Intelligent Agents in Extreme Conditions – Modeling and Simulation of Suicide Bombing for Risk Assessment

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1. Introduction

Intelligent agents in extreme conditions is an attempt to use agent based simulation to save lives, predict the outcome of catastrophic events like suicide bombing, and model the behavior of crowd in emergency situations. This work is set to implement, test, analyze and measure intelligent agents' behavior and its consequences under extreme conditions like suicide bombing through multi-agent simulation.

Suicide bombing has become one of the most lethal and favorite modus operandi of terrorist organizations around the world. It claims 48% of the casualties, while only 3% of all terrorist attacks can be classified as suicide bombing attacks. On average, there is a suicide bombing attack somewhere in the world on every 6th day that claims 13.4 lives (on average) per attack (Usmani a, 2009). While various attempts have been made to assess the impact of explosions on structures, little has been done on modeling the impact of a blast wave for an individual or a crowd. There is no tool exist to determine the impact of explosion as a function of crowd dynamics, and explosive characteristics. And there is not a single method available to map the blast overpressure to human injuries that is calibrated against the real-life victims' data. All of the existing estimates and pressure-lethality curves are based on experiments on pigs, sheep, and data collected from stationary sensors without any consideration of blockage and 3D environment.

Explosion modeling is a complicated task that requires the knowledge of physical properties of explosions, projectiles and debris, chemical properties of explosive materials and their reactions, complex details of simulating gaseous and combustion flows with boundary conditions, complex coding for blast waves and fragmentation models, know-how of computational fluid dynamics, and the overall impact of explosions on humans and structures supported by experimental and theoretical studies. This work explains the physics, explosive models, mathematics and the assumptions we need to create such a simulation. The work also describes human shields available in the crowd with partial and full blockage in both two dimensional and three dimensional environments.

A virtual simulation tool (BlastSim) has been developed which is capable of assessing the impact of crowd formation patterns and their densities on the magnitude of injury and number of casualties during a suicide bombing attack. Results indicated that the worst crowd formation is Zig-Zag (e.g., street) where 30% crowd can be dead and 45% can be injured, given typical explosive carrying capacity of a single suicide bomber. Row wise crowd formation was found to be the best for reducing the effectiveness of an attack with 18% crowd in lethal zone and 38% in injury zones. For a typical suicide bombing attack, we can reduce the number of fatalities by 12%, and the number of injuries by 7% by simply following the recommendations in this chapter. Simulation results were compared and validated by the real-life incidents and found to be in good agreement. Line-of-sight with the attacker, rushing towards the exit, and stampede were found to be the most lethal choices both during and after the attack. These findings, although preliminary, may have implications for emergency response and counter terrorism.

2. Literature Review

Suicide bombing is an operational method in which the very act of the attack is dependent upon the death of the perpetrator (Pape, 2005). The world is full of unwanted explosives, brutal bombings, accidents, and violent conflicts, and there is a need to understand the impact of these explosions on one's surroundings, the environment, and most importantly on human bodies. There is a growing need and interest in treating explosion related injuries in emergency rooms, a phenomenon traditionally only considered to be present in the emergency units of battlefields. From 1980 to 2001 (excluding 9/11/01) the average number of deaths per incident for suicide bombing attacks was 13. This number is far above the average of less than one death per incident across all types of terrorist attacks over the same time period (Harrison, 2004). In Israel, from November 2000 to November 2003 the average number of deaths per incident was 31.4 (Harrison, 2006). From 2006 to 2007 the average number of deaths in Pakistan was 14.2 (Usmani a, 2009). Suicide bombers, unlike any other device or means of destruction, can think and therefore detonate the charge at an optimal location with perfect timing 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 can be readily constructed.

A significant progress has been made in the modeling and simulation of explosion and blast waves in last two decades (Pritchard *et. al.*, 1999, Lester, *et. al.*, 2004, Clutter, *et. al.*, 2006). However, the majority of work (Redlins, 1977, HJertager, 1982, Ettouney, 2001) follows a trend of capabilities and limitations mainly influence by their requirements in industry and non-civil settings. For example, none of the models (Cates & Samuels, 1991, Baker, *et. al.* 1998, Baker, *et. al.* 1994, Berg, 1985, Arntzen, 1982, Usmani c, *et. al.*, 2009, Usmani d, *et. al.*, 2009, Usmani e, *et. al.*, 2009) have considered the open space scenarios like markets and streets for simulating explosion effects. Another important parameter missed by almost all existing models is the plotting of multiple explosions, as witnessed recently by multiple suicide bombers in Iraq and Pakistan (Usmani a, 2009).

Most of the models have also neglected the effects of the negative phase, reflection waves, and blockage shields by living and non-living objects, crowd density, projectiles and debris, different explosives, and the scenario visualization in a 3D environment. Blast/FX (Fertal & Leone, 2000) stands out to be the best available explosion model for testing and evaluation of blast loading, but it is also based on empirical studies on sheep and pigs. There is an acute need of explosion effects model based on human data. While the models work well in general, collectively they lack the following characteristics, much needed for real-life risk assessment and emergency planning in case of events like terrorism and suicide bombing:

1. Require too much computing and time resources when implemented with complex geometries and scenarios
2. Need special hardware and software to execute
3. Need a subject matter expert to tune the constants for new and different situations
4. Do not consider blockage and obstacles in a three dimensional environment
5. Lack the capability to work with different kinds of explosives
6. Do not consider crowd formations, density and demographics
7. Have no experimental data with humans
8. None of the models provide a direct mapping of over-pressure to human injuries
9. Provide no capability of new equation plug-in and algorithms
10. Provide no venue for the assessment of sensitivity analysis due to change in explosive characteristics
11. None of the models have considered the negative phase and reflection waves
12. None of the models have considered crowd formation and topologies

Resolution of these issues is needed for real-life risk assessment and emergency planning, and to develop a comprehensive model of a suicide bomber attack. Our model (BlastSim) is rightly filling the gap and providing exactly what is missing.

Few researchers have also focused on developing psychological profiles of suicide bombers, understanding the economical logic behind the attacks (Gupta & Kussum, 2005, Harrison, 2004, Harrison, 2006), explaining the strategic and political gains of these attacks, their role in destabilizing countries (Azam, 2005, Ganor, 2000), and the role of bystanders in reducing the casualties of suicide bombing attacks (Harrison, 2006, Kress, 2004). The specifics of the actual crowd formation and orientation of the bomber with respect to the crowd has not been examined. The presented simulation examines variables such as the number and arrangement of people within a crowd for typical layouts, the number of suicide bombers, and the nature of the explosion including equivalent weight of TNT and the duration of the resulting blast wave pulse for both 2D and 3D environments. The goals of the analysis are to determine optimal crowd formations to reduce the deaths and/or injuries of individuals in the crowd, to determine what architectural and geometric changes can reduce the number of casualties and injuries, and what is the correlation between variant crowd densities and formations with the weight and pulse duration of the explosives? The main objective of our research is to explore and identify crowd formation precautions that when followed will minimize the number of deaths and injuries during a suicide bombing attack.

3. Modelling Overview

Authors have developed a framework to predict the damage of a suicide bombing attack as illustrated in Figure 1. The main goal of our research is to define a general blast wave explosion model to predict and estimate the damage for such incidents. The proposed model will be a total turn-key solution for emergency response management, casualty prediction, classification of injuries, and will provide a safe distance matrix to event managers and security officials. The model will be general enough to make it unclassified (thus avoiding misuse) and specific enough to give an educated guess for the outcome.

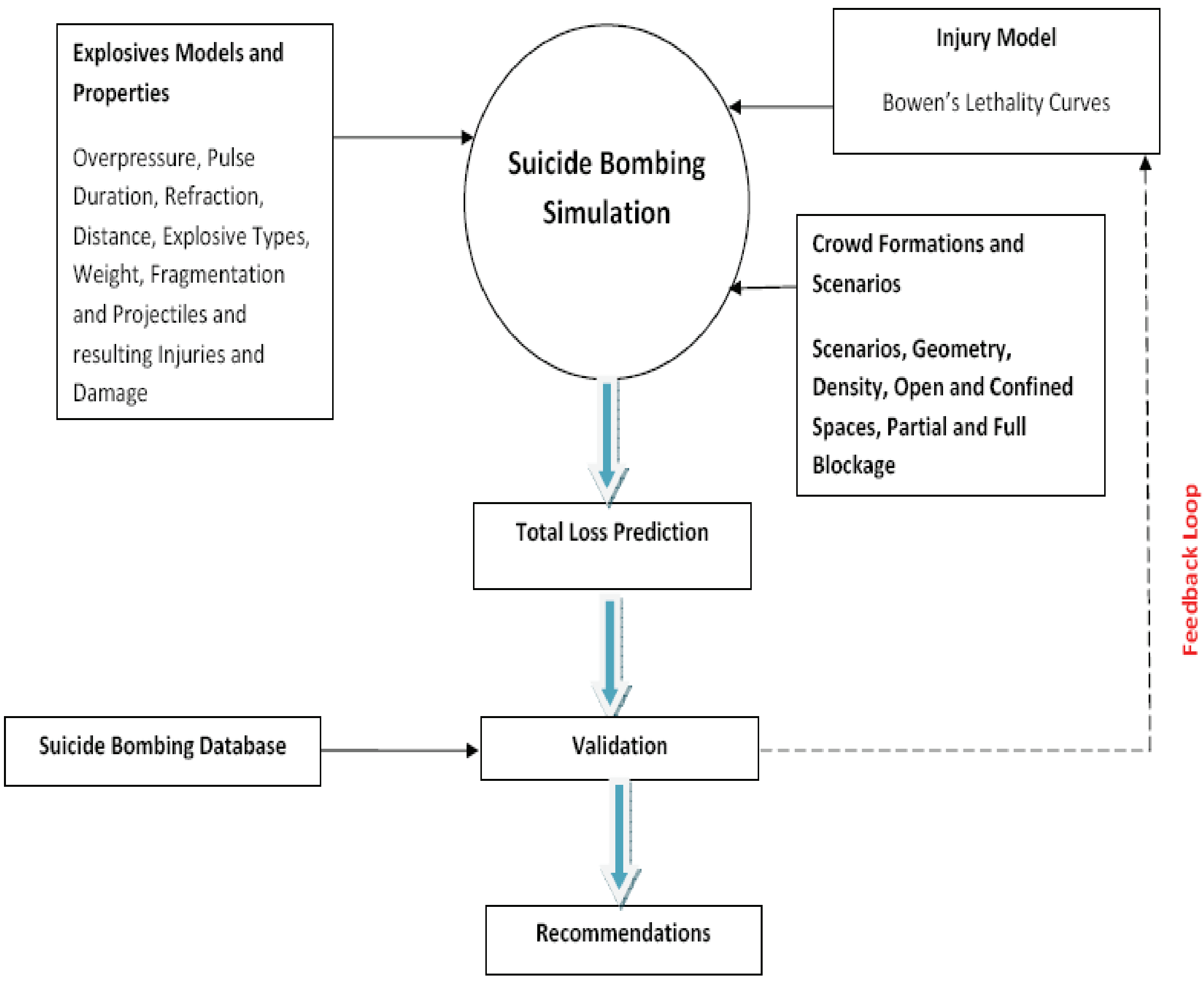


Fig. 1. Components of the suicide bombing model

The effects of an explosion are contingent upon various factors, such as: explosive type (i.e. TNT, RDX, C4, AN etc.), explosive weight (pounds) and results overpressure (pressure-per square inch PSI), ignition source and criteria, crowd density (number of people per square meter), crowd demographics (i.e. age, gender, weight, height), pulse duration (milliseconds), and reflection waves, blockage ratios (percentage), size, shape, location, and number of obstacles, projectiles, debris and fragments, and shape of the explosive carrier. A suicide bombing model and simulation should consider all of the aforementioned factors. Furthermore, the model should be easy to use, contain appropriate physics, be able to work with different scenarios, blockage ratios, injury matrices, and different ambient conditions without special time consuming tuning of parameters. The model should also have sufficient numerical accuracy to allow realistic representation of geometry and explosive strength. It should be easy to configure, and run in a short amount of time.

Some of these requirements are contradictory. For example, a complex model will require too many resources and time if it truly contains appropriate physics and complex geometries. Consequently, a good model should allow for a tradeoff between time, resources, physics, geometry and the resulting output. Sometimes there is a need of faster results to be able to save lives, and sometimes there are scarce resources to distribute for various purposes. A good model should be flexible enough to use in a diverse set of situations with varying requirements. Our proposed framework is fulfilling this gap by providing faster results while taking care of all required characteristics of a good model.

4. Explosive Model

In order to model the effects of an explosion on a given crowd formation, it is essential to properly model the deleterious properties of the blast waves themselves. A conventional bomb generates a blast wave that spreads out spherically from the origin of the explosion. The strength of the blast wave decreases exponentially with distance (Irwin, 1999, FEMA 2004). Although the physics of blast waves are complex and nonlinear, a wave may be broadly characterized by its peak overpressure (pressure above atmospheric) and the duration of the positive phase of the blast event, as shown in Figure 2. Based on those two quantities, the intensity of the blast wave can be assessed and exposure threshold limits can be determined, although this only applies to a specific scenario. Enhanced-blast explosive devices, in contrast, can have more damaging effects, and cause a greater proportion of blast injuries than conventional devices. In an enhanced-blast device, a primary blast disseminates the explosive and later triggers a secondary explosion. The high-pressure wave then radiates from a much larger area, prolonging the duration of the over pressurization phase, thus increasing the total energy transmitted by the explosion.

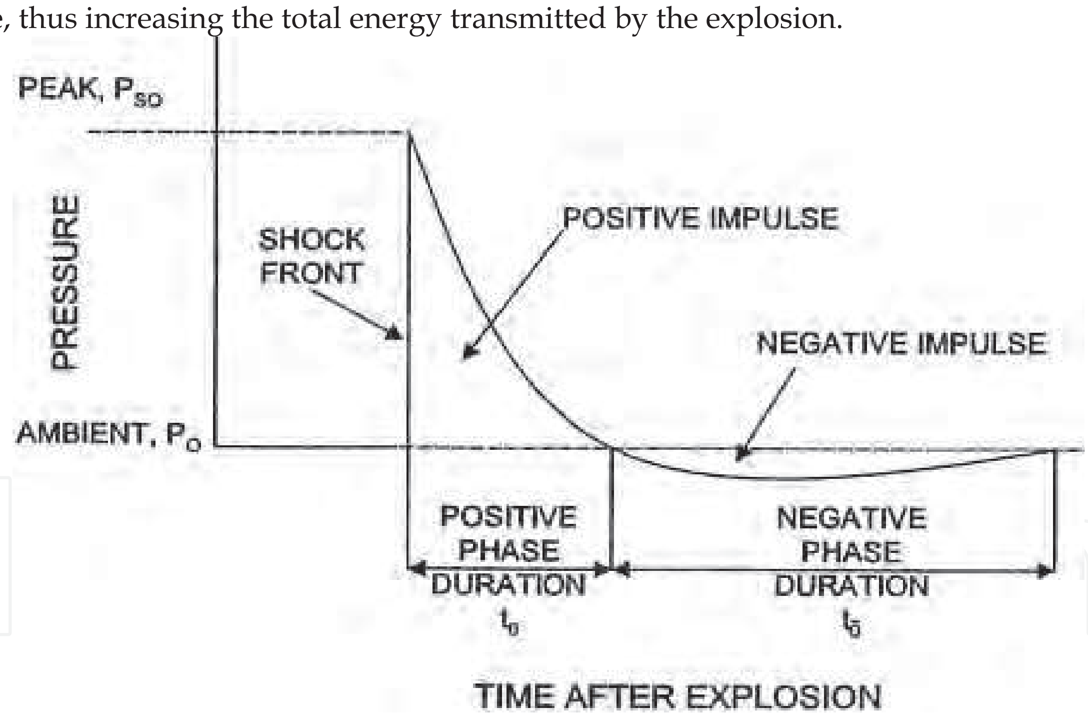


Fig. 2. Blast wave showing positive and negative phase durations. Such waves may be characterized by the peak overpressure and duration of the positive phase

Depending on the type of explosive and the proximity to the target, the positive phase duration can vary between a few microseconds up to several milliseconds (Kinney & Graham, 2985). Injury correlations as a function of peak overpressure and duration have been developed for various organs, such as the eardrums and lungs, as well as probability of fatality curves for humans in various orientations to the blast wave. Impulse, which is the force-time product of the blast wave, is also important to consider, as two profiles with identical peak overpressure and duration can have different total impulses. Studies on blast-related injuries have shown that both the peak overpressure and duration of the positive phase, which correlate to the overall impulse, each contribute to the magnitude of injury experienced by a victim.

A simulation which seeks to study the impact of a suicide bomber on casualty rates and injuries related to crowd formation must be able to adequately model the influence of peak overpressure, duration, and impulse of the explosion; the next few paragraphs discuss blast modeling and the assumptions made in the simulation.

Experimental and theoretical means have been used to obtain important parameters associated with blast waves. A theoretical analysis for peak overpressure utilizes the same mathematical approach as for a planar shock wave, but includes the effects of spherical divergence and the transient nature of the blast event (Cooper, 1996, Kinney and Graham, 1985). As an example, values for the peak overpressure generated in a standard atmosphere for the blast wave generated by a one pound spherical charge of TNT are shown in Figure 3.

At distances far from the center of an explosion, a blast wave behaves like a sound wave in that its energy-distance relation follows an inverse square law. The intensity of sound energy, however, is proportional to the square of sound pressure, so that a simple inverse relation between peak overpressure and distance is sufficiently great that the blast wave overpressure approaches zero.

Also shown in Figure 3 is the peak overpressure that would be expected at various distances had the energy been released by one pound point source of TNT. It can be seen by comparing the two curves that the effect of the explosive charge is to initially spread out the energy and so to reduce the peak overpressure to some appreciable distance from the center of the explosion – around 5 charge diameters. At intermediate distances, the large amounts of gas produced from the TNT become evident in the peak overpressure curve. At greater distances, losses due to dissociation and ionization become evident in the point source and act to reduce the energy available so that observed peak overpressure is somewhat less than that from TNT with the same energy release. This demonstrates that although knowing the total energy release is important, it is inadequate to completely describe the blast event.

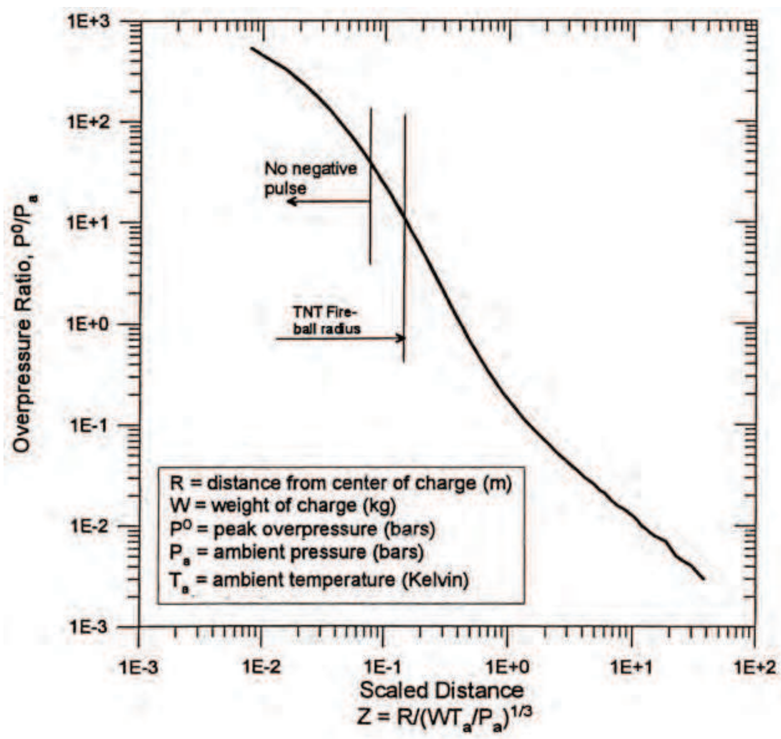


Fig. 3. Peak overpressure ratio versus scaled distance, adopted from (Kinney & Graham, 1985)

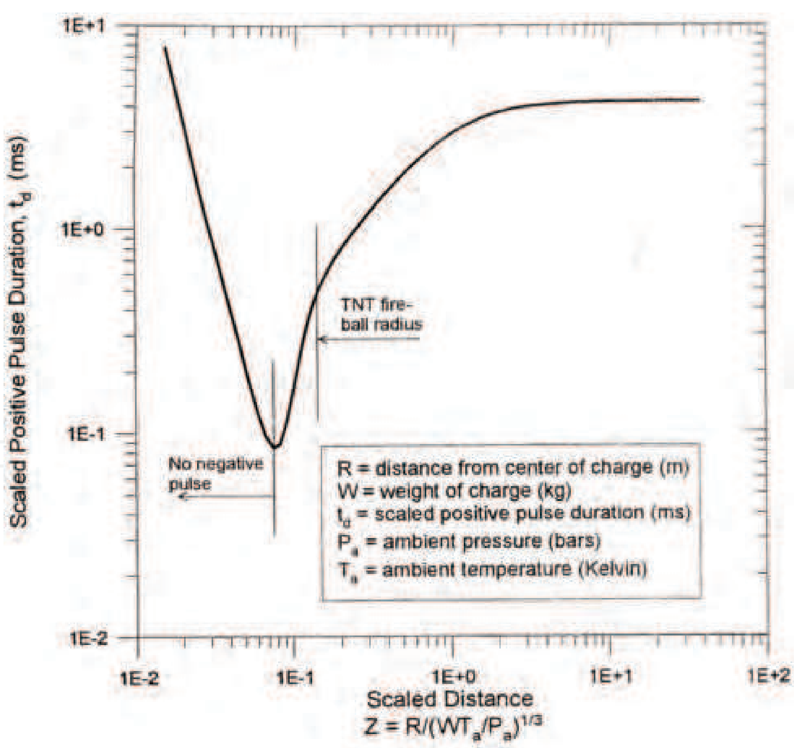


Fig. 4. Scaled positive pulse duration versus scaled distance, adopted from (Kinney & Graham, 1985)

The data depicted in Figure 3 and 4 applies for any weight of TNT through an energy-weight scaling law. Two explosions can be expected to give identical blast wave peak overpressures at distances which are proportional to the cube root of the respective energy release. For example, to produce a given blast overpressure at twice a given distance requires eight times the explosive energy release. The following scaling law is used (Cooper, 1996), which also allows for compensation in different atmospheric pressures (Pa) and temperatures (Ta):

$$Z = \frac{R}{(WT_a/P_a)^{1/3}} \tag{1}$$

The energy release factor is contained in the ratio $(R/WT_aP_a)^{1/3}$, where W is the energy release, or amount of TNT in kilograms, in the explosion to be described, R is the distance in feet, T_a is the ambient temperature in Kelvin and P_a is the ambient pressure in bars. By using this scaling law, the distance at which a given peak overpressure is produced by a reference explosion may be scaled up or down to provide a corresponding distance for other explosions. Different explosives can be considered by modifying the overpressure versus distance history or by utilizing data specific to the explosive composition.
The time duration of a blast wave must also be considered because the magnitude of injury depends in part on how long the damaging forces are applied. Because of the relationship between the speed associated with the initial shock front and the changing local speed of sound as the blast wave propagates, the duration of the blast wave increases with distance from the center of the explosion, and reaches a limiting maximum value (and ultimately vanishes) as the shock front degenerates into a sound wave. To model duration increase as a function of distance from the origin of the explosion, the digitized data of Figure 4 has been used, where the distance is scaled as for Figure 3, and the curve in Figure 4 gives the corresponding scaled positive pulse duration in a given time.
Impulse is also an important aspect of the damage-causing ability of the blast, and may become a controlling factor for short duration, small yield explosives. The significant portion of the impulse is associated with the positive phase. The decay of blast overpressure does not follow a typical logarithmic decay relation, because the overpressure drops to zero in finite time (Kinney & Graham, 1985). A quasi-exponential form for pressure in terms of a decay parameter α, and of a time t, which is measured from the instant the shock front arrives, can be given as (Cooper, 1996):

$$p = p_0\left(1 - \frac{t}{t_d}\right)e^{\frac{-\alpha t}{t_d}} \tag{2}$$

Where p is the instantaneous overpressure at time t, p_0 the maximum or peak overpressure observed when t is zero, and, t_d is the time duration. The decay parameter is also a measure of intensity of the shock system. Equation (2) may also be used in the simulation if the decay parameter α is specified, for example, to determine the evolution of the positive phase duration as a function of distance from the explosive center.

5. Injury Model

In order to tie together the influence of peak overpressure and duration to injury and fatality probability, a series of data curves were utilized. Figure 5 shows the fatality curves predicted for a 70-kg man applicable to free-steam situations where the long axis of the body is perpendicular to the direction of blast wave propagation.

Specifying the amount of TNT, using the scaling law of equation (1), and the overpressure versus distance curve of Figure 3, then allows for the calculation of the peak overpressure at any distance away from the explosive origin. Using this peak overpressure and the increasing duration given by the digitized dataset of Figure 4 a new duration of the blast wave can be calculated at any distance away from the explosion. Using these two pieces of information and injury or fatality probability curves, such as Figure 5, an estimate of the injury or fatality levels at any location of the explosion can be calculated for various crowd formations.

Injuries that occur as a result of explosions can be grouped into several broad categories, as primary, secondary and tertiary injuries. Primary injuries caused by the direct result of pressure wave impacting and travelling through the body; it includes rupture of tympanic membranes, pulmonary damage, rupture of hollow viscera. Secondary injuries result from flying debris that damage body; it includes penetrating trauma and fragmentation injuries. Tertiary blast injuries results from victim's body being thrown by blast wind, and then impacting stationary object; it includes crushing injuries and blunt trauma, penetrating or blunt trauma, fractures and traumatic amputations. And miscellaneous blast injuries are caused by flame and chemicals that includes burns, asphyxia, and exposure to toxic inhalants

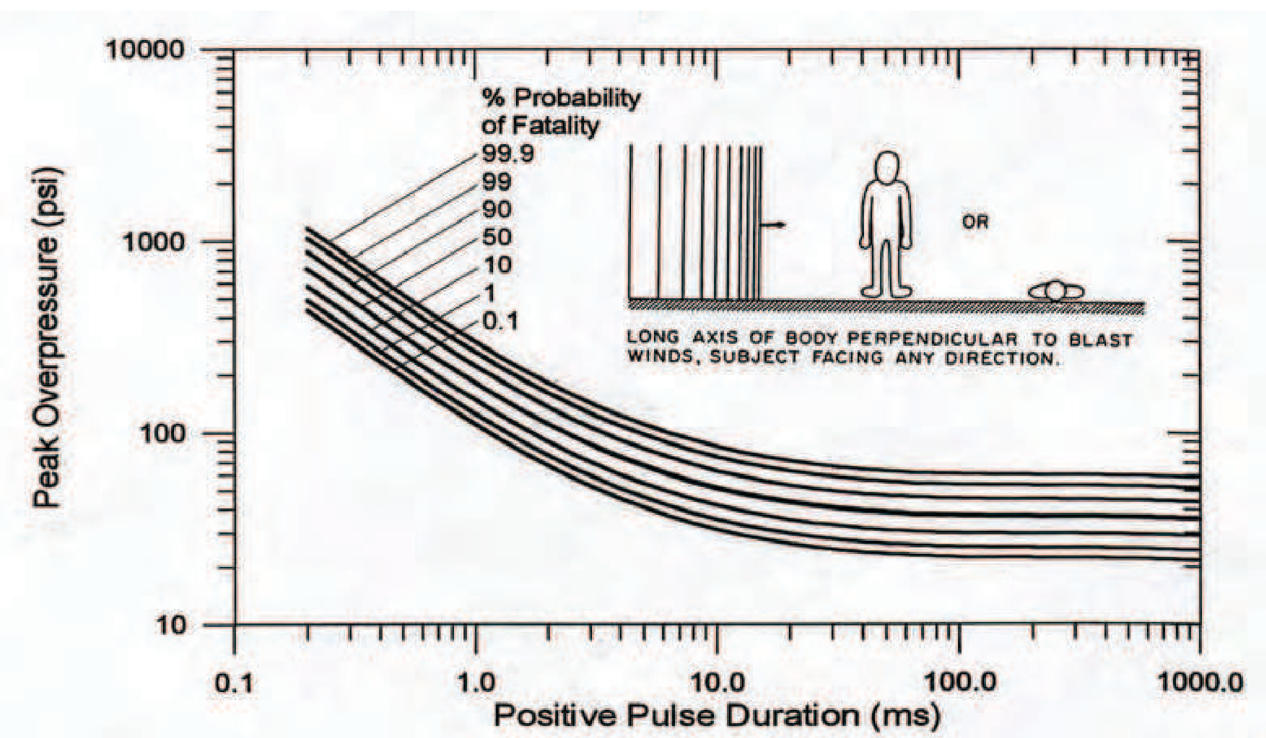


Fig. 5. Fatality curves as a function of blast wave peak overpressure and positive pulse duration (Cooper, 1996).

The exact explosive mass used in suicide attacks is hard to determine. However, it is possible to give some general indications of the overall level of injuries to be expected based on the size of an explosion, the number of participants and crowd formation. Large trucks typically contain 25,000 pounds or more of TNT equivalent, and vans typically contain 5,000 to 25,000 pounds. Small automobiles can contain 50 to 5,000 pounds of TNT equivalent. A briefcase bomb is about 50 pounds, and a suicide bomber wearing a vest belt generally carries up to 30 pounds of TNT equivalent (Air Force, 2004).
The preliminary results described in this paper are based on a division of the blast area into six zones: three for lethality, and three for injuries. Lethal zone #1 results in a 99% probability of death, lethal zone #2 results in a 50% probability of death, and the zone #3 results in a 1% probability of death. Similarly, injuries are divided into three zones. Injury zone #1 includes people who get 60 PSI or more overpressure, zone #2 refers to more than 40 and less than 60 PSI overpressure, and zone #3 for more than 20 and less than 40 PSI overpressure. In general, 60 PSI results in severe injuries such as missing body parts, amputation, brain or heart rupture, or Abbreviated Injury Score (AIS) 3. PSI of 40 usually results in the rupture of air-filled organs like lungs and kidney or AIS 2, and 20 PSI is usually responsible for minor bruises and ear-drum rupture or AIS 1. Persons below the range of 20 PSI are generally unharmed (Irwin, 1999).

Lethal Zones	**No Blocker**	**Partial Blocker**	**Full Blocker**
#1	Death 99%	Death 99%	Death 50%
#2	Death 50%	Death 1%	Unharmed
#3	Death 1%	Unharmed	Unharmed
Injury Zones			
#1	Injured 60 PSI	Injured 40 PSI	Injured 20 PSI
#2	Injured 40 PSI	Injured 20 PSI	Unharmed
#3	Injured 20 PSI	Unharmed	Unharmed

Table 1. Full and partial blockers impact

Table 1 provides the details of the respective impacts of the full and partial blockers on the lethal and injury zones. For example, a person within the 50% lethality zone blocked by a full blocker will be unharmed, on the other hand, the same person blocked by a partial blocker will be downgraded to lethal zone 3 (1% probability of death).

6. Crowd Formation – Full and Partial Blockers

Blockage or shields present in a crowd can play an important role in the event of an explosion. Even a person providing a blockage in the line-of-sight between another person and an explosion can actually save the later person’s life by absorbing most of the shrapnel or by consuming part of the blast wave overpressure. Spatial distribution of individuals in a crowd can therefore significantly alter the casualty toll. Thus different crowd formations can yield different outcomes with the same amount and type of explosive, even when the average distance to the bomber between two different crowd configurations is identical.
This section introduces 2D and 3D models for finding the exact number of full and partial blockers between each person and the point of explosion. Persons in the line of sight

between a given target and the blast point are termed *full blockers*. Blockers who are not in the line of sight, but whose body width covers some part of the body of the person from the blast projectiles, is referred as a *partial blocker*. For example, imagine a person of 4 feet standing in front of a 6 feet 10 inches person, or a person standing next to another. These persons, while not covering another person completely, can provide partial blockage.
To the best of our knowledge, this study is the first to consider partial blockers in blast wave simulation. Figure 6 presents the blockage model for 2D. Each person in the area is modeled by a vertical line segment, where the mid-point of the vertical line represents the position of the person, and the length represents their width.
Each line in the model is represented by the coordinates of its two end points. The line between the mid-point of the target and the blast point is called the *line-of-sight*. Each target is also represented by a vertical line called the *body-width-line*. The triangle, whose base is the body-width-line of the target and the blast point, is termed the *blast triangle.*

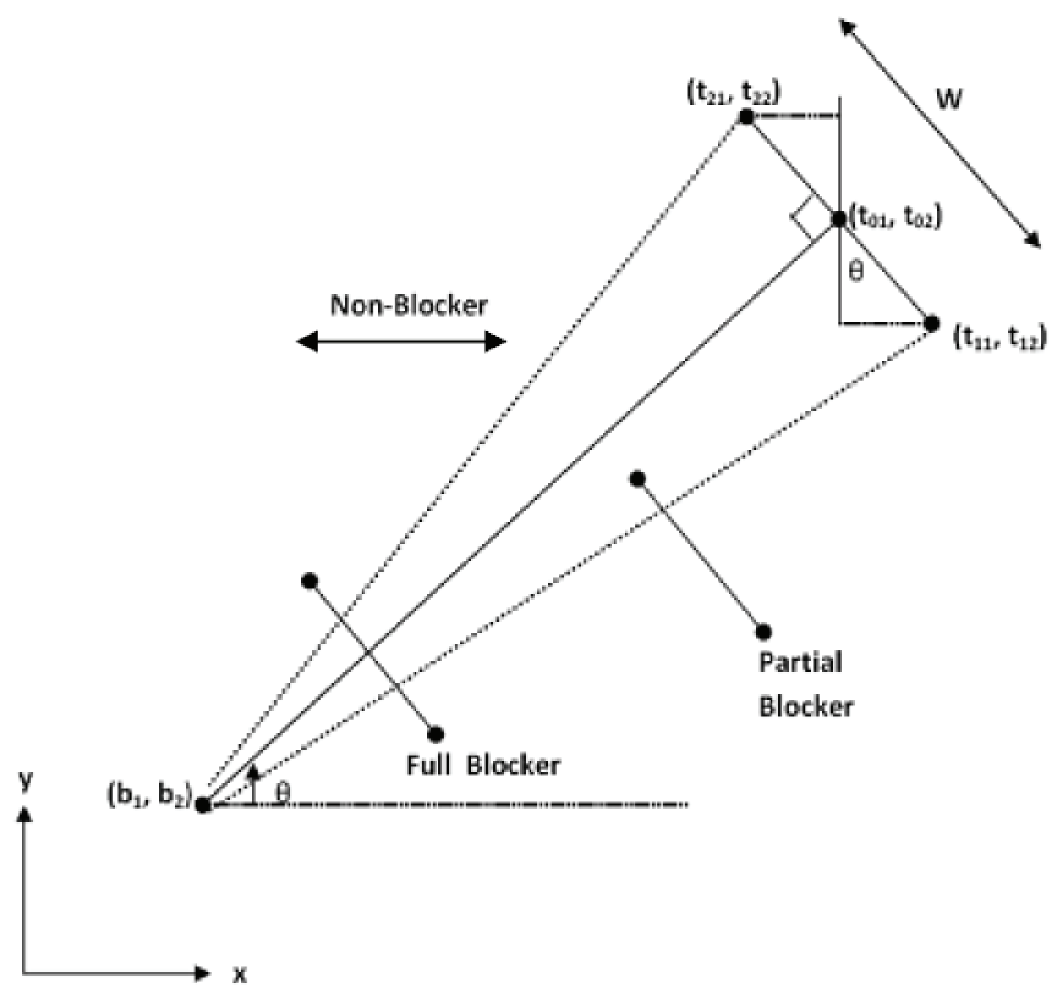


Fig. 6. Full, partial and no blockers in 2D

The line segment between the blast point (b_1, b_2) and the center of the target (t_1, t_2) is constructed and its slope is calculated. Assuming all people face towards the blast, the body-width-line of the target will be perpendicular to the line of sight. The slope of this line is the negation of the slope of the line of sight. Using simple coordinate geometry, one can easily determine the end points of the body-width-line of the target ((x,y):(z,w)) given the mid-point of the line (t_1,t_2), the body width and the slope of the line. Given the end points of the body-width-line of the target, one can easily construct the two other sides of the blast triangle. All other people's body-width-line is assumed to have the same slope as the slope of the body-width- line of the target. Taking this slope, the position coordinate, and the width, it is trivial to determine the end points of the body-width-line of each person.

It is also worth noting that all infinite slopes are approximated by $\pm 1 \times 10^6$. To determine the blockage, one has to determine if the body-width-line (representing a person) is intersecting with either the line-of-sight or the sides of the blast triangle. If a body-width-line is intersecting the line of sight, the person represented by this line is taken as full blocker. Otherwise, if it intersects with either side of the blast triangle, the person will be considered a partial blocker. Figure 6 shows full and partial blockers, and other individuals that do not provide any blockage at all (non-blockers).

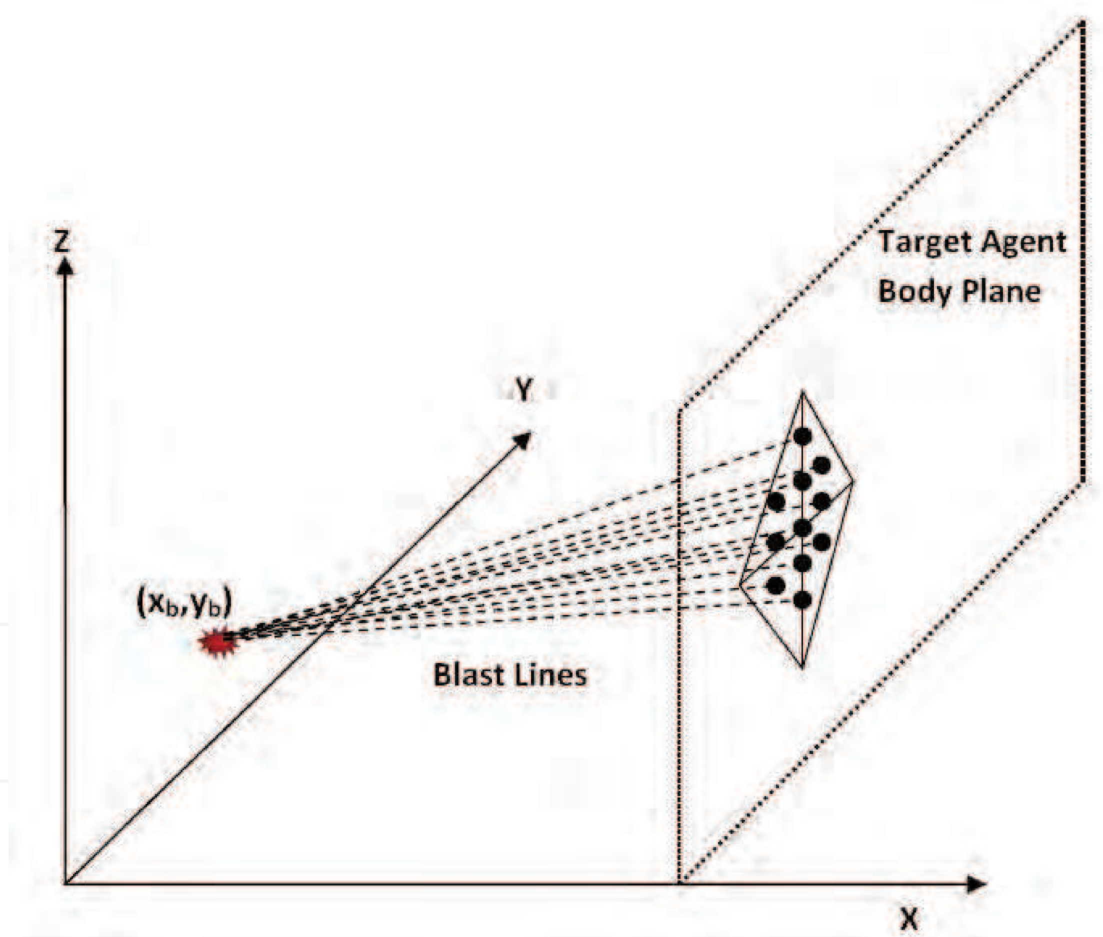


Fig. 7. Percentage of partial blocking in 3D

To find blockers in three-dimensions, a Cartesian(x-y-z) plane is used as a reference to the distribution of agents. Each agent is modeled by a four sided polygon whose dimensions are determined by their height and width. These polygons are made to lie parallel to the y-z plane to reduce the computational overhead. Figure 7 illustrates the concept.

There are four planes which enclose the cone whose vertex is the point of explosion and whose base is the four sided polygons modeling an agent. The cone referred to as the blast cone and the enclosing planes are referred to as blast cone planes. The plane containing this polygon is called the agent body plane and the polygon is called the agent body polygon. The four line segments extending from the bomb position and the corner points of the polygon are called the blast lines.

The algorithm consecutively considers each agent as a target, and checks if any other agent is interfering with it from the blast point. A blocker is referred to as a *full blocker* if its' four-sided polygon intersects the line of sight between the explosion and the target agent. An agent is referred to ask a *Partial* Blocker if it is not a full blocker, but its' four-sided polygon intrudes into the blast cone. To check if an agent is intruding into the blast cone, first the smallest distance between the line of sight and the blast lines from the position point of the agent and the explosion is calculated. If this distance is less than half of the width of the agent, the line crosses the body plane between the polygon sides and the agent is considered a blocker. If the line is the line of sight, the agent is a full blocker and if the line is only one of the blast lines, it is a partial blocker. If the smallest distance from each of the lines obtained is greater than half the width of the agents then it is not a blocker at all.

To check if an agent is intruding into the blast cone, first we find the smallest distance between the line of sight and the blast lines from the position point of the agent and the bomb. If this distance is less than half of the width of the agent, the line apparently crosses the body plane between the polygon sides and the agent will be considered as a blocker. If the line is the line of sight, it will be the full blocker and if the line is one of the blast lines, it will be considered as a partial blocker. If the smallest distance from each of the lines obtained is greater than half of the width the agent it is not a blocker.

If an agent is a partial blocker, the percentage of blockage can also be determined. This is done by constructing additional lines that extend between the target agent body plane in the polygon area and the point of explosion. The percentage of lines crossing the body plane between the sides of the polygon is used as the percentage of the partial blockage, as shown in Figure 7.

7. Suicide Bombing Database

As part of this research we have compiled a real-life bombing and injuries database from the actual records of the suicide bombing incidents in Pakistan from November 15, 1995 to April 18, 2009. During that time there was a total of 169 suicide bombing incidents in 42 cities of Pakistan that left 2,327 dead and 5,410 injured. This study compiled the records of the patients in most of these attacks from the hospitals, which include patients' medico-legal reports, X-Rays, ECGs, PSTD profiles, injury types and characteristics. The database also contains blast characteristics (explosive type, weight, shape, fragmentation signatures, and temperature of the day), crowd characteristics (crowd density, gender, age ratio, weight, and the distance from the bomber with +- 2 feet of error). To the best of our knowledge, this database is the first of its' kind one of its kinds in the blast research on human body.

8. Simulation Tool Development

The simulation is being programmed in Visual C#. Visual C# was utilized due to its extensive library of graphics and geometry functions (to generate the Cartesian grid with agents). The explosive range is determined by the explosive weight. By using the scaling law as described in Eq. 1, and the TNT overpressure versus scaled distance data of Figure 3 and 4, it is easy to calculate the exact overpressure received by each agent at particular locations given the weight and type of explosive. Specific simulation inputs are the number of individuals and bombers in the vicinity, explosive characteristics (type, weight, fragmentation etc.), and crowd formation (topology, gender, height, width, weight etc). Additionally the arrival time of the explosive pressure front to travel from the point of explosion to any given location may also be calculated.

The work has only considered primary and direct injuries. Persons who are directly in the line-of-sight with an explosion will absorb the effects, and thus act as a shield for person(s) behind them. Direct injuries mean injuries caused by the bomb's blast wave overpressure during the explosion, and not by fire or debris (pieces of furniture or glass). The simulation has, however, incorporated the effects of stampede. Stampede usually occurs when a large number of people start running towards the same direction and surpass the capacity of flow from that particular channel.

The work has also considered mostly "open space" scenarios to serve as the basis for our crowd formation types (e.g., mosques, streets, concerts etc.). The types of injury caused by overpressure depend on whether overpressure occurs in open air or within buildings. In the later case the type of injuries also depends on whether the explosion causes collapse of a building or other structure. There are numerous objects to consider in closed environments that can either increase the casualty/injury toll (primarily by working as flying debris) or decrease the toll by providing a shield to humans. Closed environments also need to entertain reflection waves. A blast wave can amplify in closed environments by reflection and reduced ventilation. Ventilation, reflection waves, and non-human objects are out of scope of this work.

There are two types of formations user can choose from – random formations and user created scenarios, like circles, zigzags, rectangular etc to represent real-life settings like cafeteria, mosques, concerts etc. – to estimate the outcome of an attack for a particular crowd formation. Figure 8 shows few examples of crowd formations, and Figure 9 shows the display after the blast is simulated.

The simulation takes care of beam and line-of-sight adjustments in cases of uneven surfaces (e.g., concert stage, mosque or shopping mall). To date, this work has not considered physical objects (like walls, trees, furniture etc.) as obstacles, or a means to harm people. A 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 a zigzag formation) on the entrance or exit gate was based upon recent attacks in Iraq, Israel and Pakistan where suicide bombers detonated their bombs at the gates of mosques and restaurants (Johnson, 2005).

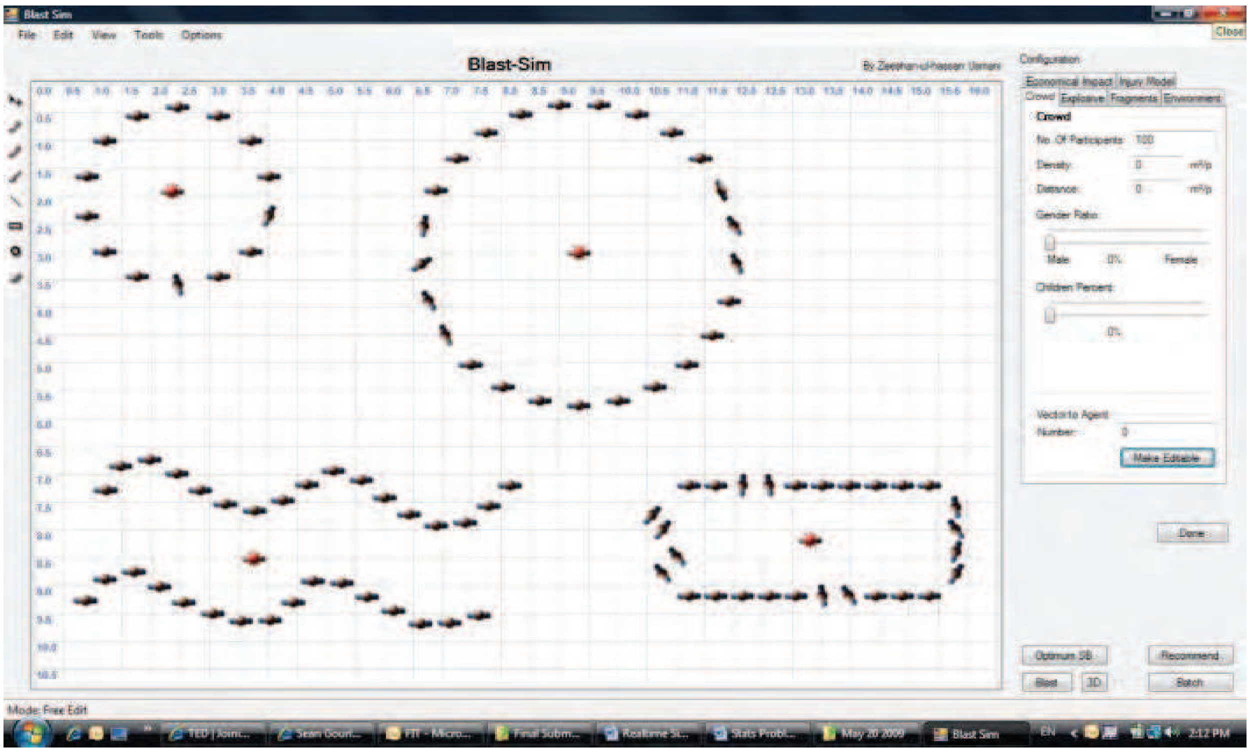


Fig. 8. An example of possible formations like circle, zigzag, and rectangular

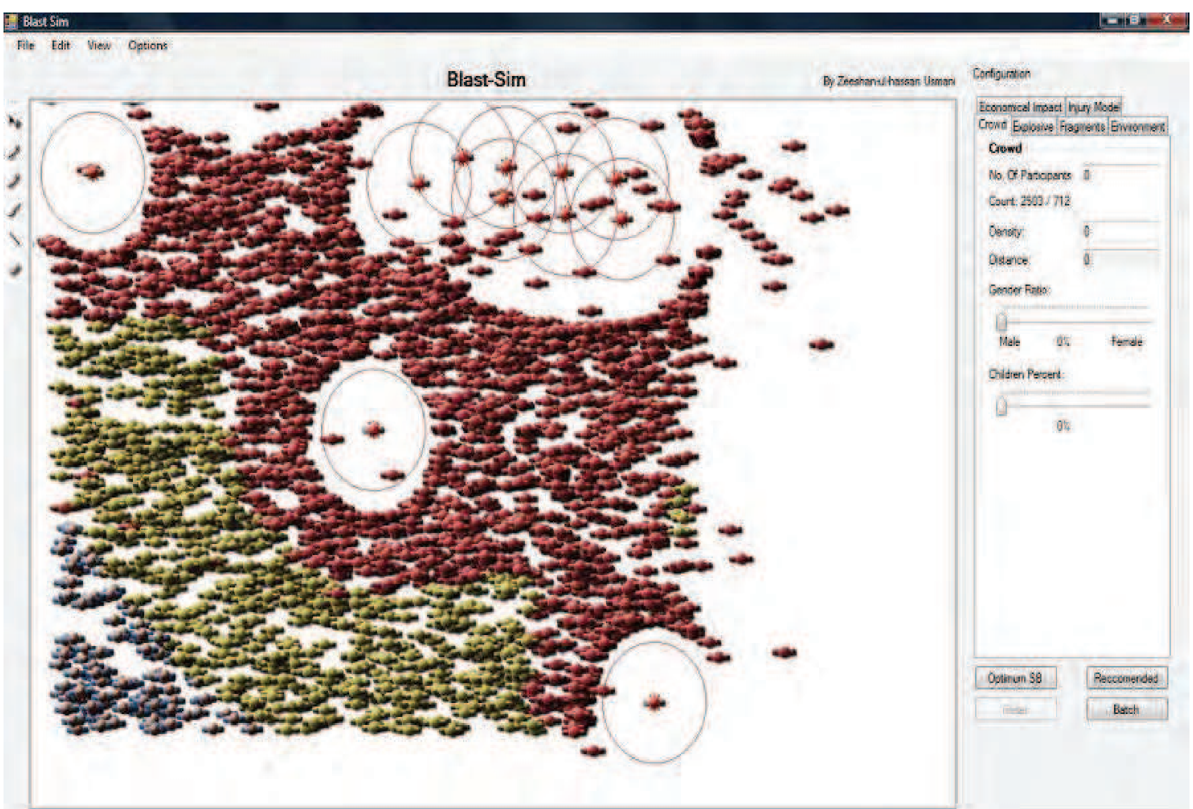


Fig. 9. Simulation screen after the blast

The simulation display depicts casualties by red colored icons, injuries in green colored icons, and unharmed individuals in blue colored icons. Thus, there are three states of victims after the blast: dead, injured and unharmed (but in panic and contributing to stampede).

The simulation can run in three different models, as presented in Table 2:

Models	Description
Model 1 (M1)	Basic simulation of a blast wave without blockage (full or partial) in 2 dimensions.
Model 2 (M2)	Simulation with full and partial blockage in 2 dimensions
Model 3 (M3)	Full simulation with partial and full blockage in 3 dimensions (incorporating the height and width of the agents).

Table 2. Models Description

9. Results and Validation

The average case scenario has been simulated for all of the models (M1, M2, and M3). The weight of the explosives used in the simulation ranged from 1 to 30 lbs. The number of participants ranged from 20 to 100 and the pulse duration ranged from 0.5 milliseconds to 2 milliseconds. The simulation was also performed for bigger crowds ranging from 500 to 1000 participants. The overall impact of a blast on participants stabilized as the number of participants increased, as shown in Figure 10. For example, the average number of participants in the lethal zone was 11, with 20 total participants (55%), and 185 with 500 total participants (37%). These findings are consistent with Moshe Kress findings (Kress, 2004).

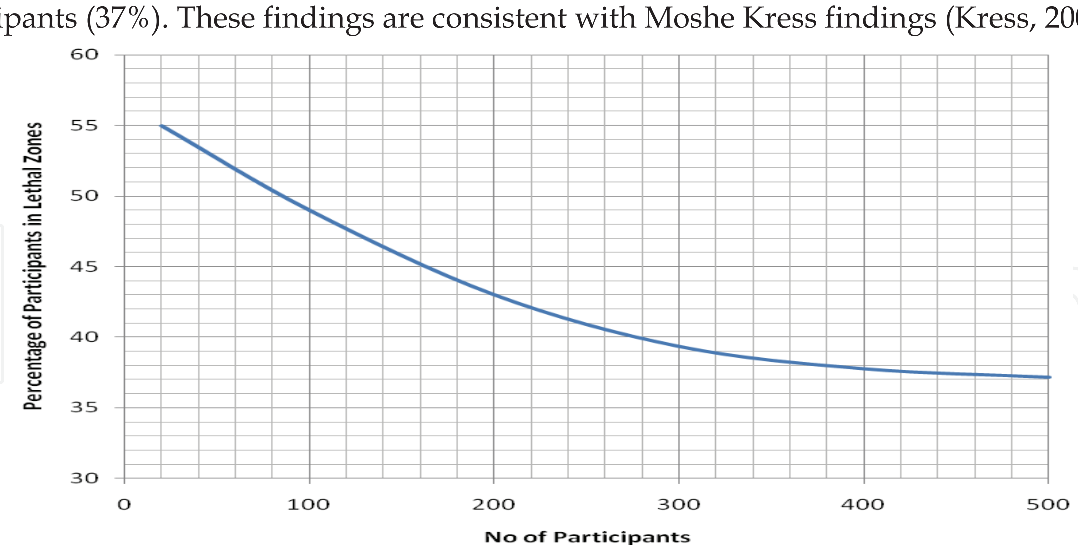


Fig. 10. Percentage of participants killed in the lethal zone vs. number of participants in the lethal zone. For this example, the bomber is carrying 30 lbs of TNT, which corresponds to a lethality radius (without blockage) of 37.5 feet. The results are based on 200 simulations with random crowd distributions.

The simulation was performed for different example crowd formations with the same number of participants and weight of explosives. The height, weight and the number of participants were exactly the same for each run for all three models. Figure 11 shows the average results of 200 simulation runs for each crowd formation with different explosive mass, pulse duration and number of participants. The expected output for the model M1 was an upper bound or least conservative, since there is no blockage available to people in the crowd, so the model should report more injuries and deaths. For M2 the expected output was a lower bound of the results or most conservative, since in two-dimensions anyone in the line-of-sight can provide blockage, thus minimizing the impact of blast wave overpressure to the people behind the shields. While the expectations for the model M3 results were in between M1 and M2, it should be lower than M1 since it is providing blockage shields to the crowd and it should be greater than M2 due to its three-dimensional capabilities. For example, a child standing in front of an adult person in 2D simulation can provide the full blockage while he will be providing only partial blockage in 3D simulation model.

Figure 11 summarizes the findings of the percentages of the people in the lethal and injury zones with given crowd formations. Each set of three bars in Figure 11 represents a crowd formation. It is clear to see that model M2 with blockers results in a fewer number of dead and injured people than M1 (without blockers), while M3 has the higher number of death and injuries as compared to M2. M3 is more realistic due to its three-dimensional capabilities. The simulation was also performed using 40 and 50 lbs of explosives (though it is uncommon to see a pedestrian suicide bombing attack of that magnitude). The relationship between the increase in the percentage of casualties and injuries with the amount of explosive is observed to be piecewise linear. This relationship is logical since augmenting the explosive material will increase the overpressure pounds per square inch (psi) in the vicinity.

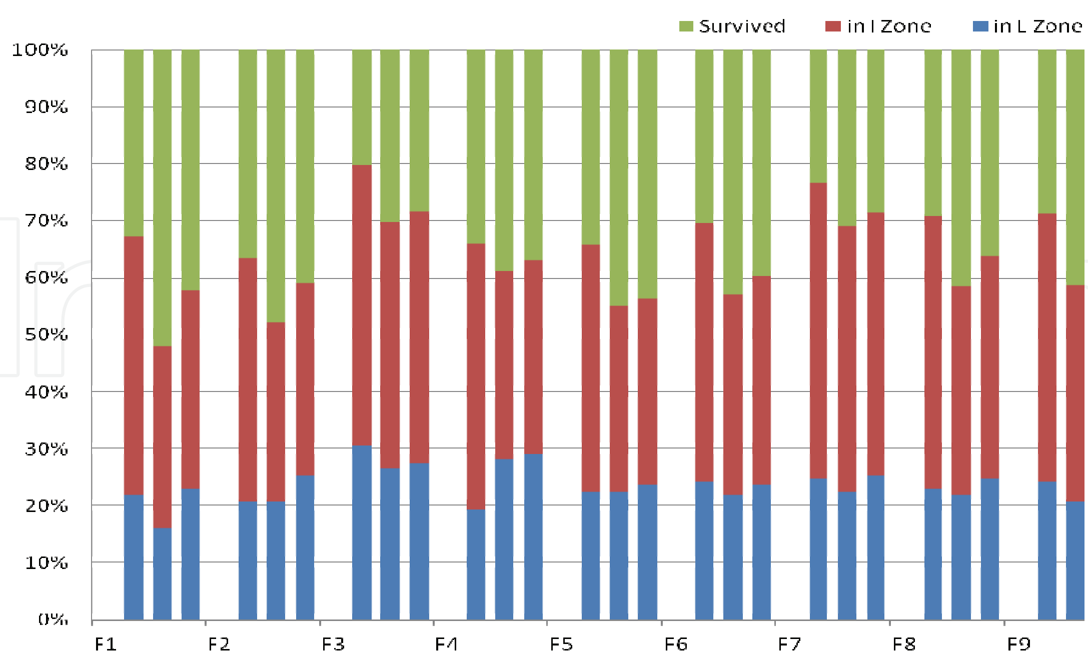


Fig. 11. Casualties and crowd formations

The average deadliest crowd formation for casualties was found to be the zigzag scenario, where 30% of participants were in the lethal zone and 45% in the injury zone. Row wise crowd formations were found to be the best for reducing the effectiveness of an attack, with on average 18% of the crowd in the lethal zone and 38% in the injury zone. Thus by only changing the way a crowd forms, one can reduce deaths by 12% and injuries by 7%, on average. This is really useful where one has control to form the crowd, like in airports by placing them in queues. One of the reasons for the dramatic change in casualties is that in row wise formations there are fewer people in the direct line-of-sight with the bomber and more people also provide the blockage to others.

To validate our results and to see how close they are with real-life incidents, the results were compared against a database of every single suicide bombing attack in Pakistan from 2000 to 2009 that fits the open-scenario criterion (Johnson, 2005). Figure 12 shows a comparison of the average number of persons killed and injured in all of the simulation runs against the suicide bombing attacks in Pakistan. The real-life averages come from mostly open-space scenarios with a single pedestrian suicide bomber. For the sake of consistency, the database excluded the suicide bombing attacks in close environments like buses or with multiple suicide bombers, or ones carried out with the help of an automobile.

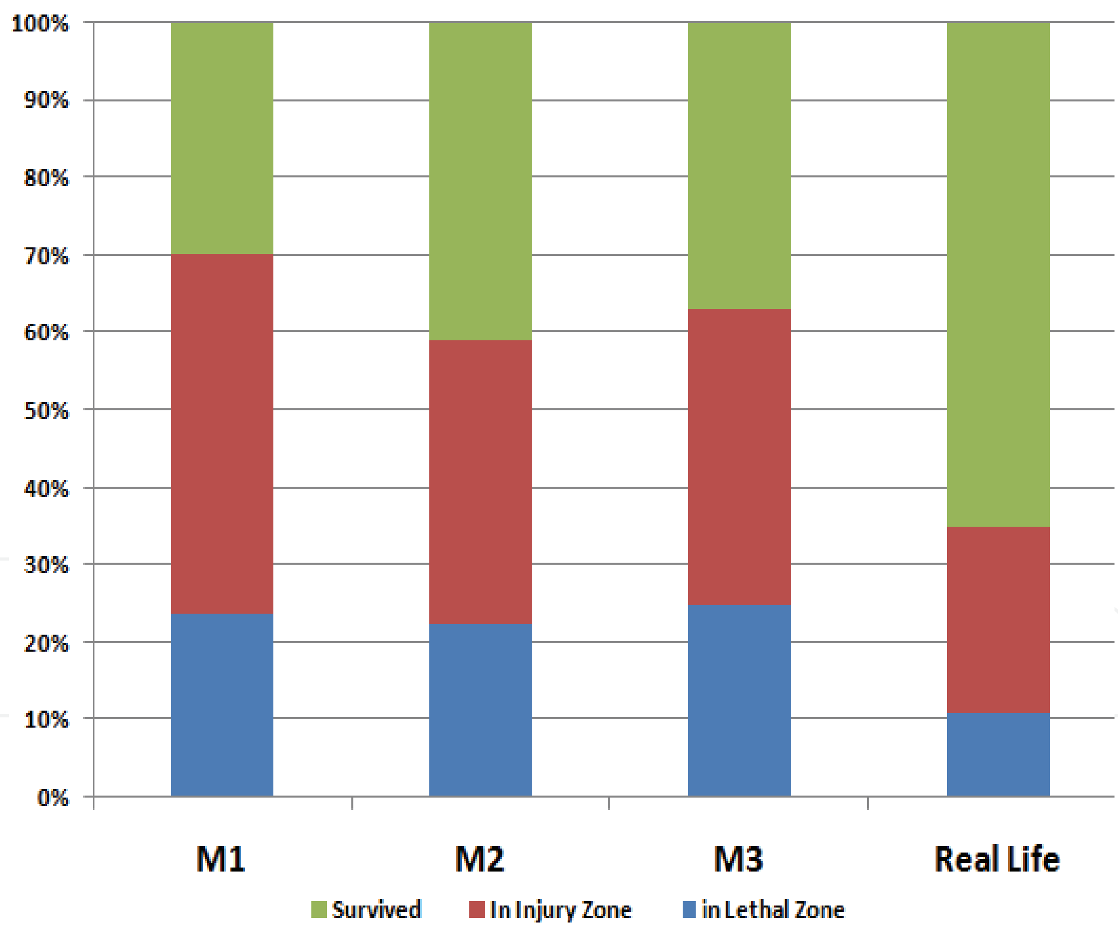
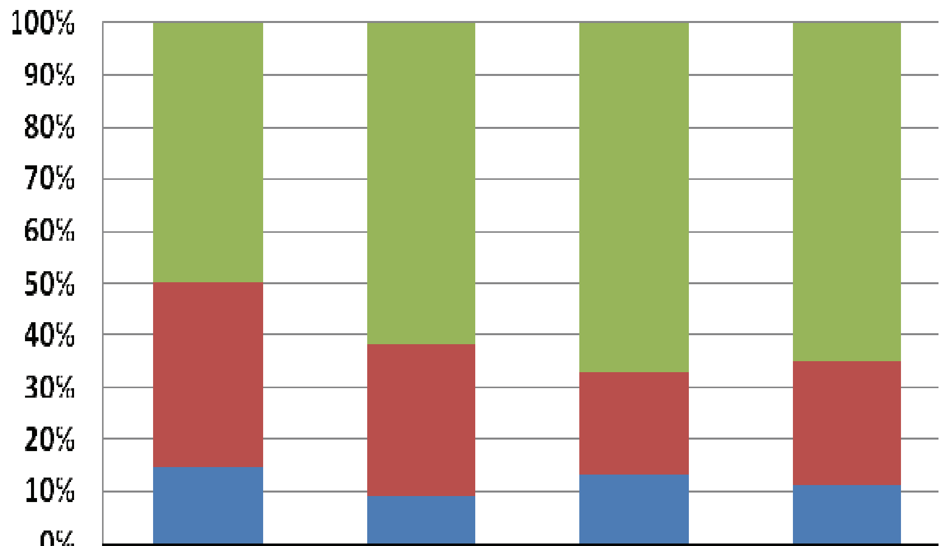


Fig. 12. Models comparison with the real-life database of suicide bombing incidents in Pakistan

Clearly, the model M3 with blockers is more close to real-life results than M1 with no blockers and M2 of blockers in 2D. The average injury per fatality ratio in real-life incidents is 2.18, that is, for every dead person there are 2.18 injured people. The number is pretty much consistent in the history of the modern world, where there are 2.6 injuries per fatality in Vietnam War, 2.8 in the Korean War, 1.8 in the World War I, and 1.6 in the World War II. Simulation models, on the other hand, had produced 1.9 injuries per fatality in M1, 1.6 for M2, and 1.54 for M3. This can be explained as follows: First the current simulation does not count for secondary and tertiary blast injuries by fire, debris, fragmentation and shrapnel. Second, the current simulation only accounts for TNT explosive, while in the real-life instances there are quite a few mixtures of explosives being used. As examples, note an RDX and TNT mixture in the recent suicide bombing attack in Pakistan that claimed the life of former Prime Minister Benazir Bhutto, and the mixture of Ammonium Nitrate and RDX in Oklahoma City bombings. Third, the simulation is not giving the exact number of dead and injured people; instead it is gives the number of people in the lethal and injury zones based on their probabilities of death and injury. For example, a person in lethal zone 3 with 1% chances of being dead is most likely to be injured and not dead, similarly a person in Injury zone 3 with 20 PSI can be unharmed.



	M1%	M2%	M3%	Real Life %
Survived	50	62	67	65
Injiury Zone	35	29	20	24
Lethal Zone	15	9	13	11

Fig. 13. Model comparison with injury and lethal levels 1

There are demographical, environmental and physical characteristics as well, that play an important role in the overall toll. For example, an infant next to a fire cracker can die while a muscular six and half foot person with 250 lbs of weight can survive a 1 pound TNT explosion. The simulation yields more realistic results with the incorporation of non-human shields, reflection waves, secondary and tertiary blast injuries and physical characteristics. However, simulation at current stage can provide a good upper bound, lower bound, and

medium estimates of the number of dead and injured for emergency preparedness, triage of patients, and the required number of medical and ambulance facilities for such an event.
The simulation was performed against the real-life results with persons only in Lethal Zone 1 (99% probability of death) and Injury Zone 1 (60 PSI). These models will be referred to as optimized models from the point forward. Figure 13 portrays the findings of this comparison.

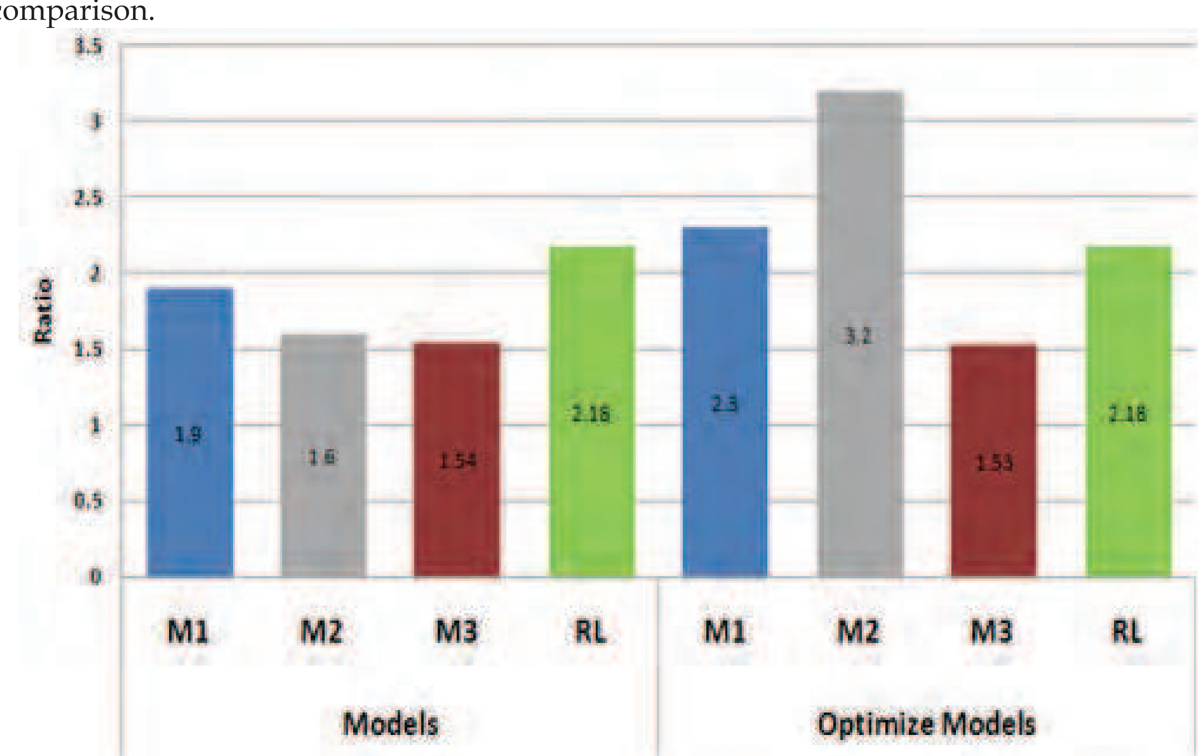


Fig. 14. Injury per fatality ratios

Figure 14 shows a comparison of injury per fatality count. Here models have provided 2.3 injuries per fatality in M1, 3.2 for M2 and 1.53 for M3. The number of deaths is higher in M1, lower in M2, and more close to real life in M3.
The results are in good agreement for the death count but are off slightly for injury counts. Beside the aforementioned reasons, one of the reasons for this difference can be totally political, where governments tend to show the manipulated figures to minimize the aftereffects (for example, riots, revenge etc) by victim supporters or a huge outcry in the home state. For example, 4,000 soldiers have been killed in Iraq so far since the invasion of the country by US forces in October 2003. Media have only concentrate on the dead, while little has known about the more than 250,000 injured soldiers. An injured soldier costs at least three times more than a dead soldier economically to the country, according to one estimate the cost is 10.1 million dollar for injured, and 3.7 million dollar for a dead soldier (Stiglitz, 2008). The government has to pay disability and social security allowances, and it is a loss of one worker from the labor force. Thus a loss of one statistical value of life, and the injured also need a caretaker, therefore another loss of the statistical value of life. According to the recent work by the authors, the cost of human life only for US soldiers in the Iraq comes to 14.8 billion dollar (Usmani b *et. al.*, 2009), readers are referred to the authors website www.FindMyWorth.com for further information. Given the current geo-political

conditions of the world and the US ongoing war in Iraq and Afghanistan, it is more necessary than ever to examine and employed the technologies to reduce the rate of injured and dead. Another reason for the gap in the number of injured might be the level of injuries – a victim who has a minor injury and was able to walk may not have been included in the actual count of the injuries in the real life events.

The sensitive analysis for all of the models was also performed. M1 or the basic model results are the same as M2 2D model without blockage. And the M2 2D models without blockage results are similar to the results of M3 3D model without blockage. The results suggest using the M1 basic model if there is no need to consider the blockage. M1 can also give an upper bound of body count. If blockage has to be considered, the results suggest using M2 2D model, since the M3 3D models contribution is statistically insignificant if only considering the blockage in the crowd. On the other hand, 3D demands more computational power and resources. M3 3D should be used when there is a need of blockage with uneven surfaces like stages or stadiums, and when the user has to work on bomb fragments, shrapnel, projectiles, and secondary and tertiary blast injuries. The 3D model is more realistic when used with the majority of blast characteristics. For the simple estimates M2 2D model is as good as 3D, while the M1 basic model can be used for quick estimation of the required number of medical and emergency management facilities.

Announcing the threat of suicide bombing in the crowd can only make the condition and the causality 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 a bomber in the majority of cases), and there will be high chances of a stampede.

10. Conclusion and Future Work

There are a number of lessons one can learn from the analysis of this suicide bombing simulation. For example, one can reduce the number of fatalities by 12% and the number of injuries by 7% by switching the crowd formation from zigzag to row-wise formation styles. Doing this reduces the minimum average distance of each person in the crowd with the bomber. For example, a blast may yield more casualties in a heavily dense crowd with fewer people than a least dense crowd with more people. The topological impact highly depends on the minimum average distance of a person from the bomber in near-field scenarios. Blockage can only play a minimum role when a person is close enough to the bomber with respect to explosive characteristics. To avoid a stampede in possible crowd formations, one could arrange more exit points than normally available. Suggestions can also be made for architectural design changes in the buildings to reduce the count. For example by placing entrance and exit gates X feet away from the main venue, victims can be reduced by Y% (the values depends on environment, crowd information and the weight of explosive). The results can also help planning for post-disaster management. For example, how many ambulances and doctors one will need if something like this should happens to a given crowd or how to direct the crowd to behave or run towards particular exits by announcing it through loudspeakers. In the light of these findings, the crowd can be manipulated in real-life by imposing formation guidelines like queues at the airport or by placing chairs in particular orders that will block the line-of-sight with of any perspective attacker.

There is an acute shortage of accurate data for many other variables and conditions that are pertinent to such an attacks (e.g. was a bomber running or standing? Carrying methods for the explosive, Weight of the explosive). It makes it difficult to validate the numbers of the simulation results with actual events. Also the simulation assumed continuous uniform distribution for the people, which is the least preferred distribution, but realistic in this case due to unknown real distribution). If that assumption is eliminated, it will have very little effect on the overall simulation results since the simulation is only calculating the blast overpressure (at this stage) from the origin of the explosion to the agent. In any case the agent will receive overpressure proportional to its distance from the bomber.
The simulation and findings are limited in that they only incorporate primary injuries. Future plans are to add secondary effects (e.g., injuries by fire, debris, etc.) so as better approximate the real world environment and provide more valid comparisons with the data of suicide bombing attack aftermaths (Usmani a, 2009). The flexibility to create a user defined crowd formation with variable number of entrances and exits will be added 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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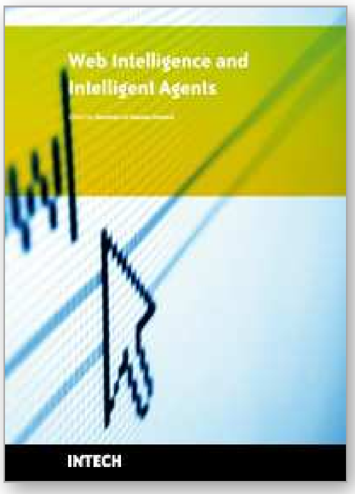

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