Modeling the Effects of a Suicide Bombing: Crowd Formations

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ABSTRACT

Suicide bombers have become increasingly deadly and there is an urgent need for the development of innovative methods to prevent or mitigate the casualties and aftermaths of such a catastrophic event. Performing simulations with variant crowd formations and densities is one approach to better understanding the effects of such an attack. This paper explores and estimates the effects of suicide bombers across multiple crowd formations and their respective densities through a virtual simulation. The ultimate goal of our empirical analysis was to determine the optimal crowd formation as it related to a reduction in the deaths and/or injuries of individuals in the crowd. The modeled crowd formations were based on real-world environments and consisted of a cafeteria, concert hall, mosque, street, hotel, bus, airport, and University campus. Specific simulation inputs are the number of individuals in the vicinity, walking speed of attacker, time associated with the trigger, setting (crowd formation), and the total weight of TNT. Results indicated that the worst crowd formation is a circular one (e.g. concerts), with a 51% death rate, 42% injury rate, thus reaching a 93% effectiveness measure. Vertical rows (e.g. mosques) were found to be the best crowd formation for reducing the effectiveness of an attack, with a 20% death rate, 43% injury rate, reaching a 63% effectiveness measure. Line-of-sight with the attacker, rushing towards the exit, and stampede were found to be the most lethal choices both during the attack and post-explosion. These findings, although preliminary, may have implications for emergency response and counter terrorism. There are number of physical and social variables we plan on integrating into this simulation in the future. These include modeling physical objects (e.g., landscape, furniture, etc.) and psychological variables (e.g., crowd behaviors). There are numerous applications for this simulation, ranging from special event planning to emergency response.

ABOUT THE AUTHORS

Zeeshan-ul-hassan Usmani is a Fulbright Scholar. He holds a M.S. in Computer Science and is currently working towards his Ph.D. in Computer Science at Florida Institute of Technology. As part of his Master's thesis, Zeeshan developed a simulation of supermarkets to observe and quantify the effects of herd behavior on impulse shopping by customers. His work has been mentioned in MIT's Technology Review and The Economist. Zeeshan has authored dozens of articles and three books. He is the chief editor of the Fulbright book series. Zeeshan's strengths include real-world simulation, programming, human emergent behaviors and modeling of catastrophic events.

Andrew English is the President of SIMetrix Solutions and a Research Professor at Florida Institute of Technology. Andrew has experience in the evaluation and development of computer-based training systems. He has produced several reports on using advanced technologies for training and exercising for the Department of Homeland Security, the Department of Defense, and the Australian Defense Simulation Office. Andrew's strengths include: instructional systems design, learning technologies, experimental design, and the measurement of both psychological and team constructs. He is actively involved in research spanning the areas of team training and advanced technology to personality assessment and theories of individual differences. Andrew holds a Ph.D. in Industrial Organizational Psychology.

Richard Griffith received his degree in Industrial Organizational Psychology from The University of Akron in 1997. He is currently the Director of the I/O Psychology program at Florida Tech. He has designed and provided training in the area of developmental feedback, employee retention, business communications, executive presentations, and team building for Fortune 500 companies. He has extensive experience with non-profit organizations, and has conducted needs analysis and developed the training curriculum for local and national non-profit financial institutions, as well as providing training for the Florida Small Business Development Center in the areas of stress and time management and cultural awareness. Dr. Griffith has designed and conducted team-building and leadership programs in the military, public, and private sectors and is the current leadership instructor for the Brevard County Chamber of Commerce. In addition, he has developed selection systems for Florida Law Enforcement, and served as a training and retention advisor to the Florida Police Chiefs Association. Richard is well versed in the areas of testing and assessment of individual differences. He is the author of over 30 publications and presentations in the area of response distortion and has recently authored *A Closer Examination of Applicant Faking Behavior*. His work has been featured in *Time* magazine and *The Wall Street Journal*.

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INTRODUCTION

Suicide bombing is an operational method in which the very act of the attack is dependent upon the death of the perpetrator (Ganor, 2000). A suicide attack can be defined as a politically motivated and violent action intended, with prior intent, by one or more individuals who choose to take their own life in the course of the operation with the chosen target. Suicide bombing is not a new phenomenon and has become one of the most lethal, unforeseeable and favorite modus operandi of terrorist organizations. Al-Qaeda has become the driver behind the internationalization of suicide terrorism "transforming it from a local phenomenon to an international phenomenon. Ideologically, Al-Qaeda introduced the idea of self-sacrifice as the jewel in the crown of global jihad" (Serluco, 2007). While suicide bombers were once predominantly male, in the past 20 years female suicide bombers represent nearly 15% of the overall number of actual suicide bombers and those intercepted in the final stages before an attack (Serluco, 2007).

Suicide Bombers, unlike any other device or means of destruction, can think and therefore can detonate the charge at optimal location with perfect timings to cause maximum carnage and destruction. Suicide bombers are adaptive and can quickly change targets if forced by security risk or the availability of better targets. Suicide attacks are relatively inexpensive to fund and technologically primitive, as IEDs (Improvised Explosive Devices) can be readily constructed. Suicide bombing works most of the time and requires no escape plan (Ganor, 2000).

Suicide bombing is being used for strategic, political and financial gains by terrorists, political and religious groups (Weinberg, 2003). Though only 3% of all terrorist attacks around the world can be classified as suicide bombing attacks, these account for 48% of the casualties (Pape, 2004). The average number of deaths per incident for suicide bombing attacks is 13 over the period of 1980 to 2001 (excluding 9/11). This number is far above the average of less than one death per incident across all types of terrorism attacks over the same time period (Harrison, 2006). In Israel, the average number of deaths per incident is 31.4 over the period of November 2000 to November 2003 (Harrison, 2006).

Past research has focused on developing psychological profiles of suicide bombers, understanding the economical logic behind the attacks (Lester, 2004, Harrison, 2004, Gupta 2005), explaining the strategic and political gains of these attacks, their role in destabilizing countries (Dolnik, 2003, Azam, 2005), and the role of bystanders in reducing the casualties of suicide bombing attacks (Harrison, 2006). The main objective of this research is to explore and identify precautions that when followed will minimize the number of deaths and injuries during a suicide bombing attack.

To observe the differential effects of suicide bombing attacks across crowd formations, nine different crowd formation styles were identified based upon real-world settings (e.g., hotel, concert, Mosque). The nine crowd formations were modeled to measure their impact on the outcome (casualty and injury count), taking into consideration the number of participants in the crowd, number of suicide bombers, and variable mass of explosives.

One might argue to use Computational Fluid Dynamics (CFD) computer programs to predict the blast and its effects, but these programs require special equipment and training. The simulation presented in this paper can provide useful data regarding formation styles and crowd densities as they relate to mitigating casualties in both a cost effective and timely manner.

Section 2 gives an overview of the science of blast explosion and how it is different from natural disasters. Section 3 discusses the animated environment in which the simulation takes place, our basic assumptions, and the mechanism of suicide bombing attacks in given settings and layouts. Section 4 starts with the pseudo code of counting the victims and defines various parameters, settings, and crowd formation styles. Finally, Section 5 documents the results and findings of this study and concludes the paper with a brief summary of findings, limitations of current work and directions for future research.

BLAST EXPLOSION

An explosion is an extremely rapid release of energy in the form of heat, light, sound, and a shock wave. A shock wave consists of highly compressed air traveling outward from the source at supersonic velocities. When the shock wave expands, pressures decrease rapidly (with the cube of the distance) and, when it meets a surface that is in line-of-sight of the explosion, it is reflected and amplified by a factor of up to thirteen (FEMA, 2004). Pressures also decay exponentially over time and have a very brief span of existence, measured typically in milliseconds. After some time in an explosive event, the shock wave becomes negative, creating suction and the air rushes in the vacuum created by the shockwave causing winds carrying flying debris. A portion of the energy is also imparted to the ground and generates a ground shock wave similar to a short duration earthquake.

An explosive blast is different from earthquakes, hurricanes or floods in the following ways:

- The intensity of the pressures can be greater to several orders of magnitude. The pressure can go up to 1000 pounds per square inch (psi), causing major damage to buildings and humans in the surrounding
- Explosive pressures decrease rapidly over distance, thus causing more localized damage.
- The duration of the event is really short (measured in milliseconds). This differs from earthquakes (measured in seconds),, hurricanes or flood situations (measured in hours or days).

Table 1 provides the general weights of trinitrotoluene (TNT) across four types of suicide bombing attacks along with their pressure (measured in pounds per square inch) over different distances (Air Force, 2004). Large scale trucks typically contain 25,000 pounds or more of TNT equivalent. Vans typically contain 5,000 to 25,000 pounds of TNT equivalent. Other small automobiles can contain 50 to 5,000 lbs of TNT equivalent. A briefcase bomb is approximately 50 pounds, and a suicide bomber wearing a vest belt generally carries up to 12 pounds of TNT equivalent.

Table 1. PSI over Variable TNT and Distances

Type	TNT Weight (Lbs)	PSI over Distance (ft)			
		500	**1,000**	**1,500**	**2,000**
Truck	25,000 – 100,000	10.0	2.0	1.0	0.5
Van	5,000 – 25,000	7.0	1.5	0.7	0.4
Auto	50 – 5,000	5.0	1.0	0.6	0.3
Person with Vest Belt	1 – 50	2.0	0.7	0.3	0.1

Table 2 provides the damage approximation based on incident overpressure (psi) (Kinney & Kenneth, 1985). An overpressure of as little as 0.5 to 1.5 psi can be lethal for humans in the vicinity of an attacker (FEMA, 2004). Hurricane Katrina overpressure in pounds per square inch was 12.1 psi (Brill, 2005).

Table 2. Damage Approximation

Damage	Overpressure (psi)
Window Glass Breakage	0.15 – 0.22
Minor Damage to Buildings	0.5 – 1.1
Panels of Sheet Metal Buckled	1.1 – 1.8
Failure of Concrete block Walls	1.8 – 2.9
Collapse of Wood Framed Buildings	Over 5.0
Serious Damaged to Steel Framed Buildings	4 – 7
Severe Damaged to Concrete Structures	6 – 9
Probable Total Destruction	10 – 12

Despite the unknown mass of explosive being used by a suicide bomber, explosive type and resulting psi, it is still possible to give some general indications of the overall level of injuries to be expected in an attack, based on the size of the explosion, number of participants and crowd formation style. Concussive force is only one variable in determining the effectiveness of the suicide bomber. In the following section we will discuss these variables and the assumption underlying the simulation.

ANIMATED ENVIRONMENT AND ASSUMPTIONS

The crowd is uniformly distributed throughout the area in each of the nine formation styles (discussed in detail in Simulation Section). The total area in the simulation for a crowd is projected to be 50 x 50 sq feet. The explosive range is determined by its weight. The amount of explosive being used in the simulation is between 1 - 8 pounds.

Where:

```
1 Lb  = 05 x 05 sq feet
2 Lbs = 10 x 10 sq feet
4 Lbs = 20 x 20 sq feet
      and so on…
```

To kill everybody in the crowd (in the simulation), the suicide bomber needs at least 10 pounds of explosives in his/her belt. The weights of explosives and ranges are intentionally disguised due to security reasons. More accurate weights and ranges can be easily entered into the simulation software. We have only considered the primary and direct injuries. Persons who are directly in the line-of-sight with the suicide bomber will get the effects and thus act as a shield for person(s) behind them. Direct Injuries means injuries caused by bomb fragments during the explosion and not by fire or debris (pieces of furniture or glass). However, we have incorporated the effects of stampede in our simulation. Stampede usually occurs when large number of people start running towards the same direction and the number of people in the crowd surpass the capacity of flow from that particular channel.

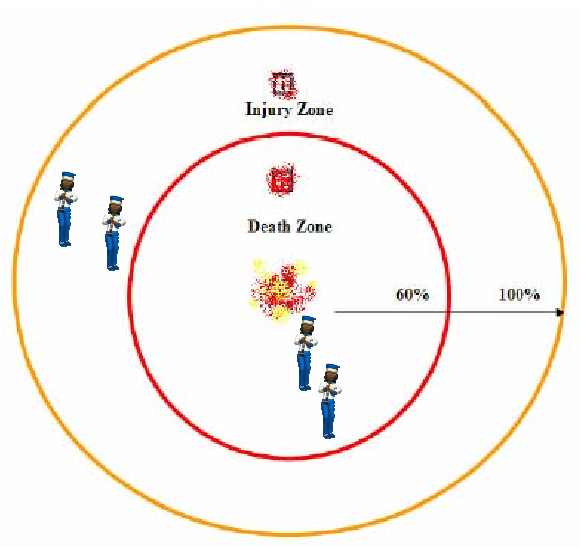


Figure 1. Range of an Explosive

Figure 1 presents the overall effectiveness and working mechanism of an explosive being used in the suicide bombing simulation. Energy from a blast decreases rapidly over distance. Range is measured from the center of gravity of the charge located in the belt of the Suicide Bomber. The victims who are in 60% of the radius of an attacker (determined by the amount of trinitrotoluene (TNT) being used) will be killed and those who are between 61% to 100% radius will get injured. The ranges given here are the generalization of the blast range to effects defined by Federal Emergency Management Association (FEMA) (FEMA, 2004). If a person is within the death zone (60% of the radius) but guarded by another person (or not directly in the line-of- sight with suicide bomber) he will only be injured. If a person is within the injury zone (60%+ to 100% radius) but guarded by another person, he will be safe.

We have considered mostly "open space" scenarios to serve as the basis for our crowd formation types (e.g., mosques, streets, concerts). There are numerous objects to consider in close environments that can either increase the casualty/injury toll by working as flying debris, or decrease the toll by providing a shield to humans.

The number of participants used across most of the experiments is 200 (unless otherwise), and the weight of TNT is 8 pounds (unless otherwise).

SUICIDE BOMBING SIMULATION

The pseudo code to count the number of persons killed, injured and unharmed is given in Figure 2. Range is measured from the position of the suicide bomber. The direct count to increase the number of victims is given in Steps 1 and 3, while the shielded decrease in severity is accounted for at Steps 2 and 4.

There are nine different settings a user can choose from the simulation main screen to estimate the outcome of an attack for a particular crowd formation. These nine settings were derived from the findings of Mark Harrison, where the majority of the suicide bombing attacks from November 2000 to November 2003 in Israel, occurred in Streets, Cafeterias, Buses or other open spaces (Mark, 2006). Users can also define number of participants (victims), number of attackers (suicide bombers), bomb strength (TNT weight in grams), and bomb-timer (if any). Figure 3 shows the starting screen of the simulation, Figure 4 shows the selection menu for crowd formation styles, and Figure 5 shows the display after the blast is simulated.

```
Count (Range, Shield)

Input:
Range (Integer value of range from
the suicide bomber)
Shield: Boolean value of 0 or 1 to
indicate whether the victim is
guarded by another person or not.

Output:
Killed, Injured, Unharmed: Integer
variables with total number of counts
for each category

1. IF (Range is between 1 to 60) AND
(Shield = 0) Killed = Killed + 1

2. ELSE IF (Range is between 1 to 60)
AND (Shield = 1) Injured = Injured +
1

3. ELSE IF (Range is between 61 to
100) AND (Shield = 0) Injured =
Injured + 1

4. ELSE IF (Range is between 61 to
100) AND (Shield = 1) Unharmed =
Unharmed + 1

5. END
```

Figure 2. Pseudo Code (Count)

There are nine crowd formation styles in this simulation with the spot for the suicide bomber. There are formations for Conference, Market, Street, Bus, Concert, Hotel, Shopping Mall, Mosque and University Campus.

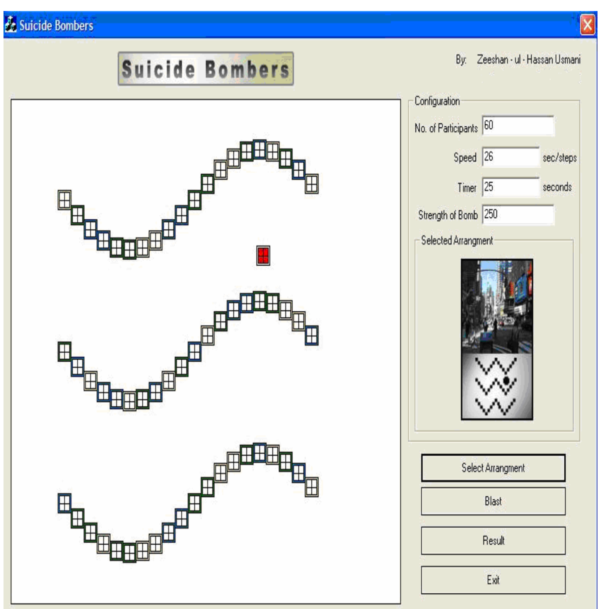


Figure 3. Simulation Start Session

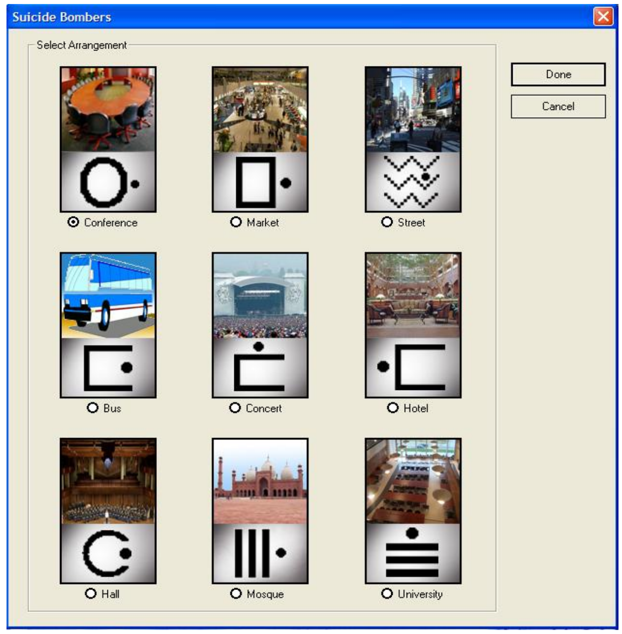


Figure 4. Nine Possible Crowd Formations

The simulation takes care of the beam and line-of-sight adjustments in cases of uneven surfaces (e.g., concert stage, mosque or shopping mall). We have not considered physical objects (like wall, tree, furniture etc) as obstacles or means to harm people at this point of time. The suicide bomber is a pedestrian in all cases and the explosion does not originate from a moving vehicle. The reason for choosing a suicide bomber location in almost all cases (except in Street scenario) on the entrance or exit gate was based upon the recent attacks in Iraq and Israel where suicide bombers detonated their bombs at the gates of mosques and restaurants.

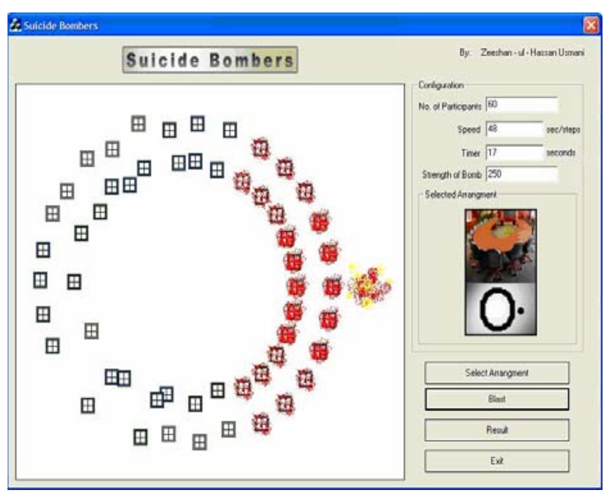


Figure 5. Simulation Screen after the Blast

The display depicts the casualties by red colored icons, those with injuries in light red colored icons, and those who remain unharmed in the attack in blue colored icons. Thus, there are three states of participants after the blast: dead, injured and unharmed (but in panic and contributing in stampede). The simulation program stores this detailed information in a text file.

RESULTS

The worst crowd formation is found to be in the live Concerts (Rectangular) scenario, where 51% of the participants were killed and 42% injured using only 8 pounds of explosive. The overall effect comes to 93% in this formation style. While, the same number of participants and the amount of explosive in formation style of the Mosque (vertical rows) caused only 34% deaths with additional 36% injured, the overall effect in this scenario is 70%. The best way to form a crowd to reduce the expected number of deaths is found to be in formations utilizing vertical rows.

The worst crowd formation style according to number of injuries is the Streets scenario (Number 3, Zig-Zag), where 51% persons were injured given the same number of participants and amount of explosive being used in other experiments. The best way to form a crowd to reduce the expected number of injuries and casualties is style number 8 (mosques) where only 36% participants were injured.
Figure 6 summarizes the findings of percentage of persons killed and injured with given crowd formations.

Figure 7 and Figure 8 present the growth in percentage of participants killed and injured with the increase in explosive weight. The relationship between the increase in the percentage of casualties and injuries with the amount of explosive is observed to be linear. This relationship is logical since augmenting the explosive material will increase the overpressure pounds per square inch (psi) in the vicinity, and the persons are bounded to 50 x 50 Sq ft area in the simulation.

Figure 9 documents the simulation results on the effects of crowd densities over total number of casualties. The results supplement the findings of Moshe Kress (Moshe, 2004), where increase in number of participants in the crowd is not directly proportional to the increase in the number of casualties. The number of casualties gets stabilized with increase in number of participants in the crowd. The one logical reason behind this finding could be the less chances of being in the line-of-sight with the suicide bomber and thus more human bodies as guards for others.

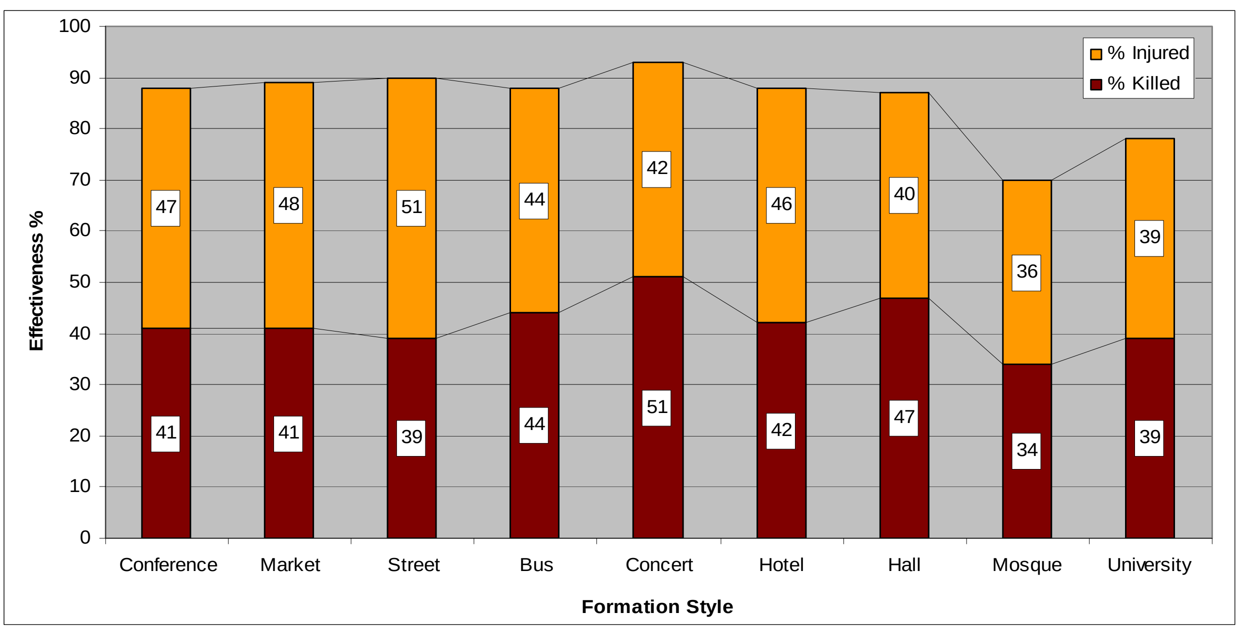


Figure 6. Percentage of Casualties and Injuries with Different Crowd Formation

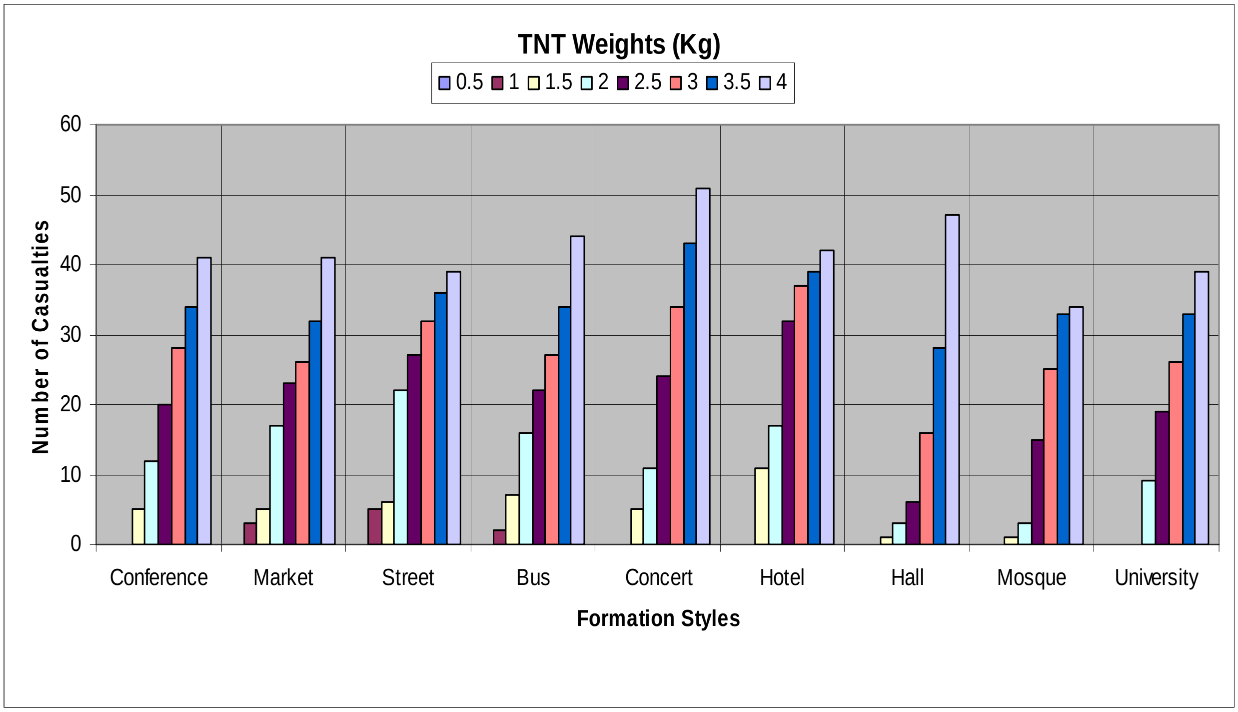


Figure 7. Number of Casualties With Variable Explosive Weights

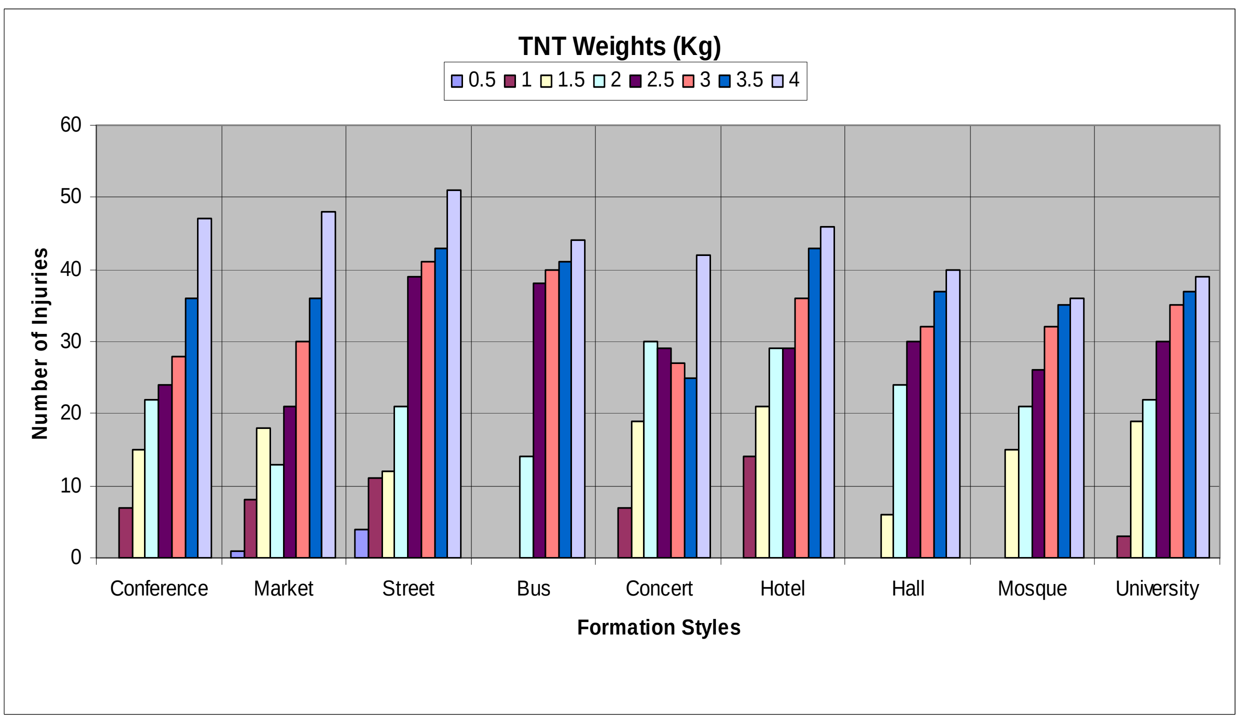
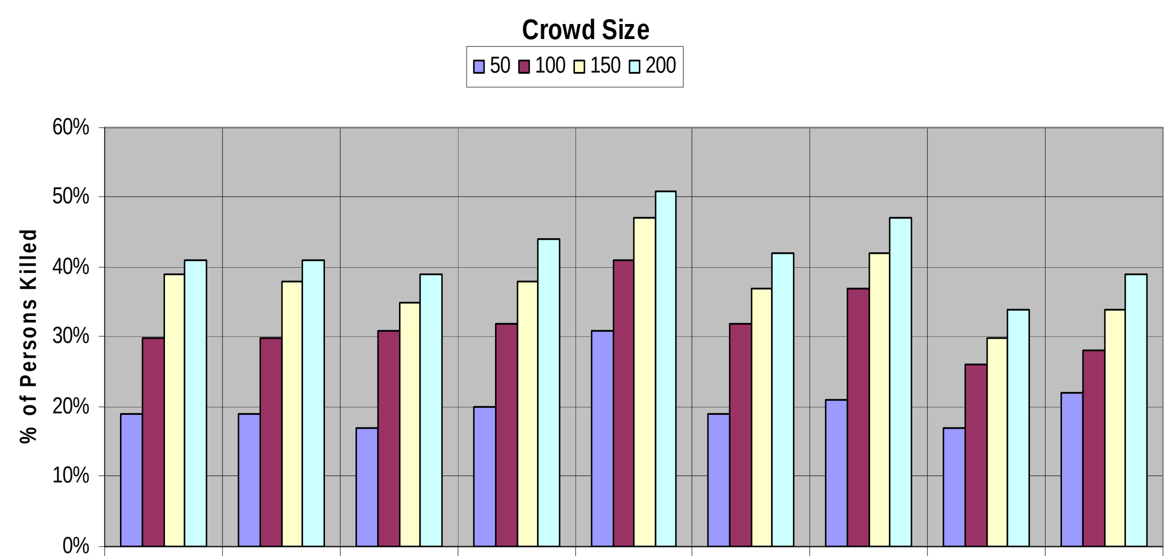


Figure 8. Number of Injuries With Variable Explosive Weights



	Conference	Market	Street	Bus	Concert	Hotel	Hall	Mosque	University
50	19%	19%	17%	20%	31%	19%	21%	17%	22%
100	30%	30%	31%	32%	41%	32%	37%	26%	28%
150	39%	38%	35%	38%	47%	37%	42%	30%	34%
200	41%	41%	39%	44%	51%	42%	47%	34%	39%

Formation Style

Figure 9. Number of Participants and the Percentage of Persons Killed

Announcing the threat of suicide bombing in the crowd can only make the condition and toll much worse. People will panic and thus increase the possibility of more victims in the line-of-sight with the suicide bomber than before. People will also try to rush towards the exit gates (thus coming closer to suicide bomber in majority of cases) and there will be higher chances of stampede. The situation of stampede is found to be highly dangerous in the shopping malls.

CONCLUSION AND FUTURE WORK

There are a number of lessons we can learn from the initial empirical analysis of this suicide bombing simulation with given crowd formation styles. For example, we can reduce the number of casualties by forming the crowd in the best possible order (vertical rows in this case).

There is an acute shortage of accurate data for many other variables and conditions that are pertinent to such an attacks (e.g., Was the bomber running? How he is carrying the explosive? How much explosive?), making it difficult to validate the numbers of the simulation results with actual events.

The simulation and findings are limited in that it only incorporates the primary injuries. Future plans are to add secondary effects (e.g., injuries by fire, debris, etc.) to better approximate the real world environment and provide more valid comparisons with the data of suicide bombing attack aftermaths (Pape, 2005). We will also add the flexibility to create the user defined crowd formations with variable number of entrances and exits in the future. This paper provides an interesting direction for future research to take in investigating the catastrophic event of the suicide bomber attack in hopes of making the world a safer place.

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