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Modeling and Simulation of Explosion Effectiveness as a Function of Blast and Crowd Characteristics

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Abstract

Explosions in civil settings are becoming the daily news. While various explosive simulations and models have been developed for battlefield and industrial settings, much less has been done for civil settings and urban terrains. This paper presents the science of suicide bombing and explains the physics, explosive models, mathematics, and the assumptions we need to create such a simulation. The proposed simulation tool 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 indicate that the worst crowd formation is a street (zigzag) where 30% of the crowd can be dead and 45% can be injured, given the 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% of the crowd in the lethal zone and 38% in the injury zone. Crowd blockage and densities can reduce the fatalities by 12% and injuries by 7%. Simulation results were compared and validated by real-life incidents and found to be in good agreement. These findings, although preliminary, may have implications for emergency response and counter terrorism.

Keywords

simulation and modeling of explosions, human blockage, suicide bombing, terrain simulation, emergency management, risk analysis

1. Introduction

Suicide bombing is an operational method in which the very act of the attack is dependent upon the death of the perpetrator.[1] Though only 3% of all terrorist attacks around the world can be classified as suicide bombing attacks, these account for 48% of the casualties.[1] Explosions and suicide bombings have become the modus operandi of terrorist organizations throughout the world. 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, on 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 11 September 2001) 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.[2] In Israel, from November 2000 to November 2003, the average number of deaths per incident was 31.4.[3] From 2006 to 2007 the average number of deaths in Pakistan was 14.2.[4] 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

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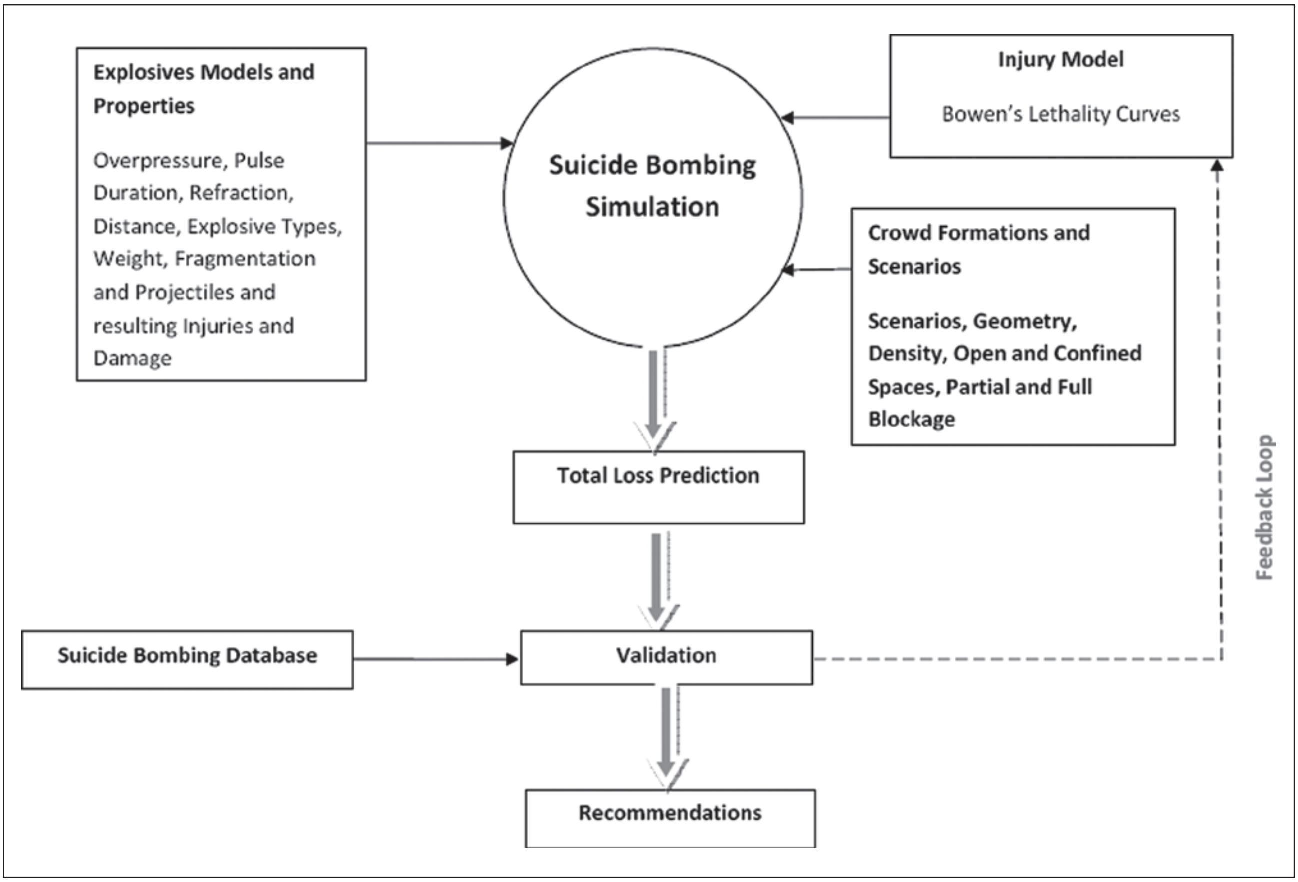


Figure 1. Components of the suicide bombing model: (1) explosion modeling, (2) quantification of crowd formation, (3) model to predict casualty and injury level, and (4) database for model validation

inexpensive to fund and technologically primitive, as improvised explosive devices (IEDs) can be readily constructed.

Past research has focused on developing psychological profiles of suicide bombers, understanding the economical logic behind the attacks,[2,3,5] explaining the strategic and political gains of these attacks, their role in destabilizing countries,[6,7] and the role of bystanders in reducing the casualties of suicide bombing attacks.[3,8] 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 two-dimensional (2D) and three-dimensional (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 to find 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.

2. Modeling Overview

The 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 turnkey solution for emergency response management, casualty prediction, and classification of injuries, and provides 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.

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 resulting 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

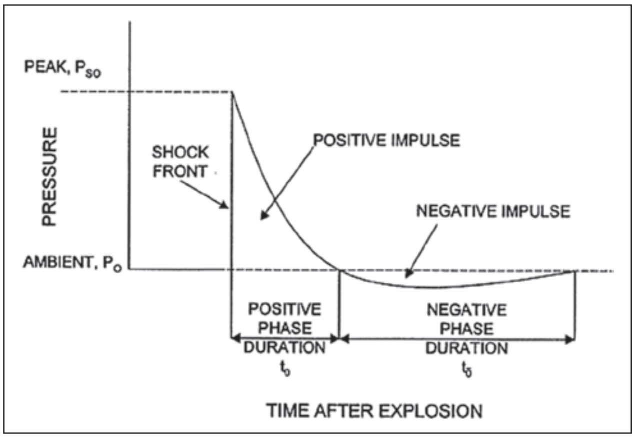


Figure 2. Blast wave showing positive and negative phase durations. Such waves may be characterized by the peak overpressure and duration of the positive phase

(milliseconds), 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, and 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 among 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 the required characteristics of a good model.

3. 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.[9,10] Although the physics of blast waves is 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 overpressurization phase, thus increasing the total energy transmitted by the explosion.

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.[11] 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 of blast-related injuries have shown that the peak overpressure and the duration of the positive phase, which correlate to the overall impulse, both 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.[11,12] 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 a 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 at some appreciable distance from the center of the explosion – around five charge diameters.

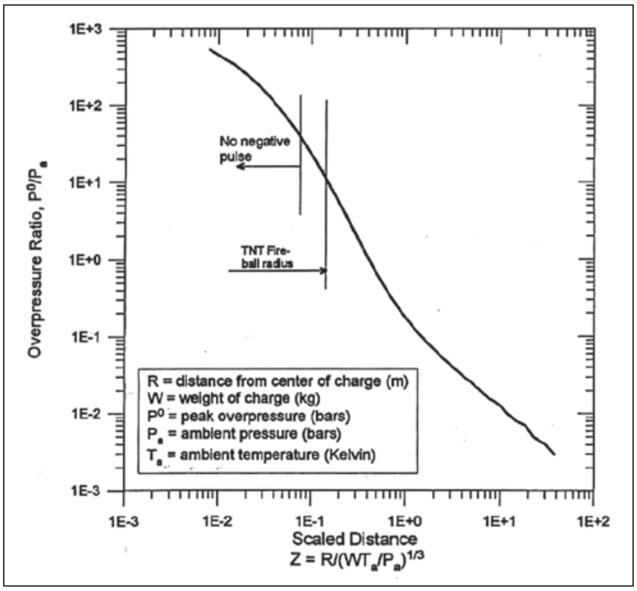


Figure 3. Peak overpressure ratio versus scaled distance, adopted from Kinney and Graham[11]

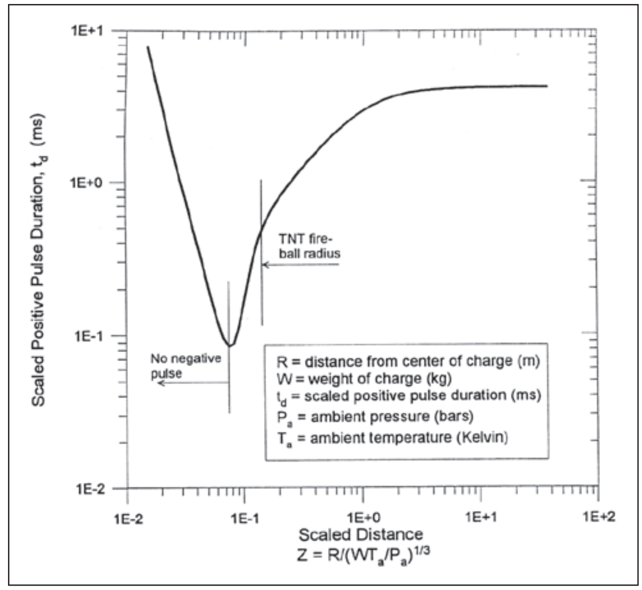


Figure 4. Scaled positive pulse duration versus scaled distance, adopted from Kinney and Graham[11]

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.

The data depicted in Figures 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,[12] which also allows for compensation in different atmospheric pressures (P_a) and temperatures (T_a):

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

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.[12] 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[12]

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

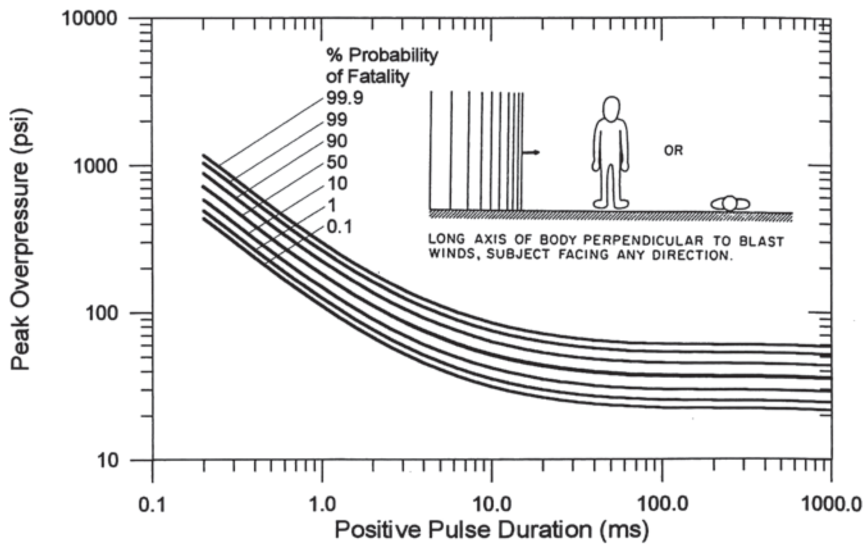


Figure 5. Fatality curves as a function of blast wave peak overpressure and positive pulse duration[12]

where p is the instantaneous overpressure at time t, p_0 is 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.

4. Injury Model

In order to tie together the influence of peak overpressure and duration on 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-stream 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 are caused as the direct result of pressure waves impacting and traveling through the body; they include rupture of tympanic membranes, pulmonary damage, and rupture of hollow viscera. Secondary injuries result from flying debris that damages the body; they include penetrating trauma and fragmentation injuries. Tertiary blast injuries result from the victim's body being thrown by blast wind, and then impacting a stationary object; they include crushing injuries and blunt trauma, penetrating or blunt trauma, fractures, and traumatic amputations. And, miscellaneous blast injuries are caused by flame and chemicals that include burns, asphyxia, and exposure to toxic inhalants

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 the crowd formation. Large trucks typically contain 25,000 pounds or more of TNT equivalent, and vans typically contain 5000 to 25,000 pounds. Small automobiles can contain 50 to 5000 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.[13]

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 lethal 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 refers to more than 20 and less than 40 PSI overpressure. In general,

Table 1. Full and partial blockers' impact

Lethal zones	Non-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

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 kidneys 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.[9]

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).

5. 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 foot 10 inch person, or persons standing next to one 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.*

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 that 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 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 a full blocker. Otherwise, if it intersects 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).

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 polygon 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 as a *partial blocker* if it is not a full blocker, but its four-sided

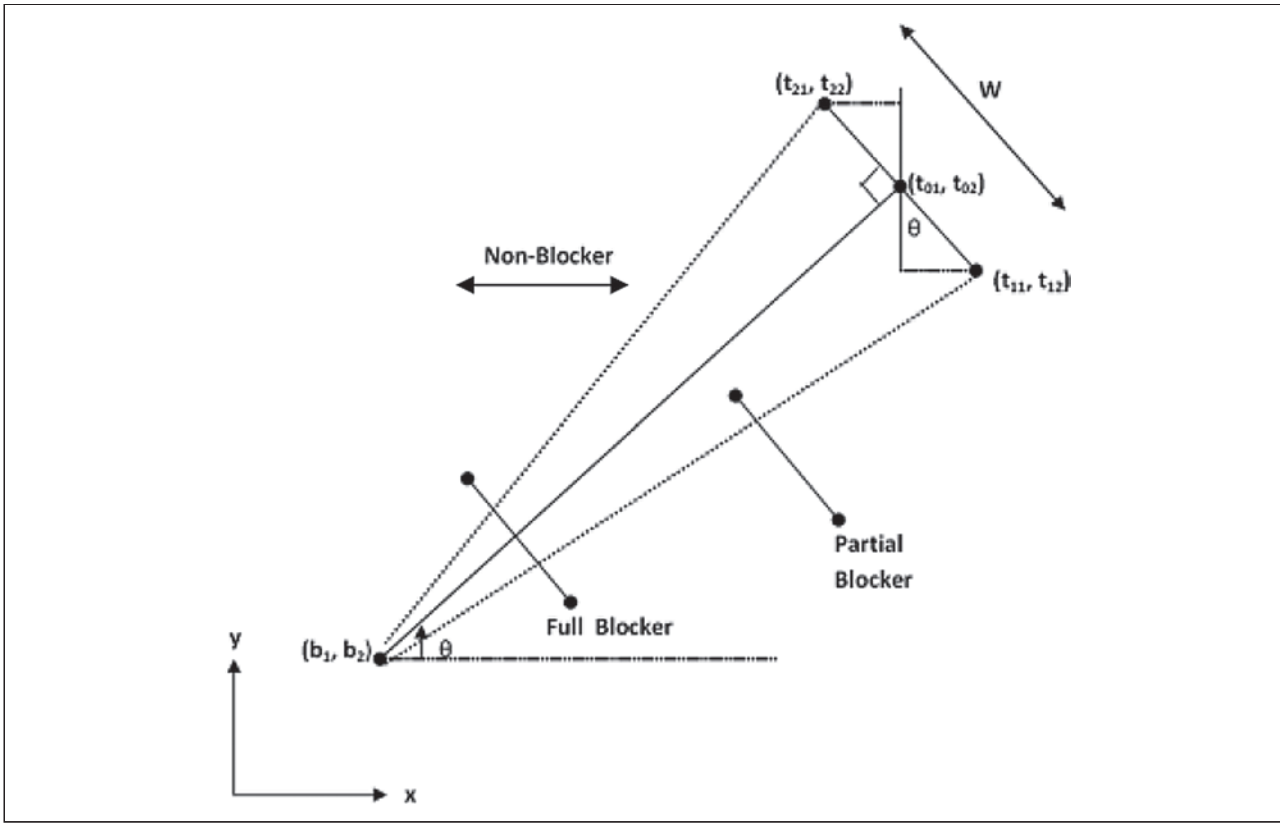


Figure 6. Full, partial, and non-blockers in 2D

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 agent, 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 of 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.

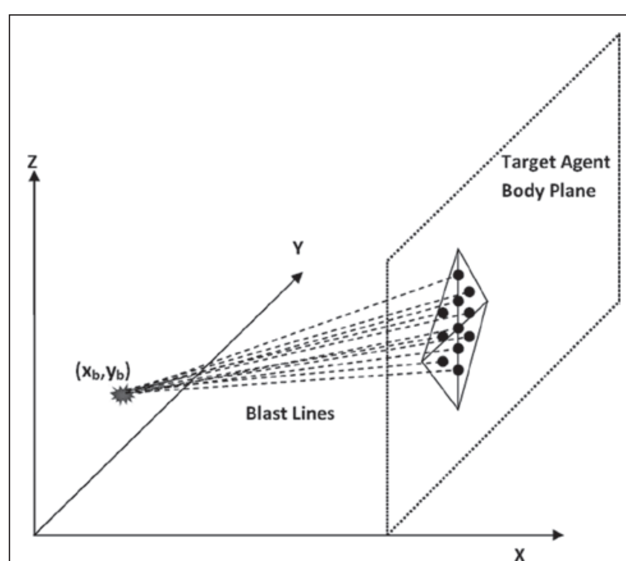


Figure 7. Percentage of partial blocking in 3D

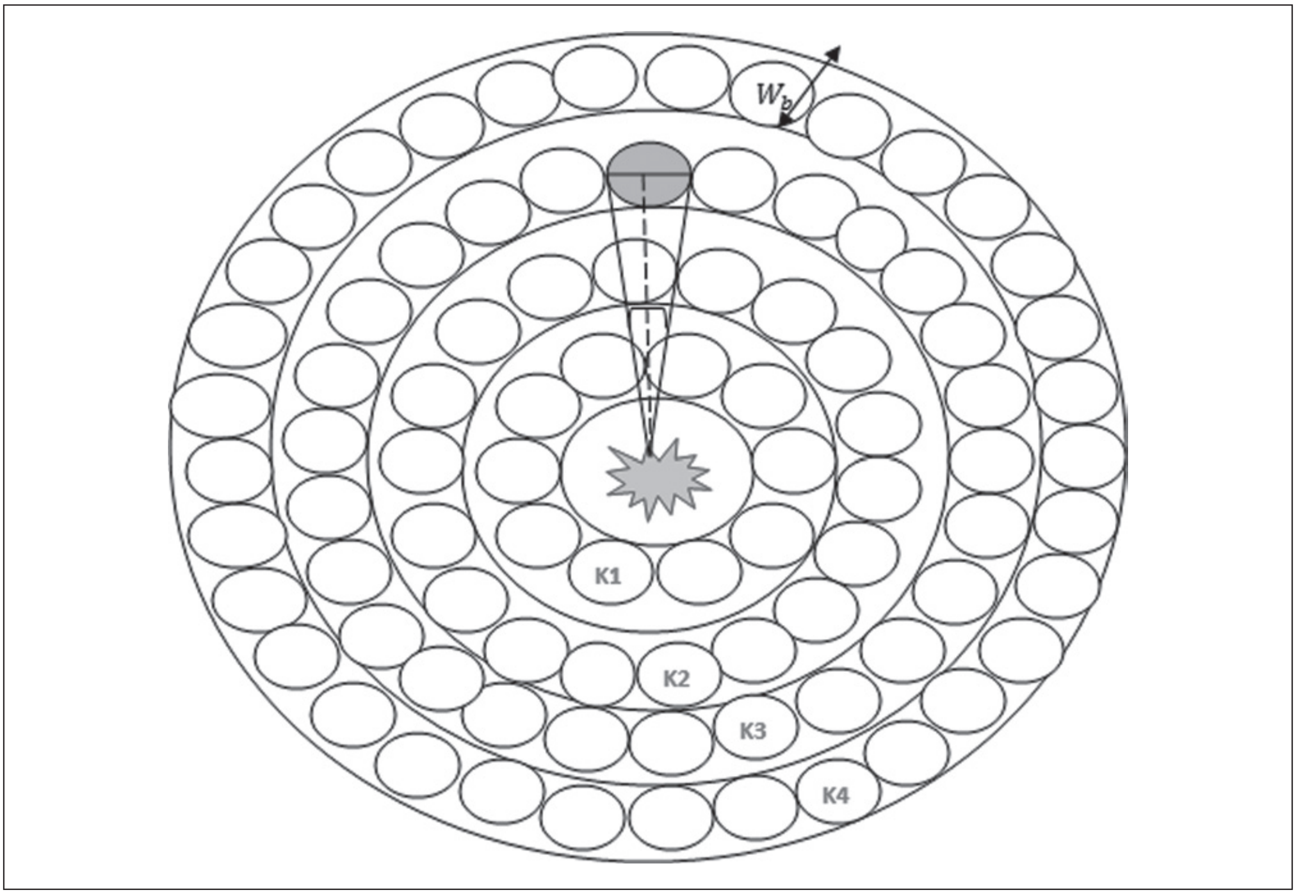


Figure 8. Agents in a situation with a bomber and blockers

6. 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 15 November 1995 to 18 April 2009. During that time there were a total of 169 suicide bombing incidents in 42 cities of Pakistan that left 2327 dead and 5410 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, and 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 in blast research on the human body.

7. Statistical Analysis of Suicide Bombing Attacks

We can perform the proposed Monte Carlo simulation for any given topology and event with blast and crowd characteristics. In this section we have performed statistical analysis for the expectation of our results and to find how many agents and/or simulation runs we will need to have good results with a higher level of confidence.

The probability of an agent being a blocker if dropped randomly in the arena can be calculated by the following method; the hypothetical situation is illustrated by Figure 8.

1. Let W_b be an average width of an agent and the radius of the arena be R.
=> Number of circles

$$N_c = floor\left(\frac{R}{W_b}\right)$$

where 'floor' rounds the entry to the nearest integer towards zero

2. To determine the maximum number of spots in each circle.
If a spot is in the Kth circle

$$A_0 = (k-1)W_b + \frac{W_b}{2} = \left(k - \frac{1}{2}\right)W_b$$

$$\theta_k = 2\tan^{-1}\left(\frac{\frac{W_b}{2}}{\left(k-\frac{1}{2}\right)W_b}\right)$$

$$\theta_k = 2\tan^{-1}\left(\frac{1}{2K-1}\right)$$

=> The number of spots in the Kth circle is

$$N_k = \frac{360^\circ}{\theta_k} \quad \text{=> Total number of spots} \quad N_s = \sum_{k=1}^{N_c} N_k$$

3. Probability of not being a blocker.
Assume that $N_A < N_S$ (number of agents is less than number of spots).
The probability that an agent thrown into the arena is not a blocker is the probability that no spot behind it is occupied or partially occupied.
Assuming a uniform distribution:
Probability of not being occupied is

$$P_{Not\ Occupied} = \frac{N_S - N_A}{N_S}$$

=> Probability of not being a blocker is

$$P_{Not\ Occupied} = \sum_{k=1}^{N_C} P_k\ x(P_{Not\ Occupied})^{N_{C-k}}$$

where P_k is the probability of being thrown into the kth circle, given by

$$P_k = \frac{N_k}{N_s} \tag{3}$$

Pseudo-code to find probability of a blocker:

1. Find $N_C = floor\left(\frac{R}{W_b}\right)$
2. Find $\theta_k = 2\tan^{-1}\left(\frac{1}{2k-1}\right)$ *for each* $k \le N_C$
3. Find $N_k = \frac{360^\circ}{\theta_k}$ *for each* $k \le N_C$
4. Find $N_S = \sum_{k=1}^{N_C} N_k$
5. Find $P_{Not\ Occupied} = \frac{N_S - N_A}{N_S}$
6. Find $P_k = \frac{N_k}{N_S}$ *for each* $k \le N_C$
7. Find $P_{Not\ Occupied} = \sum_{k=1}^{N_C} P_k x(P_{Not\ Occupied})^{N_{C-k}}$
8. Find $P_{Blocker} = 1 - P_{Not\ Blocker}$

We have also analyzed the statistical results with the simulation runs, as portrayed in Table 2.

As shown in the above table, the error margin of the random Monte Carlo simulation result reduces with the number of runs and the number of agents. Therefore, if the user wants to run the simulation with only five agents, he/she should run it at least 500 times to get results with an error margin of 0.003%; if the user has 250 or more agents, then 100 runs will be enough to yield results with the same confidence level.

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

Table 2. Comparison of expected statistical output with simulation runs

No. of agents	Stats	Simulation	Difference
50 runs			
5	0.96	0.95	0.01
10	0.89	0.84	0.05
50	0.712	0.75	0.038
100	0.536	0.55	0.014
250	0.284	0.3	0.016
500	0.155	0.15	0.005
Overall error margin			0.022166667
100 runs			
5	0.96	0.97	0.01
10	0.89	0.86	0.03
50	0.712	0.74	0.028
100	0.536	0.52	0.016
250	0.284	0.3	0.016
500	0.155	0.154	0.001
Overall error margin			0.016833333
250 runs			
5	0.96	0.967	0.007
10	0.89	0.87	0.02
50	0.712	0.73	0.018
100	0.536	0.53	0.006
250	0.284	0.29	0.006
500	0.155	0.154	0.001
Overall error margin			0.009666667
500 runs			
5	0.96	0.965	0.005
10	0.89	0.885	0.005
50	0.712	0.71	0.002
100	0.536	0.53	0.006
250	0.284	0.28	0.004
500	0.155	0.155	0.000000
Overall error margin			0.003666667

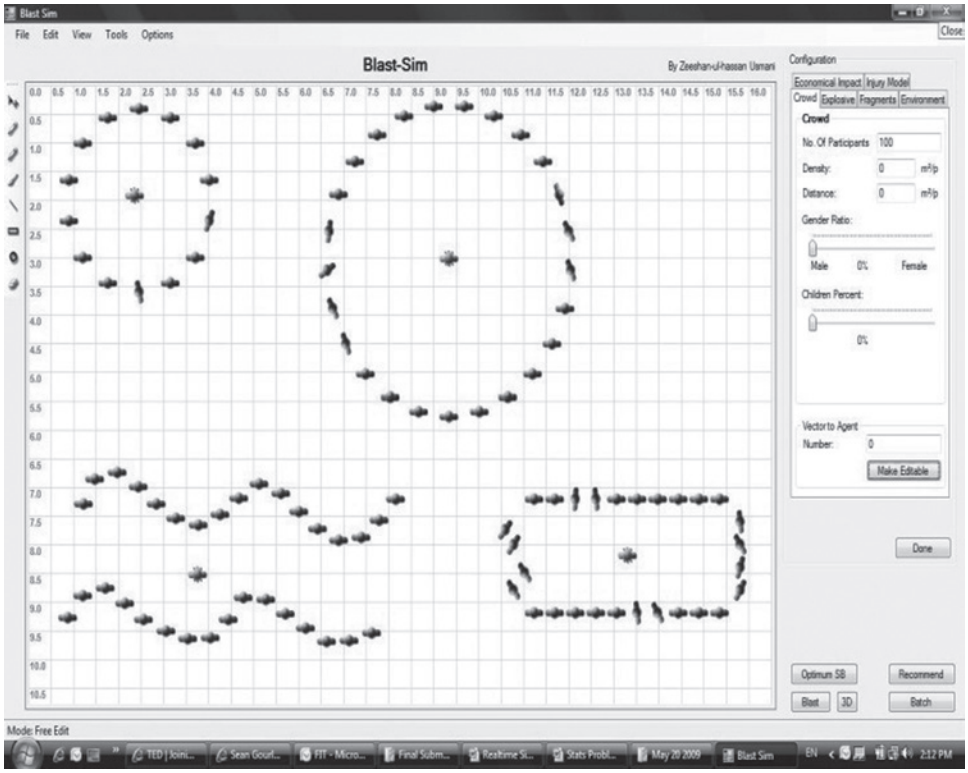


Figure 9. An example of possible formations like circle, zigzag, and rectangular

Equation (1), and the TNT overpressure versus scaled distance data of Figures 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 in 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 beyond the scope of this work.

There are two types of formations users can choose from – random formations and user-created scenarios, like circles, zigzags, rectangles, etc. to represent real-life settings like cafeterias, mosques, concerts, etc. – to estimate the outcome of an attack for a particular crowd formation. Figure 9 shows the selection menu for crowd formation styles, and Figure 10 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

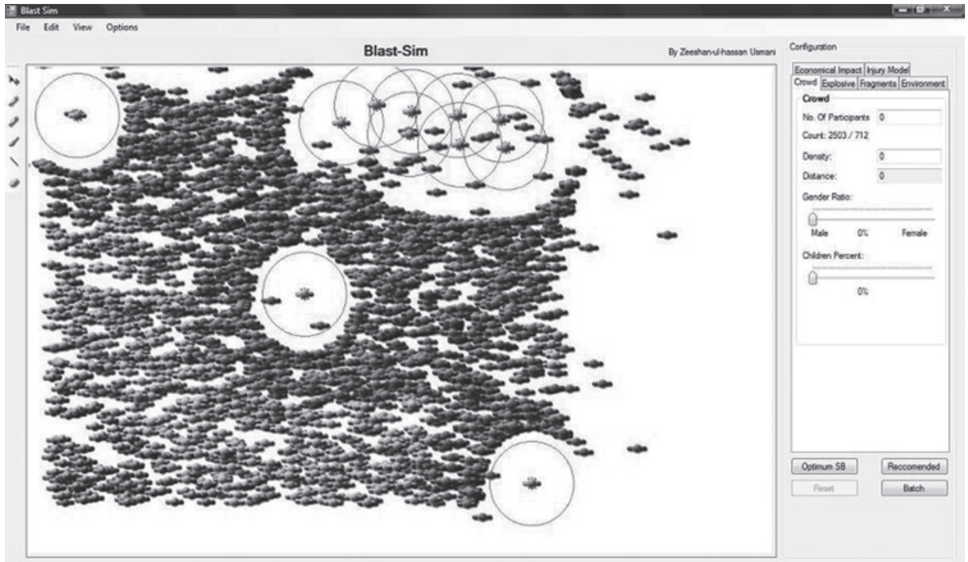


Figure 10. Simulation screen after the blast

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.[14]

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:

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

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 pounds. The number of participants ranged from 20 to 100 and the pulse duration ranged from 0.5 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 11. 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 Kress's findings.[8]

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 12 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 output 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 the 3D simulation model.

Figure 12 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 12

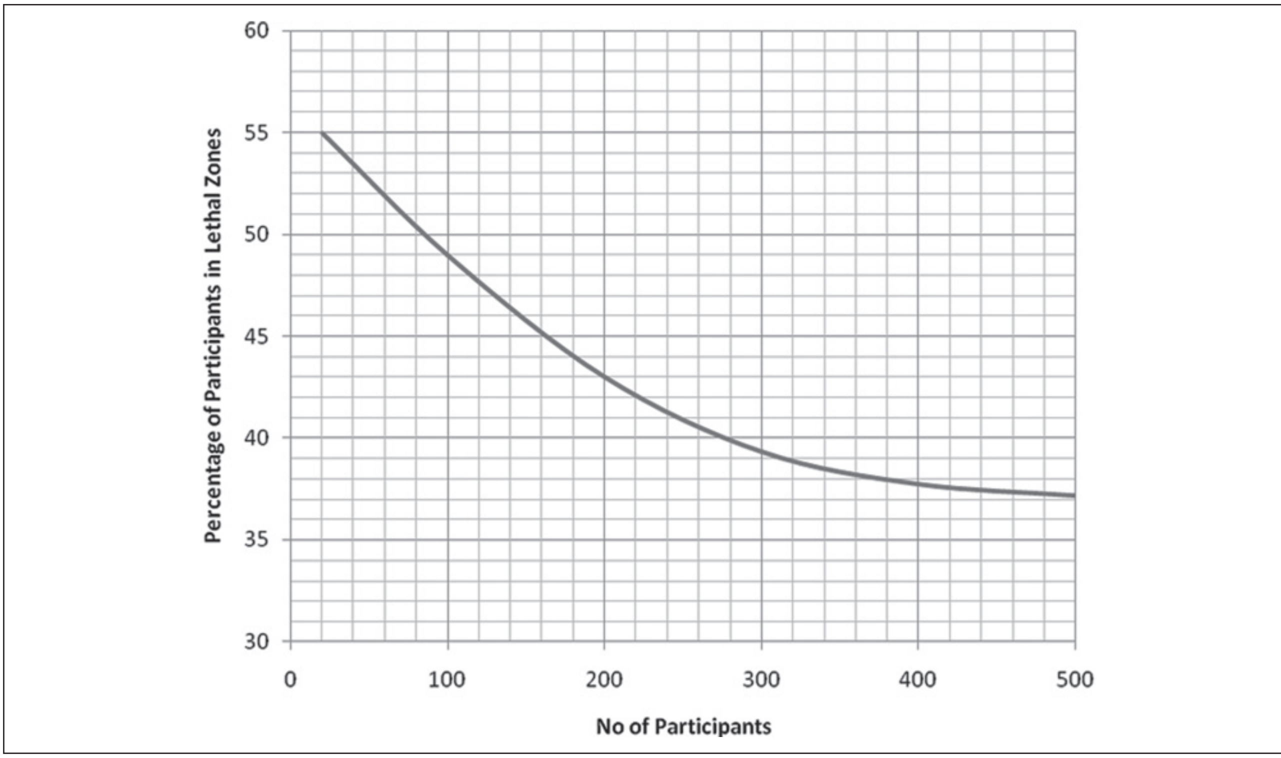


Figure 11. Percentage of participants killed in the lethal zone versus number of participants in the lethal zone. For this example, the bomber is carrying 30 pounds of TNT, which corresponds to a lethality radius (without blockage) of 37.5 feet. The results are based on 200 simulations with random crowd distributions

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 pounds 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.

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.[14] Figure 13 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.

Clearly, the model M3 with blockers is more close to real-life results than M1 with non- 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 the Vietnam War, 2.8 in the Korean War, 1.8 in World War I, and 1.6 in 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

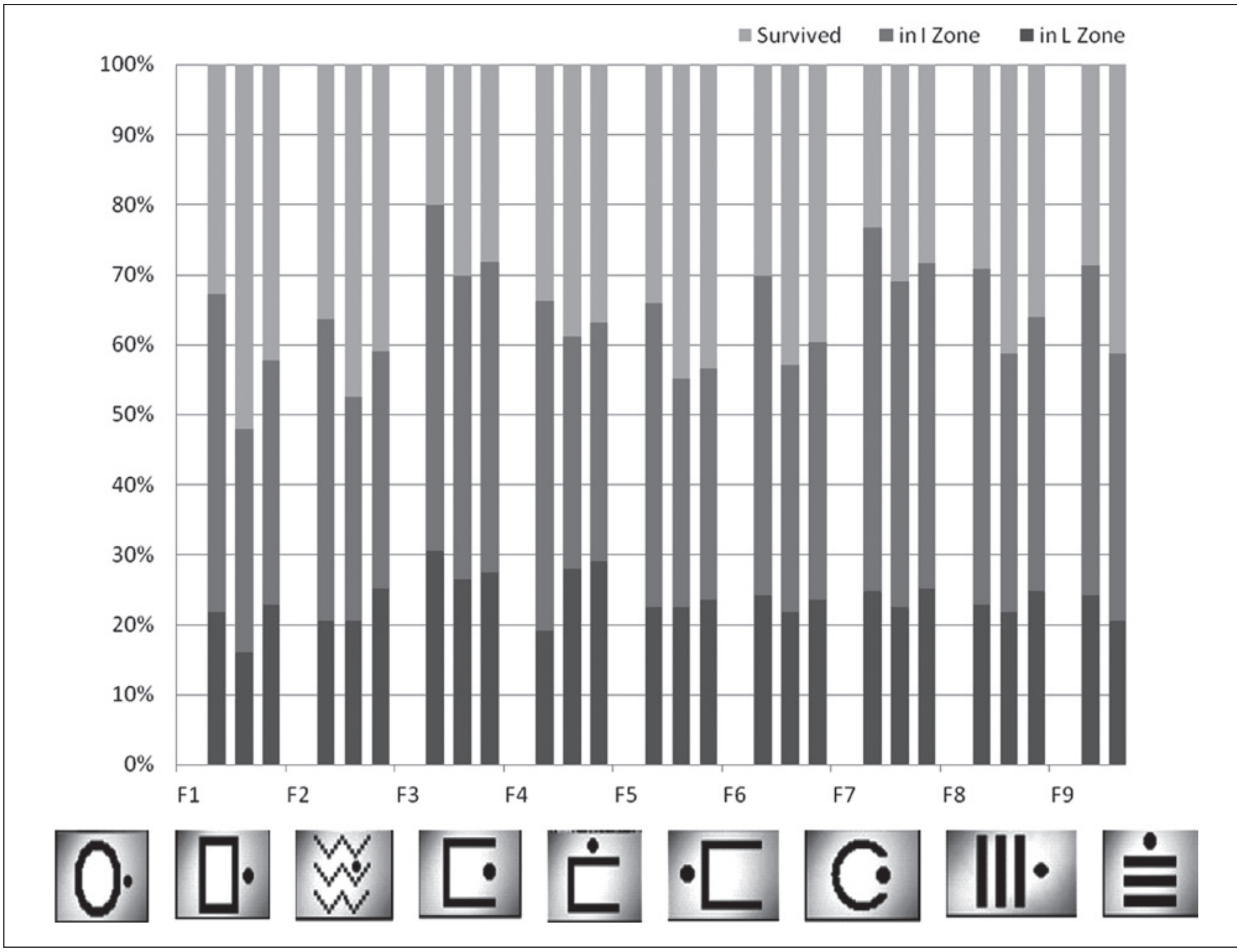


Figure 12. Casualties and crowd formations

explained as follows: first, the current simulation does not account 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 the 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% chance 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.

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 foot six inch person of 250 pounds in 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 the 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 this point forward. Figure 14 portrays the findings of this comparison.

Figure 15 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

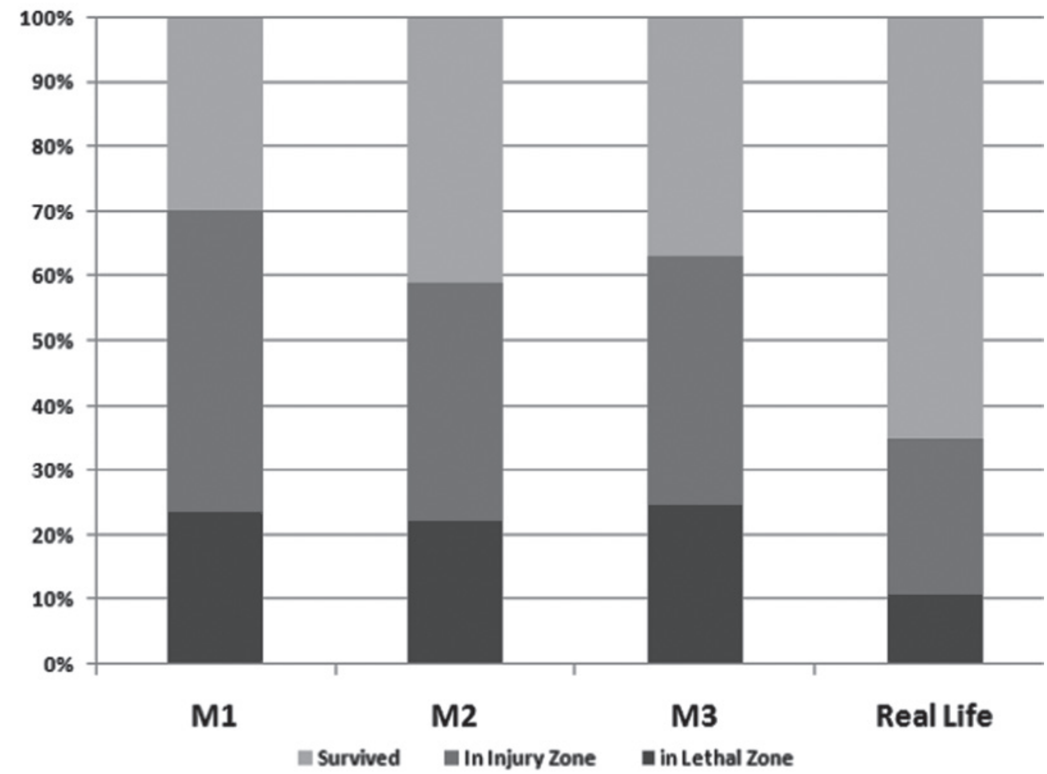
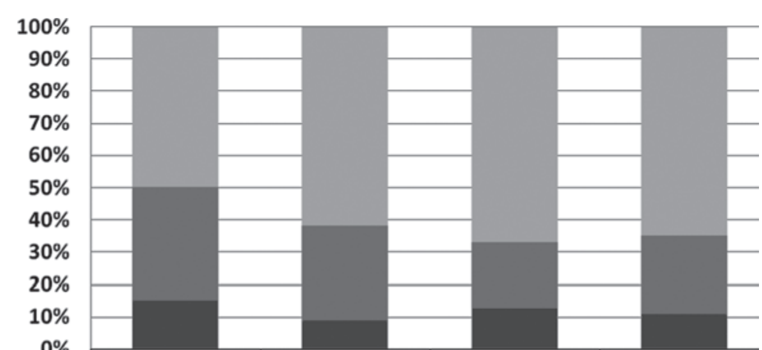


Figure 13. Model comparison with the real-life database of suicide bombing incidents in Pakistan



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

Figure 14. Model comparison with injury and lethal levels 1

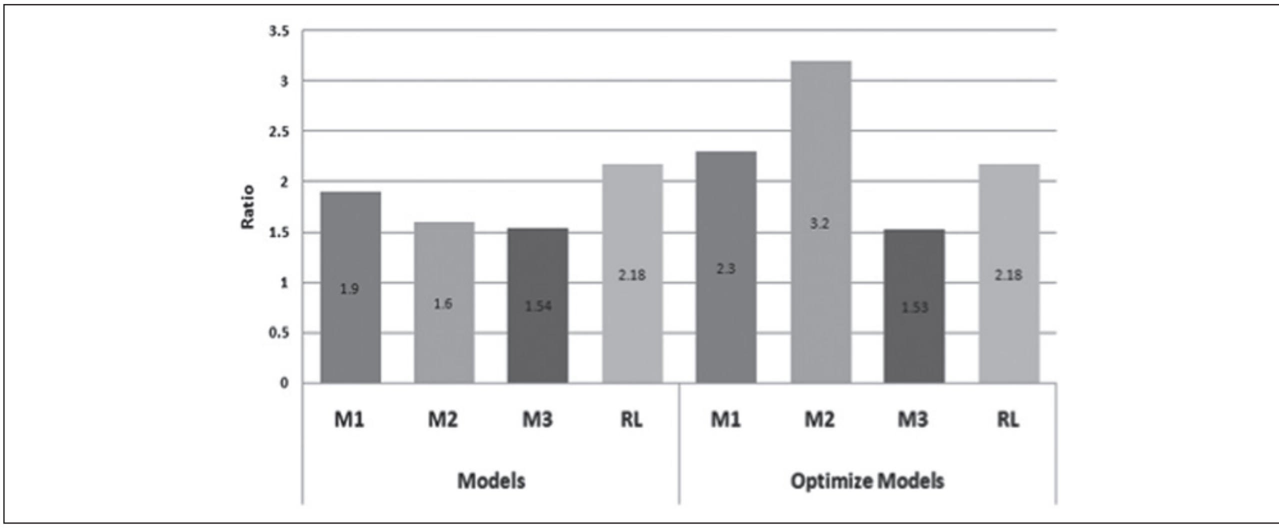


Figure 15. Injury per fatality ratios

reasons, one of the reasons for this difference can be totally political, where governments tend to show manipulated figures to minimize the aftereffects (for example, riots, revenge, etc.) by victim supporters or a huge outcry in the home state. For example, 4000 soldiers have been killed in Iraq so far since the invasion of the country by US forces in October 2003. Media have only concentrated on the dead, while little has been 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 dollars for an injured soldier and 3.7 million dollars for a dead soldier.[15] 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 needs 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 Iraq comes to 14.8 billion dollars;[16] 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 employ 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.

A sensitive analysis for all of the models was also performed. M1 or the basic model results are the same as the M2 2D model without blockage. And, the M2 2D model without blockage results are similar to the results of the 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 the M2 2D model, since the M3 3D model's contribution is statistically insignificant if only considering the blockage in the crowd. On the other hand, 3D demands more computational power and resources. The M3 3D model 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, the 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 casualty 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.

The simulation used the Cooper blast overpressure model[12] as described in Section 2. A user can use other available models like those of Smith,[17] Palmer,[18] US Army,[19] Brode,[11] and Bulmash[20] based on job requirement and industry.

10. Conclusions 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 less 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 depend on environment, crowd information, and 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 happen 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 any prospective attacker.

There is an acute shortage of accurate data for many other variables and conditions that are pertinent to such an attack (e.g. whether a bomber was 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 a continuous uniform distribution for the people, which is the least preferred distribution, but realistic in this case due to an 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 and tertiary injuries (e.g. injuries by fire, debris, fragments, shrapnel, building collapse, bodily transitions, etc.) so as better approximate the real-world environment and provide more valid comparisons with the data of suicide bombing attack aftermaths.[21] The flexibility to create a user-defined crowd formation with variable numbers of entrances and exits will be added in the future. Future developments also include the modeling of non-living objects like cars, electric poles and structures, and plants with appropriate blockage and damage criteria and corresponding heat maps for blast overpressure. The authors would also like to incorporate multiple injury models based on the direct mapping of human injuries to impulse overpressure, and experimental models to estimate blast overpressure on any given point. This paper provides an interesting direction for future research to take in investigating the catastrophic event of the suicide bomber attack in the hope of making the world a safer place.

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