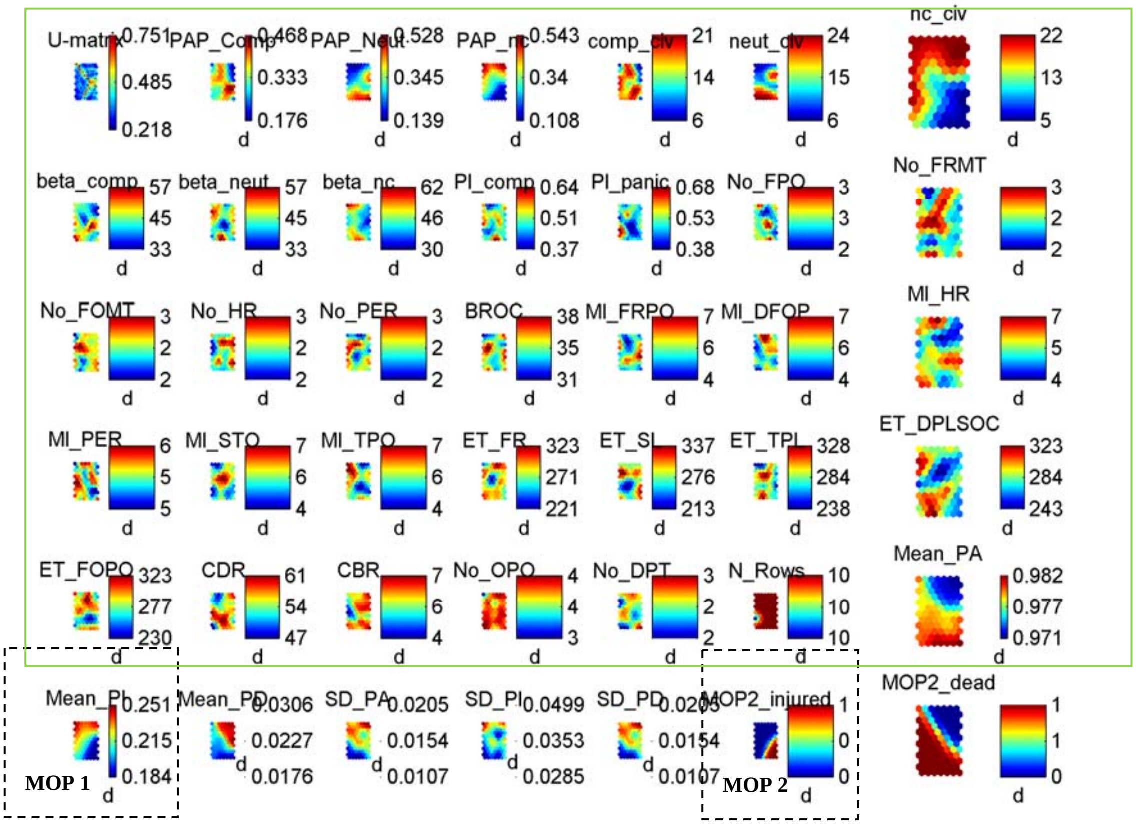


Figure 61. Overview of correlation plots for scenario #1.

D. CLUSTERING ANALYSIS FOR SCENARIO #1: INDOOR CIED

Figure 61 shows three dominant clusters representing the 257 data points used in the simulation run. Values in parenthesis represent the number of data points that sit inside each cluster. Outliers, identified by a black hexagon, appear to occur in this data set. Each cluster is associated with a series of mean values, allowing us to classify the clusters as “good” and “bad.” To do this, analysis uses the means of the attributes in clusters generated in COADM to determine which cluster is the best for our purposes. With reference to Table 15, cluster 2 is a “good” cluster as it has a mean for MOP 1 of

A

B

0.190, which translates to a mean percentage level of 19% for civilian injury. Compared to the base case reference of 20.0%, conditions in this cluster may reveal slight improvements in MOP 1. Three black cluster cells appear in cluster 2. The cluster cell containing design points 1, 2, 3, and 4 appear to have significantly lower conditions were one of the three compliance groups is missing from the scenario. In addition, the civilian numbers are too small to be operationally realistic (rather, they represent the area in the wee hours of the working day!). The MOP 1 value for design point 240 is the same as that for cluster 2; therefore, it is deemed not of interest.

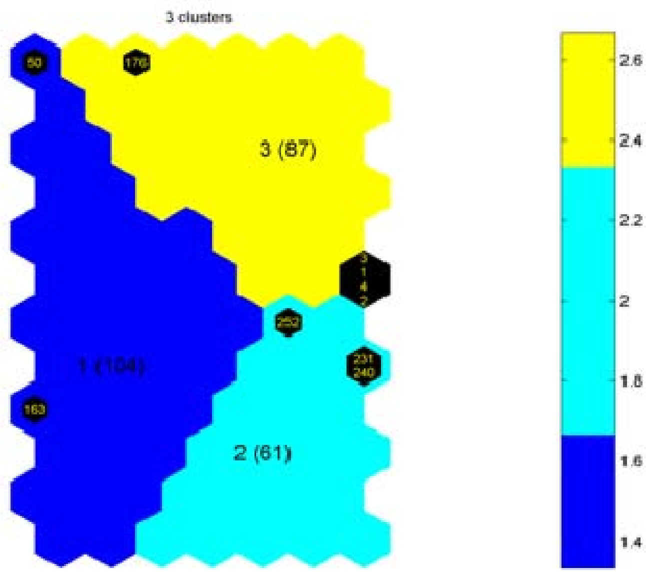


Figure 62. Clustering analysis for scenario #1.

CLUSTER 1	**CLUSTER 2**	**CLUSTER 3**
beta_comp 46.000 +/- 28.758	beta_comp 47.000 +/- 24.814	beta_comp 42.000 +/- 23.126
beta_nc 47.000 +/- 27.211	beta_nc 44.000 +/- 25.834	beta_nc 43.000 +/- 25.190
beta_neut 45.000 +/- 26.874	beta_neut 45.000 +/- 27.003	beta_neut 46.000 +/- 24.779
BROC 35.000 +/- 9.163	BROC 35.000 +/- 8.666	BROC 34.000 +/- 8.463
CBR 6.000 +/- 2.251	CBR 6.000 +/- 2.524	CBR 6.000 +/- 2.310
CDR 55.000 +/- 15.246	CDR 57.000 +/- 14.541	CDR 54.000 +/- 13.704
comp_civ 16.000 +/- 8.165	comp_civ 17.000 +/- 8.833	comp_civ 14.000 +/- 8.836
ET_DPLSOC 290.000 +/- 88.047	ET_DPLSOC 284.000 +/- 106.615	ET_DPLSOC 273.000 +/- 102.037
ET_FOPO 281.000 +/- 94.848	ET_FOPO 269.000 +/- 100.412	ET_FOPO 296.000 +/- 100.175
ET_FR 275.000 +/- 96.679	ET_FR 281.000 +/- 91.630	ET_FR 286.000 +/- 104.226
ET_SL 268.000 +/- 103.010	ET_SL 286.000 +/- 92.090	ET_SL 289.000 +/- 94.213
ET_TPL 292.000 +/- 100.602	ET_TPL 283.000 +/- 100.908	ET_TPL 285.000 +/- 91.209
Mean_PA 0.979 +/- 0.003	Mean_PA 0.980 +/- 0.004	Mean_PA 0.974 +/- 0.004
Mean_PD 0.021 +/- 0.003	Mean_PD 0.021 +/- 0.015	Mean_PD 0.028 +/- 0.009
Mean_PI 0.218 +/- 0.021	**Mean_PI 0.190 +/- 0.011**	**Mean_PI 0.222 +/- 0.048**
MI_DFOP 5.000 +/- 2.638	MI_DFOP 5.000 +/- 2.447	MI_DFOP 6.000 +/- 2.672
MI_FRPO 6.000 +/- 2.477	MI_FRPO 6.000 +/- 2.664	MI_FRPO 5.000 +/- 2.798
MI_HR 6.000 +/- 2.635	MI_HR 6.000 +/- 2.718	MI_HR 5.000 +/- 2.616
MI_PER 6.000 +/- 2.434	MI_PER 5.000 +/- 2.748	MI_PER 6.000 +/- 2.765
MI_STO 6.000 +/- 2.738	MI_STO 5.000 +/- 2.537	MI_STO 6.000 +/- 2.633
MI_TPO 6.000 +/- 2.685	MI_TPO 5.000 +/- 2.748	MI_TPO 5.000 +/- 2.566
MOP 2_dead 1.000 +/- 0.000	MOP 2_dead 1.000 +/- 0.321	MOP 2_dead 0.000 +/- 0.000
MOP 2_injured 0.000 +/- 0.000	**MOP 2_injured 1.000 +/- 0.180**	**MOP 2_injured 0.000 +/- 0.291**
N_Rows 10.000 +/- 0.588	N_Rows 10.000 +/- 0.000	N_Rows 10.000 +/- 0.000
nc_civ 16.000 +/- 7.290	nc_civ 6.000 +/- 3.530	nc_civ 19.000 +/- 6.969
neut_civ 14.000 +/- 8.807	neut_civ 17.000 +/- 8.248	neut_civ 13.000 +/- 8.466
No_DPT 2.000 +/- 1.053	No_DPT 2.000 +/- 0.923	No_DPT 3.000 +/- 0.874
No_FOMT 2.000 +/- 1.032	No_FOMT 3.000 +/- 0.922	No_FOMT 3.000 +/- 0.913
No_FPO 3.000 +/- 0.903	No_FPO 2.000 +/- 0.959	No_FPO 2.000 +/- 1.043
No_FRMT 3.000 +/- 0.934	No_FRMT 2.000 +/- 0.942	No_FRMT 2.000 +/- 0.983
No_HR 2.000 +/- 0.941	No_HR 3.000 +/- 0.942	No_HR 3.000 +/- 0.994
No_OPO 4.000 +/- 1.307	No_OPO 4.000 +/- 1.078	No_OPO 4.000 +/- 1.244
No_PER 2.000 +/- 1.043	No_PER 3.000 +/- 0.886	No_PER 2.000 +/- 0.896
PAP_Comp 0.350 +/- 0.151	PAP_Comp 0.397 +/- 0.205	PAP_Comp 0.309 +/- 0.172
PAP_nc 0.346 +/- 0.142	PAP_nc 0.161 +/- 0.083	PAP_nc 0.393 +/- 0.150
PAP_Neut 0.316 +/- 0.149	PAP_Neut 0.396 +/- 0.210	PAP_Neut 0.287 +/- 0.168
PI_comp 0.500 +/- 0.258	PI_comp 0.520 +/- 0.320	PI_comp 0.490 +/- 0.312
PI_panic 0.510 +/- 0.308	PI_panic 0.450 +/- 0.266	PI_panic 0.500 +/- 0.286
SD_PA 0.015 +/- 0.005	SD_PA 0.014 +/- 0.004	SD_PA 0.017 +/- 0.005
SD_PD 0.015 +/- 0.005	SD_PD 0.014 +/- 0.004	SD_PD 0.017 +/- 0.005
SD_PI 0.033 +/- 0.015	SD_PI 0.032 +/- 0.011	SD_PI 0.034 +/- 0.018

Table 15. Table of mean cluster attributes by variables. MOP 1 and MOP 2 are in bold.

E. CORRELATION PLOTS FOR SCENARIO #3: OUTDOOR VBIED

The correlation plots for scenario #3 demonstrate the same characteristics as that for scenario #1. MOP 1 and MOP 2 are in close agreement. When compared to the regression tree analysis conducted on Figure 62, factors noted to be significant (boxed “A,” “B1,” “B2,” and “C”) correspond in terms of cluster correlation. In addition, it can be seen from the correlation charts that a few other factors are positively correlated to the color strength noted for MOP 1. In particular, the maximum influence of hazmat responders (“D”) and number of pump engine rescuers (“E”) may be used to improve MOP 1 given this slight positive correlation.

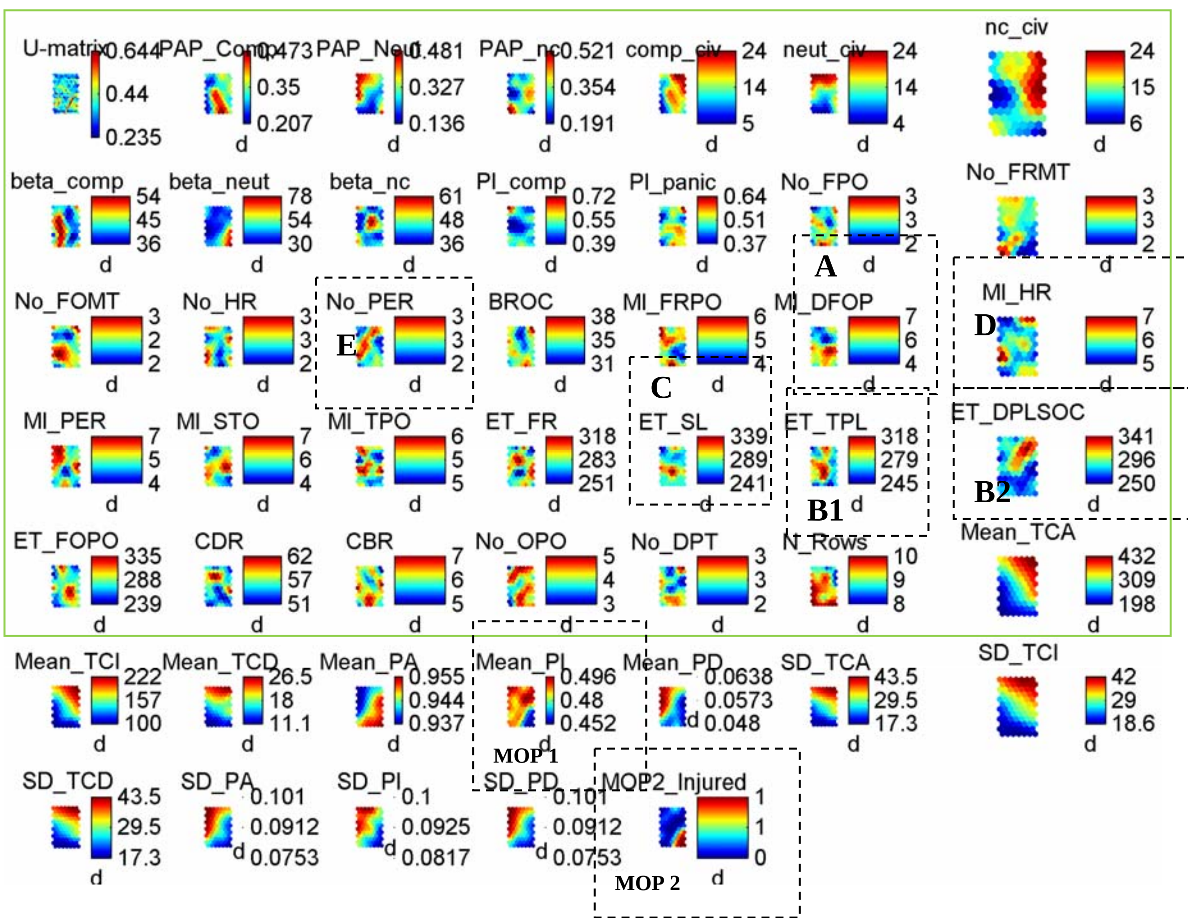


Figure 63. Overview of correlation plots for scenario #3.

F. CLUSTERING ANALYSIS FOR SCENARIO #3: INDOOR VBIED

Figure 63 shows the clusters generated for scenario #3, which is more diverse than previously seen for scenario #1. Ten clusters were generated by COADM. Based on the data shown in tables 16 through 18, clusters 9 and 10 are identified as "good" clusters. From these clusters, outlier cells exist only in cluster 10. All these outliers lack either one sub-population of civilians, or they have very low population numbers set by the design matrix.

Of better interest are the cluster cells 42 and 212, which are located in clusters 4 and 6; both have a mean percentage injured civilian value of 49%. Cluster cells 42 and 212 have MOP 1 values of 43% and 45%, whereas the cluster they are in has a 49% mean value for MOP 1. Conditions corresponding to these two points were implemented as scenario files for further analysis. However, error messages from Pythagoras indicate that both scenarios cannot load. This is still under investigation.

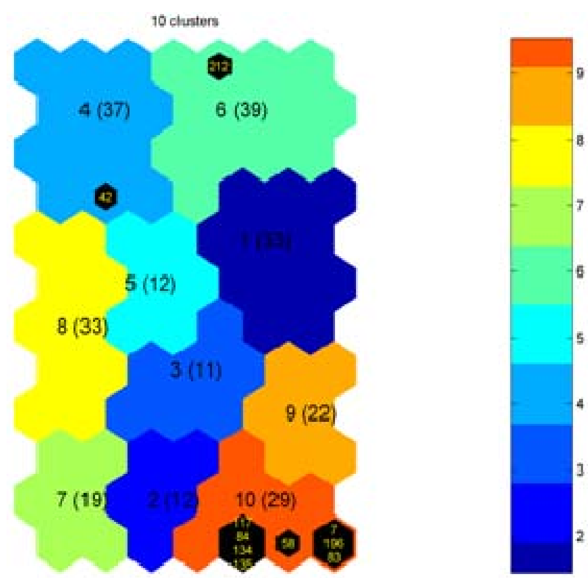


Figure 64. Clustering analysis for scenario #3

CLUSTER 1	**CLUSTER 2**	**CLUSTER 3**	**CLUSTER 4**
beta_comp 41.000 +/- 25.224	beta_comp 49.000 +/- 31.443	beta_comp 47.000 +/- 23.161	beta_comp 46.000 +/- 25.401
beta_nc 51.000 +/- 24.906	beta_nc 42.000 +/- 24.196	beta_nc 46.000 +/- 22.149	beta_nc 44.000 +/- 28.653
beta_neut 45.000 +/- 24.913	beta_neut 45.000 +/- 19.998	beta_neut 40.000 +/- 20.961	beta_neut 40.000 +/- 23.324
BROC 34.000 +/- 8.338	BROC 35.000 +/- 10.687	BROC 34.000 +/- 9.720	BROC 34.000 +/- 8.640
CBR 6.000 +/- 2.526	CBR 7.000 +/- 2.275	CBR 6.000 +/- 2.366	CBR 6.000 +/- 2.373
CDR 56.000 +/- 12.617	CDR 53.000 +/- 10.790	CDR 53.000 +/- 16.823	CDR 58.000 +/- 15.721
comp_civ 19.000 +/- 7.933	comp_civ 14.000 +/- 5.351	comp_civ 18.000 +/- 6.546	comp_civ 13.000 +/- 6.815
ET_DPLSOC 290.000 +/- 104.040	ET_DPLSOC 269.000 +/- 88.357	ET_DPLSOC 277.000 +/- 74.091	ET_DPLSOC 285.000 +/- 100.655
ET_FOPO 288.000 +/- 105.681	ET_FOPO 286.000 +/- 88.358	ET_FOPO 314.000 +/- 125.341	ET_FOPO 280.000 +/- 99.521
ET_FR 289.000 +/- 95.206	ET_FR 280.000 +/- 89.350	ET_FR 260.000 +/- 66.819	ET_FR 285.000 +/- 97.841
ET_SL 277.000 +/- 92.370	ET_SL 289.000 +/- 108.040	ET_SL 319.000 +/- 83.295	ET_SL 267.000 +/- 102.737
ET_TPL 271.000 +/- 99.554	ET_TPL 290.000 +/- 121.967	ET_TPL 307.000 +/- 98.175	ET_TPL 269.000 +/- 101.759
Mean_PA 0.948 +/- 0.011	Mean_PA 0.949 +/- 0.020	Mean_PA 0.945 +/- 0.002	Mean_PA 0.938 +/- 0.007
Mean_PD 0.052 +/- 0.011	Mean_PD 0.053 +/- 0.027	Mean_PD 0.055 +/- 0.002	Mean_PD 0.062 +/- 0.007
Mean_PI 0.490 +/- 0.016	**Mean_PI 0.486 +/- 0.032**	**Mean_PI 0.486 +/- 0.010**	**Mean_PI 0.492 +/- 0.025**
Mean_TCA 360.400 +/- 67.176	Mean_TCA 231.400 +/- 86.768	Mean_TCA 280.100 +/- 20.592	Mean_TCA 320.300 +/- 38.879
Mean_TCD 18.444 +/- 3.258	Mean_TCD 11.900 +/- 4.962	Mean_TCD 15.600 +/- 1.361	Mean_TCD 21.500 +/- 2.617
Mean_TCI 187.600 +/- 33.882	Mean_TCI 117.100 +/- 48.661	Mean_TCI 140.200 +/- 10.085	Mean_TCI 166.900 +/- 23.913
MI_DFOP 5.000 +/- 2.335	MI_DFOP 6.000 +/- 3.049	MI_DFOP 6.000 +/- 2.898	MI_DFOP 5.000 +/- 2.760
MI_FRPO 5.000 +/- 2.755	MI_FRPO 6.000 +/- 2.151	MI_FRPO 5.000 +/- 2.501	MI_FRPO 6.000 +/- 2.421
MI_HR 6.000 +/- 2.443	MI_HR 5.000 +/- 2.125	MI_HR 5.000 +/- 2.339	MI_HR 5.000 +/- 2.576
MI_PER 6.000 +/- 2.582	MI_PER 6.000 +/- 2.393	MI_PER 4.000 +/- 2.760	MI_PER 7.000 +/- 2.823
MI_STO 6.000 +/- 2.640	MI_STO 5.000 +/- 2.746	MI_STO 6.000 +/- 2.240	MI_STO 5.000 +/- 2.421
MI_TPO 5.000 +/- 2.609	MI_TPO 5.000 +/- 2.275	MI_TPO 6.000 +/- 2.914	MI_TPO 6.000 +/- 2.772
MOP 2_Injured 0.000 +/- 0.000	**MOP 2_Injured 0.000 +/- 0.000**	**MOP 2_Injured 0.000 +/- 0.000**	**MOP 2_Injured 0.000 +/- 0.315**
N_Rows 9.000 +/- 1.908	N_Rows 9.000 +/- 3.143	N_Rows 9.000 +/- 0.000	N_Rows 9.000 +/- 2.401
nc_civ 22.000 +/- 4.931	nc_civ 13.000 +/- 9.326	nc_civ 14.000 +/- 5.679	nc_civ 15.000 +/- 7.539
neut_civ 15.000 +/- 7.685	neut_civ 6.000 +/- 7.004	neut_civ 9.000 +/- 4.202	neut_civ 21.000 +/- 5.960
No_DPT 2.000 +/- 0.983	No_DPT 3.000 +/- 1.073	No_DPT 2.000 +/- 1.128	No_DPT 2.000 +/- 0.765
No_FOMT 2.000 +/- 0.933	No_FOMT 3.000 +/- 1.073	No_FOMT 3.000 +/- 1.027	No_FOMT 2.000 +/- 1.006
No_FPO 2.000 +/- 0.969	No_FPO 3.000 +/- 1.073	No_FPO 3.000 +/- 0.831	No_FPO 2.000 +/- 0.990
No_FRMT 2.000 +/- 0.966	No_FRMT 3.000 +/- 0.793	No_FRMT 3.000 +/- 1.120	No_FRMT 3.000 +/- 1.042
No_HR 3.000 +/- 0.890	No_HR 2.000 +/- 1.231	No_HR 2.000 +/- 0.944	No_HR 2.000 +/- 0.901
No_OPO 4.000 +/- 1.223	No_OPO 4.000 +/- 0.905	No_OPO 4.000 +/- 1.104	No_OPO 4.000 +/- 1.449
No_PER 2.000 +/- 0.902	No_PER 2.000 +/- 0.905	No_PER 3.000 +/- 0.874	No_PER 2.000 +/- 0.978
PAP_Comp 0.340 +/- 0.121	PAP_Comp 0.397 +/- 0.230	PAP_Comp 0.407 +/- 0.164	PAP_Comp 0.278 +/- 0.129
PAP_nc 0.390 +/- 0.098	PAP_nc 0.356 +/- 0.232	PAP_nc 0.344 +/- 0.129	PAP_nc 0.308 +/- 0.165
PAP_Neut 0.270 +/- 0.131	PAP_Neut 0.188 +/- 0.144	PAP_Neut 0.233 +/- 0.107	PAP_Neut 0.418 +/- 0.117
PI_comp 0.500 +/- 0.316	PI_comp 0.530 +/- 0.289	PI_comp 0.450 +/- 0.269	PI_comp 0.550 +/- 0.262
PI_panic 0.480 +/- 0.276	PI_panic 0.520 +/- 0.272	PI_panic 0.530 +/- 0.271	PI_panic 0.450 +/- 0.291
SD_PA 0.085 +/- 0.008	SD_PA 0.084 +/- 0.032	SD_PA 0.090 +/- 0.004	SD_PA 0.100 +/- 0.009
SD_PD 0.085 +/- 0.008	SD_PD 0.084 +/- 0.032	SD_PD 0.090 +/- 0.004	SD_PD 0.100 +/- 0.009
SD_PI 0.090 +/- 0.010	SD_PI 0.089 +/- 0.032	SD_PI 0.093 +/- 0.006	SD_PI 0.097 +/- 0.015
SD_TCA 32.182 +/- 3.832	SD_TCA 19.050 +/- 7.782	SD_TCA 25.285 +/- 2.222	SD_TCA 34.435 +/- 4.380
SD_TCD 32.182 +/- 3.832	SD_TCD 19.050 +/- 7.782	SD_TCD 25.285 +/- 2.222	SD_TCD 34.435 +/- 4.380
SD_TCI 33.629 +/- 5.519	SD_TCI 19.789 +/- 7.522	SD_TCI 26.576 +/- 3.209	SD_TCI 34.493 +/- 5.714

Table 16. Table of mean cluster attributes by variables, for clusters 1-4. MOP 1 and MOP 2 are in bold.

CLUSTER 5	**CLUSTER 6**	**CLUSTER 7**	**CLUSTER 8**
beta_comp 49.000 +/- 24.774	beta_comp 42.000 +/- 27.982	beta_comp 48.000 +/- 29.455	beta_comp 49.000 +/- 25.391
beta_nc 53.000 +/- 17.681	beta_nc 44.000 +/- 24.803	beta_nc 49.000 +/- 25.426	beta_nc 41.000 +/- 25.658
beta_neut 36.000 +/- 21.625	beta_neut 39.000 +/- 22.592	beta_neut 40.000 +/- 23.656	beta_neut 33.000 +/- 19.401
BROC 34.000 +/- 7.786	BROC 35.000 +/- 9.932	BROC 34.000 +/- 9.977	BROC 36.000 +/- 7.933
CBR 6.000 +/- 1.913	CBR 6.000 +/- 2.456	CBR 6.000 +/- 2.270	CBR 6.000 +/- 2.274
CDR 55.000 +/- 14.241	CDR 56.000 +/- 14.563	CDR 53.000 +/- 14.589	CDR 56.000 +/- 15.700
comp_civ 18.000 +/- 5.429	comp_civ 21.000 +/- 6.208	comp_civ 7.000 +/- 3.560	comp_civ 11.000 +/- 8.221
ET_DPLSOC 309.000 +/- 53.177	ET_DPLSOC 314.000 +/- 89.569	ET_DPLSOC 276.000 +/- 84.784	ET_DPLSOC 276.000 +/- 102.720
ET_FOPO 288.000 +/- 117.177	ET_FOPO 276.000 +/- 85.017	ET_FOPO 258.000 +/- 78.595	ET_FOPO 283.000 +/- 97.142
ET_FR 300.000 +/- 90.008	ET_FR 279.000 +/- 101.597	ET_FR 276.000 +/- 99.304	ET_FR 288.000 +/- 103.285
ET_SL 292.000 +/- 100.819	ET_SL 283.000 +/- 100.900	ET_SL 280.000 +/- 103.025	ET_SL 300.000 +/- 85.785
ET_TPL 302.000 +/- 70.314	ET_TPL 286.000 +/- 101.507	ET_TPL 272.000 +/- 105.197	ET_TPL 293.000 +/- 87.521
Mean_PA 0.942 +/- 0.004	Mean_PA 0.942 +/- 0.006	Mean_PA 0.945 +/- 0.005	Mean_PA 0.939 +/- 0.004
Mean_PD 0.058 +/- 0.004	Mean_PD 0.057 +/- 0.006	Mean_PD 0.055 +/- 0.005	Mean_PD 0.062 +/- 0.011
Mean_PI 0.487 +/- 0.008	**Mean_PI 0.492 +/- 0.026**	**Mean_PI 0.488 +/- 0.012**	**Mean_PI 0.487 +/- 0.028**
Mean_TCA 284.100 +/- 22.024	Mean_TCA 389.333 +/- 53.452	Mean_TCA 203.200 +/- 52.259	Mean_TCA 230.600 +/- 45.138
Mean_TCD 17.600 +/- 2.070	Mean_TCD 23.667 +/- 3.975	Mean_TCD 11.400 +/- 2.881	Mean_TCD 15.000 +/- 3.708
Mean_TCI 145.600 +/- 11.843	Mean_TCI 201.500 +/- 27.471	Mean_TCI 102.300 +/- 26.034	Mean_TCI 119.900 +/- 24.131
MI_DFOP 5.000 +/- 2.480	MI_DFOP 5.000 +/- 2.929	MI_DFOP 6.000 +/- 3.022	MI_DFOP 6.000 +/- 2.352
MI_FRPO 6.000 +/- 2.570	MI_FRPO 6.000 +/- 2.552	MI_FRPO 6.000 +/- 3.007	MI_FRPO 6.000 +/- 2.958
MI_HR 6.000 +/- 2.902	MI_HR 6.000 +/- 2.680	MI_HR 5.000 +/- 2.522	MI_HR 6.000 +/- 3.059
MI_PER 5.000 +/- 2.691	MI_PER 5.000 +/- 2.536	MI_PER 5.000 +/- 2.009	MI_PER 6.000 +/- 2.322
MI_STO 6.000 +/- 2.290	MI_STO 5.000 +/- 2.910	MI_STO 6.000 +/- 3.064	MI_STO 6.000 +/- 2.575
MI_TPO 6.000 +/- 2.811	MI_TPO 5.000 +/- 2.552	MI_TPO 5.000 +/- 3.186	MI_TPO 6.000 +/- 2.712
MOP 2_Injured 0.000 +/- 0.000	**MOP 2_Injured 0.000 +/- 0.389**	**MOP 2_Injured 0.000 +/- 0.000**	**MOP 2_Injured 0.000 +/- 0.364**
N_Rows 10.000 +/- 1.730	N_Rows 9.000 +/- 2.451	N_Rows 10.000 +/- 0.229	N_Rows 10.000 +/- 0.364
nc_civ 12.000 +/- 5.895	nc_civ 19.000 +/- 7.852	nc_civ 16.000 +/- 7.152	nc_civ 8.000 +/- 4.955
neut_civ 12.000 +/- 3.473	neut_civ 22.000 +/- 5.741	neut_civ 6.000 +/- 4.012	neut_civ 14.000 +/- 5.867
No_DPT 2.000 +/- 1.138	No_DPT 3.000 +/- 1.095	No_DPT 3.000 +/- 1.124	No_DPT 3.000 +/- 0.966
No_FOMT 3.000 +/- 0.793	No_FOMT 2.000 +/- 1.069	No_FOMT 2.000 +/- 1.049	No_FOMT 3.000 +/- 0.854
No_FPO 3.000 +/- 1.115	No_FPO 2.000 +/- 0.996	No_FPO 2.000 +/- 1.012	No_FPO 3.000 +/- 0.833
No_FRMT 3.000 +/- 0.996	No_FRMT 3.000 +/- 0.913	No_FRMT 3.000 +/- 0.911	No_FRMT 2.000 +/- 0.936
No_HR 2.000 +/- 0.866	No_HR 2.000 +/- 1.016	No_HR 3.000 +/- 0.749	No_HR 3.000 +/- 1.021
No_OPO 4.000 +/- 1.193	No_OPO 4.000 +/- 1.030	No_OPO 4.000 +/- 1.134	No_OPO 4.000 +/- 1.156
No_PER 3.000 +/- 0.996	No_PER 3.000 +/- 0.923	No_PER 3.000 +/- 1.124	No_PER 3.000 +/- 0.893
PAP_Comp 0.400 +/- 0.134	PAP_Comp 0.348 +/- 0.101	PAP_Comp 0.271 +/- 0.144	PAP_Comp 0.308 +/- 0.217
PAP_nc 0.289 +/- 0.126	PAP_nc 0.319 +/- 0.111	PAP_nc 0.453 +/- 0.178	PAP_nc 0.260 +/- 0.149
PAP_Neut 0.297 +/- 0.083	PAP_Neut 0.353 +/- 0.094	PAP_Neut 0.206 +/- 0.119	PAP_Neut 0.396 +/- 0.203
PI_comp 0.420 +/- 0.326	PI_comp 0.480 +/- 0.288	PI_comp 0.530 +/- 0.238	PI_comp 0.430 +/- 0.308
PI_panic 0.520 +/- 0.320	PI_panic 0.530 +/- 0.273	PI_panic 0.430 +/- 0.324	PI_panic 0.500 +/- 0.269
SD_PA 0.094 +/- 0.003	SD_PA 0.094 +/- 0.006	SD_PA 0.089 +/- 0.006	SD_PA 0.098 +/- 0.005
SD_PD 0.094 +/- 0.003	SD_PD 0.094 +/- 0.006	SD_PD 0.089 +/- 0.006	SD_PD 0.098 +/- 0.005
SD_PI 0.095 +/- 0.009	SD_PI 0.094 +/- 0.012	SD_PI 0.092 +/- 0.010	SD_PI 0.096 +/- 0.012
SD_TCA 27.897 +/- 2.288	SD_TCA 38.682 +/- 6.197	SD_TCA 18.362 +/- 4.722	SD_TCA 23.688 +/- 4.378
SD_TCD 27.897 +/- 2.288	SD_TCD 38.682 +/- 6.197	SD_TCD 18.362 +/- 4.722	SD_TCD 23.688 +/- 4.378
SD_TCI 28.612 +/- 2.457	SD_TCI 39.433 +/- 7.704	SD_TCI 19.201 +/- 5.233	SD_TCI 23.763 +/- 4.572

Table 17. Table of mean cluster attributes by variables, for clusters 5-8. MOP 1 and MOP 2 are in bold.

Cluster 9	Cluster 10
beta_comp 39.000 +/- 27.211	beta_comp 42.000 +/- 26.407
beta_nc 41.000 +/- 25.434	beta_nc 44.000 +/- 26.235
beta_neut 66.000 +/- 28.733	beta_neut 62.000 +/- 25.728
BROC 35.000 +/- 8.465	BROC 36.000 +/- 7.922
CBR 6.000 +/- 2.054	CBR 6.000 +/- 2.745
CDR 56.000 +/- 15.225	CDR 54.000 +/- 14.060
comp_civ 16.000 +/- 8.074	comp_civ 15.000 +/- 7.612
ET_DPLSOC 267.000 +/- 100.210	ET_DPLSOC 268.000 +/- 109.827
ET_FOPO 300.000 +/- 101.734	ET_FOPO 294.000 +/- 102.730
ET_FR 303.000 +/- 92.505	ET_FR 286.000 +/- 93.373
ET_SL 293.000 +/- 78.785	ET_SL 281.000 +/- 101.842
ET_TPL 268.000 +/- 89.520	ET_TPL 262.000 +/- 99.126
Mean_PA 0.949 +/- 0.005	Mean_PA 0.952 +/- 0.008
Mean_PD 0.051 +/- 0.005	Mean_PD 0.053 +/- 0.019
Mean_PI 0.460 +/- 0.013	**Mean_PI 0.460 +/- 0.080**
Mean_TCA 320.900 +/- 55.391	Mean_TCA 235.900 +/- 63.254
Mean_TCD 17.000 +/- 3.494	Mean_TCD 12.700 +/- 3.590
Mean_TCI 155.900 +/- 27.231	Mean_TCI 113.400 +/- 33.626
MI_DFOP 6.000 +/- 2.328	MI_DFOP 6.000 +/- 2.637
MI_FRPO 4.000 +/- 2.704	MI_FRPO 5.000 +/- 2.503
MI_HR 5.000 +/- 2.760	MI_HR 6.000 +/- 2.477
MI_PER 5.000 +/- 2.703	MI_PER 5.000 +/- 2.600
MI_STO 5.000 +/- 2.630	MI_STO 5.000 +/- 2.724
MI_TPO 6.000 +/- 2.901	MI_TPO 5.000 +/- 2.086
MOP 2_Injured 1.000 +/- 0.000	**MOP 2_Injured 1.000 +/- 0.186**
N_Rows 9.000 +/- 2.122	N_Rows 10.000 +/- 0.000
nc_civ 19.000 +/- 6.984	nc_civ 10.000 +/- 6.055
neut_civ 14.000 +/- 6.943	neut_civ 8.000 +/- 8.329
No_DPT 3.000 +/- 0.913	No_DPT 3.000 +/- 0.797
No_FOMT 2.000 +/- 0.859	No_FOMT 3.000 +/- 0.871
No_FPO 3.000 +/- 0.848	No_FPO 3.000 +/- 1.021
No_FRMT 2.000 +/- 0.945	No_FRMT 2.000 +/- 0.940
No_HR 2.000 +/- 1.012	No_HR 2.000 +/- 0.967
No_OPO 4.000 +/- 1.065	No_OPO 4.000 +/- 1.320
No_PER 2.000 +/- 0.964	No_PER 3.000 +/- 0.829
PAP_Comp 0.333 +/- 0.149	PAP_Comp 0.417 +/- 0.197
PAP_nc 0.367 +/- 0.135	PAP_nc 0.296 +/- 0.169
PAP_Neut 0.300 +/- 0.119	PAP_Neut 0.247 +/- 0.269
PI_comp 0.510 +/- 0.305	PI_comp 0.520 +/- 0.287
PI_panic 0.560 +/- 0.310	PI_panic 0.550 +/- 0.291
SD_PA 0.083 +/- 0.008	SD_PA 0.079 +/- 0.013
SD_PD 0.083 +/- 0.008	SD_PD 0.079 +/- 0.013
SD_PI 0.086 +/- 0.008	SD_PI 0.085 +/- 0.016
SD_TCA 27.658 +/- 4.869	SD_TCA 19.176 +/- 5.837
SD_TCD 27.658 +/- 4.869	SD_TCD 19.176 +/- 5.837
SD_TCI 28.301 +/- 5.109	SD_TCI 20.046 +/- 6.410

Table 18. Table of mean cluster attributes by variables, for clusters 9-10. MOP 1 and MOP 2 are in bold.

G. BASECASE AND SCENARIO #2

Errors in the compilation process of the cluster and outlier analysis occurred for the base case scenario and the scenario #2. COADM returned “NaN,”“divide by zero” and “eig(en) value problem” error messages. This continued when design matrices for both data sets were reset back to the orders indicated by original DOE files. DSO has been informed of this error and the solution is currently being determined.

H. CONCLUSIONS

The cluster analysis appears to agree with the analysis conducted in Chapter V. In general, no “bad” outliers exist in “good” clusters, but supposedly “good” outliers can be explained as a caveat of the scripted DOE conditions that have little operational worth and should be disregarded.

APPENDIX J. PYTHAGORAS 2.0.X ISSUES ENCOUNTERED

A. DRAWING DISPLAY BUG

1. Problem Description

In the version 2.0.0 alpha release, an issue occurs at maximum scenario map size. While implementing a test file to model agent attribute changes, the player was not displaying the scenario landscape at the right size. It was assumed that the problem was due to the program not refreshing after implementing a new map size. Saving, reopening and resizing did not rectify the problem.

2. Follow-Up Actions

SEED center Research Mary McDonald and Pythagoras developer Ed Bitinas were contacted. A file with some polygons included to illustrate the issue was submitted to the developers.

3. Remedy

The issue was noted by developers and was corrected in Pythagoras 2.0.3.

B. TERRAIN FEATURE ISSUE

1. Problem Description

In the version 2.0.0 alpha release, scenario files could not be saved when not all terrain types were used to generate polygons on the map. Upon saving the file, the program opens an error box with “polygon not represented in scenario.” One must generate and use all terrain types in order to save the scenario file, or else risk an xml error.

2. Follow-Up Actions

The issue was submitted to the developers via email and was acknowledged.

3. Remedy

None

C. CLONE ISSUE

1. Problem Description

While attempting to implement the “Obedience and Orders” tutorial in Pythagoras 2.0, the scenario file could not be saved immediately after cloning Blue subordinates'. The activity prior to this event was the implementation of blue subordinates, as per page 9 of the Pythagoras 1.10 manual tutorial walk-through for obedience and orders.

2. Follow-Up Actions

SEED Center researcher Mary McDonald and Pythagoras developer Ed Bitinas were contacted. The issue was acknowledged by the developers

3. Remedy

Renaming the cloned blue forces to have no spaces in their names, or deleting the clones, allowed the file to be saved again.

D. OUTPUT FILE FOR TIME SERIES ISSUE

1. Problem Description

While attempting to record the time series data of MOEs for the scenario, the output file indicated a change in behavior for the agent being investigated. This change, however, was only indicated for one time step and void for the remaining time steps in the run. Comparisons of behaviors in the player screen and the behaviors recorded in the output do not match.

2. Follow-Up Actions

The issue was submitted to SEED Center researcher Mary McDonald and Pythagoras developer Ed Bitinas. A reply is pending.

3. Remedy

There was no remedy for this issue. The time series investigation of change in survivorship and panic was therefore removed from the study.

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