Keywords: Blast Forensics, Blast Modeling, Blast Waves

Abstract

New challenges and problems emerge everyday with the current wave of terrorism. Suicide bombing, and explosions – a phenomenon only believed to exist in the battlefields – witnessed and experienced by thousands in civil settings. Traditional approaches and conventional solutions often fail to understand the emerging problems, and help us mitigate the effects. When modeling explosions for investigation, and forensics tools, or developing a simulation for training, or emergency response, developers often struggles due to lack of knowledge about underlying physics, gaseous properties, exposure characteristics, geometrical, and exposure constraints, and wide variety of explosive types. This lack of knowledge most of the time leads to unreal explosive behaviors and output. This paper is set to provide a tutorial on agent based explosion modeling for situation awareness, resource management, emergency response, architectural recommendations, crowd formations and topologies, and forensics investigations.

I. INTRODUCTION

Explosions and suicide bombing became the part of daily life in troubled countries like Iraq, Afghanistan, and Pakistan to name a few. There is a growing interest and need to develop real-life modeling and simulation tools to understand, investigate, and plan such events for a better defense. Modeling explosions cannot and should not be compared or adopted from gaming or film industry. In reality, things not just only explode but it also has heat, noise, and blast wave, overpressure and suction effects to name a few. Following sections are an attempt to give developers basic knowledge about explosions and underlying physics, so they can maintain the real properties of an explosion, and the physical behavior of a blast wave while writing the code. This knowledge can also help in developing models for risk assessments, and when designing or assessing features (e.g., enhanced structural loading capability, helmets, body armor, etc) to mitigate blast effects.

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, sex, weight, height)
- pulse duration (milliseconds)
- blockage ratios (percentage)
- reflection waves
- size, shape, and location of obstacles
- number of obstacles
- projectiles, debris, and fragments
- shape of the explosive carrier

A good explosive simulation should consider most of the aforementioned factors. Furthermore, a model should be easy to use, contain appropriate physics, should be able to work with different scenarios, blockage ratios, injury matrices, and different ambient conditions without special time-consuming tuning of constants. A model should also use accurate numerical code for simulation that allows accurate 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 simulation model will require too many resources and time if it truly contains appropriate physics and complex geometries. Consequently, a good simulation model should allow for a tradeoff among time, resources, physics, geometry, and the resulting output. Sometimes there is a need of faster results to meet the hardware and software requirement (i.e., online game streaming), or 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 and varying requirements.

Section II of this paper describes the fundamental physics of an explosion, basic scaling laws and TNT equivalence for other explosives. Section III explains simulation in detail with blast wave overpressure-distance plots, pulse duration, and lethality curves. Section IV demonstrates an example of the proposed model in C#, and paper ends with Conclusion in Section V.

II. PHYSICS OF AN EXPLOSION

In order to model the effects of an explosion in a given scenario it is essential to properly model the deleterious properties of the blast waves themselves. An explosion is a sudden release of energy that generates light, heat, noise and
most importantly pressure, which results in a blast wave. Part of the energy is released as thermal radiation, and the other part is coupled into the air (air blast) and soil (ground-shock) as radially expanding shock waves [8]. A chemical explosion is caused by the energy released from a rapid chemical reaction. The chemical reaction may occur spontaneously (i.e., infinite rate kinetics approximation) or can be initiated by an ignition source (i.e., finite rate kinetics models) such as an electrical charge or flame [17]. Explosions happen in very short time durations, typically in thousandths of a second (milliseconds). Gas generated by an explosion expands rapidly in every direction from the point of explosion. The rapidly expanding gas pushes into the stationary gas in front of it, causing a region of high pressure known as a blast wave. This wave represents the shock front consisting of highly compressed air at overpressure much greater than in the region behind it [16]. The blast wave expands outwards at a very high velocity, oftentimes greater than the speed of sound. The blast wave loses energy quickly as its distance increases from the point of the explosion [18].

The difference between the blast wave pressure and the ambient air pressure is called the overpressure of the blast wave. Because the blast wave expands outwards so rapidly, behind the blast wave is a region of low air pressure. This low-pressure region “sucks” the air along with it, causing a wind that initially follows the blast wave, thus creating a suction effect. As the blast wave continues outward, the relative pressure in front of, and behind the blast wave changes such that the direction of the wind can reverse direction, and for a time it can blow in towards the point of the explosion.

The resulting pressure effect from an explosion damages organs in people and animals, particularly at air-fluid interfaces. The wind propels fragments and people, causing penetrating or blunt injuries. The shock wave travelling outwards from the source is reflected when it meets with objects with higher density than atmospheric pressure (i.e., ground) and travels back to the origin. The overpressure of the reflected wave may exceed the overpressure of the incident wave, and due to its higher velocity, will eventually catch up with the incident wave [16]. The resulting wave will travel horizontally and forms a single shock front know as Mach front or Mach Stem. The point where incident and reflected waves meet at some distance above the ground is usually referred as a triple point [2, 3].

While the physical nature and source of explosions can vary greatly, the pressure-time profile of all blast waves have several critical features which are used to quantify the wave [15]. When an explosive charge detonates, the detonation products will expand and a shock wave will be generated as shown in Figure 1. The shock wave will instantly rise to peak pressure and then exponentially decay to values that may be at or below ambient pressure. The shock wave will decrease with distance away from the explosive origin [13, 14]. The pressure time history above the ambient pressure is called positive overpressure and the portion of overpressure below zero is called the negative or suction phase [16]. When the shock wave interacts with an object, reflection waves will be generated. The reflected pressure may be much higher than the incident pressure. The maximum impulse delivered is the area under the positive phase of the reflected pressure-time curve. Both the pressure and impulse (or duration time) are required to define the blast loading. Figure 1 depicts the overall mechanics of the blast wave defined in this section.

![Figure 1. Qualitative pressure-time history of a blast wave [7]](image)

A more complex pressure-time history can be generated when the blast wave interacts with other objects like walls, plants, humans or vehicles. Figure 2 shows an example of a more complex blast wave pattern.

![Figure 2. Pressure-time trace recorded behind a barrier after firing a 155 mm shell. Complex wave form results from reflections and reverberations [15]](image)

Depending on the type of explosive, there may also be a fireball associated with the explosion, which is produced during the initiating chemical reactions. Most of the damage by an explosion to people, vehicles, and structures, however, is done by the overpressure in the blast wave, rather than by the fireball radius, which is confined relatively closely to the
blast origin. In contrast, the blast overpressure can be damaging over distances of hundreds of initial blast diameters.

Figure 3: Qualitative amplitude-frequency distribution for different hazards [7]

It is important to note the difference between static, dynamic, and short-term dynamic loads. Generally, static loads such as gravity do not produce inertia effects and are not time dependent [9]. Dynamic loads, in contrast often times induced by earthquake or such things as wind gusts, are dependent on time (typically measured in tenths of seconds). Short term dynamic loads, like ones produced by explosions and debris, are non-oscillatory pulse loads which are measured in milliseconds [9]. Figure 3 provides an example of different types of loads with their noise frequency and respective intensity on amplitude scales.

Depending on the type of explosive and the proximity to the target, the positive phase duration can vary between a few microseconds and several milliseconds [11, 19]. Injury correlations as a function of peak overpressure and duration have been developed for various organs, such as eardrums and lungs, as well as the 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 the duration of the positive phase, which correlate to the overall impulse, each contribute to the magnitude of injury experienced by a victim.

With so many different explosives available, it would be extremely useful to be able to compare all explosive materials on an equal footing. Bashera [5] states that most of the data related to explosions used TNT and thus data related to any other explosive should be benchmarked against its TNT equivalent. This can be done by relating some measure of the explosive energy produced with x amount of an explosive to that produced by an equivalent amount of TNT. However, the equivalence may be affected by material shape (e.g., flat, square), number and type of explosives, confinement, nature of source and pressure range being considered [3, 10]. The energy output $W_{TNT}$ for explosive material relative to that of TNT can be expressed as:

$$W_{TNT} = \frac{H_{exp}}{H_{TNT}} W_{exp} \quad (1)$$

Where $W_{TNT}$ is the equivalent TNT charge weight, $H_{TNT}$ is the heat of detonation of TNT, $H_{exp}$ is the heat of detonation of explosive, and $W_{exp}$ is the explosive weight.

Table 1 gives the TNT equivalents ($W_{TNT}$) of commonly used explosives in civilian and military applications:

<table>
<thead>
<tr>
<th>Explosive</th>
<th>TNT Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>TNT</td>
<td>1</td>
</tr>
<tr>
<td>C4</td>
<td>1.18</td>
</tr>
<tr>
<td>Ammonium nitrate</td>
<td>0.42</td>
</tr>
<tr>
<td>Ammonium nitrate with fuel oil</td>
<td>0.8</td>
</tr>
<tr>
<td>Natural gas</td>
<td>0.16</td>
</tr>
<tr>
<td>Ammonium Picrate</td>
<td>0.97</td>
</tr>
<tr>
<td>HMX-3</td>
<td>1.02</td>
</tr>
<tr>
<td>Military Dynamite (MVD)</td>
<td>1.07</td>
</tr>
<tr>
<td>Perosite</td>
<td>1.15</td>
</tr>
<tr>
<td>Torpex</td>
<td>1.20</td>
</tr>
<tr>
<td>Trolonal</td>
<td>0.93</td>
</tr>
<tr>
<td>Black Powder</td>
<td>0.55</td>
</tr>
<tr>
<td>Amatol 80/20</td>
<td>1.17</td>
</tr>
<tr>
<td>MI Dynamite</td>
<td>1.12</td>
</tr>
<tr>
<td>Tetrytol 75/25</td>
<td>1.20</td>
</tr>
<tr>
<td>Tetryl</td>
<td>1.25</td>
</tr>
<tr>
<td>Sheet Explosives M118/M136</td>
<td>1.14</td>
</tr>
<tr>
<td>Nitroglycerin</td>
<td>1.50</td>
</tr>
<tr>
<td>Bangalore Torpedo (M1A2)</td>
<td>1.17</td>
</tr>
<tr>
<td>Shaped Charges (M2A3, M2A4, M3A1)</td>
<td>1.17</td>
</tr>
<tr>
<td>Composition B</td>
<td>1.35</td>
</tr>
<tr>
<td>Composition C4 and M112</td>
<td>1.34</td>
</tr>
<tr>
<td>PETN</td>
<td>1.66</td>
</tr>
<tr>
<td>RDX</td>
<td>1.60</td>
</tr>
</tbody>
</table>

The amount of explosive energy released and the nature of the propagation medium determine the characteristics of the blast wave generated by an explosion. Experiments have been carried out to measure these properties under control conditions with a given reference set of explosion data. The experimental results can be used to obtained data for other explosions using scaling laws. Readers are directed to [2, 3] for a comprehensive description of explosive scaling laws and their properties.

The cube root scaling law is the most commonly used form of blast scaling. This law states that when two charges of the same explosive and geometry (but of different size) are detonated in the same atmosphere, the shock waves produced are similar in nature at the same scaled distances. For example, to produce a given blast overpressure at twice a
given distance requires eight times the explosive energy release.

The scaled distance or the proximity factor $Z$ is defined as:

$$Z = \frac{R}{(WT_a/P_a)^{1/3}} \quad (2)$$

Where $R$ is the distance from the center of the explosion to the target location, $W$ is the energy of the explosive, or equivalent weight of TNT, in the explosion to be described, $T_a$ is the ambient temperature and $P_a$ is the ambient pressure.

Using this scaling law one can determine the blast overpressure on any given point from the explosion to the target.

### III. SIMULATION OF AN EXPLOSION

A simulation that models the impact of an explosion on casualty rates and injuries related to crowd formation must be able to demonstrate 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 [1, 4]. As an example, values for the peak overpressure generated in a standard atmosphere for the blast wave generated from a one pound spherical charge of TNT are shown in Figure 4.

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

![Figure 4](image1.png)

**Figure 4.** Peak overpressure ratio versus distance for explosions with a yield of one pound of TNT [1].

![Figure 5](image2.png)

**Figure 5.** Scaled positive pulse duration Vs Scaled Distance [1].

Also shown in Figure 4 is the peak overpressure that would be expected at various distances had the energy released by the one pound point source is somewhat less than from TNT been concentrated into a point source. It can be seen by comparing the two curves that the effect of finite size of the explosive charge source is initially to spread out the energy and so to reduce the peak overpressure, and that this effect holds out 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 begin to 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 from a point source so that peak overpressure observed far from a point source are somewhat less than those 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. In this simulation, either the point source or spherical TNT charge can be selected, with the TNT charge giving more realistic, and higher, estimates casualty and injury rates.

In order to apply the behavior depicted in Figure 4 and 5 for any weight of TNT, scaling laws for explosions based on geometrical similarity are used as described in earlier section.

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 also 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, a
baseline set of data was used and a scaling law employed.
Blast wave duration at the bomber’s location can be varied
from 0.5 ms to 2.0 ms, and the
duration will increase in
proportion to the scaled data set, in other words following the
same shape, but corrected for time and distance [4].

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 [6]. A quasi-
exponential form, in terms of a decay parameter, \( \alpha \), and of a
time, \( t \), which is measured from the instant the shock front
arrives, the pressure can be given as:

\[
p = p_0 \left(1 - \frac{t}{t_d}\right) e^{-\alpha t}
\]  

(3)

Where \( p \) is the instantaneous overpressure at time \( t \), \( p_0 \) the
maximum or peak overpressure observed when \( t \) is zero, and,
\( t_d \), 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, \( \alpha \), is specified, for
example to determine the evolution of the positive phase
duration as a function of distance from the explosive center.

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 6 shows the fatality curves
predicted for 70-kg man applicable to free-stream situations
where the long axis of the body is perpendicular to the
direction of propagation of the shocked blast wave.

The inputs to the simulation are the equivalent amount of
TNT that the bomber is carrying and the initial duration (or \( \alpha \)
if equation (2) is used) of the blast wave at the explosion’s
location. Specifying the amount of TNT, using the scaling law
of equation (2), and the overpressure versus distance curve of
Figure 4, then allows for the calculation of the peak
overpressure at any distance away from the bomber. Using
this peak overpressure and the increasing duration given by
the scaled baseline data set a new duration of the blast wave
can be calculated at any distance away from the bomber.
Using these two pieces of information and injury or fatality
probability curves, such as Figure 6, an estimate of the injury
or fatality levels at any location of the bomber can be
calculated for various crowd formations.

IV. PRACTICAL EXAMPLE

The following example is programmed in Visual C#. We
choose the Visual C# programming language due to its
extensive library of graphics and geometry functions (to
generate the Cartesian grid with agents) and exceptional
coverage of code integration with other third party tools like
MatLab® (to code the blast overpressure and explosion
models). The explosive range is determined by its weight.
Specific simulation inputs are the number of individuals in the
vicinity, walking speed of the attacker, time associated with
the trigger, crowd formation, pulse duration and the total
weight of TNT that is detonated. Additionally the arrival time
of the explosive pressure front to travel from the bomber to
any given location may also be calculated within the
simulation.

![Figure 7. Nine Possible Crowd Formations](image)

We have considered mostly “open space” scenarios to
serve as the basis for our crowd formation types (e.g.,
mosques, streets, concerts etc.). Type of injury caused by overpressure depends on whether overpressure occurs outdoor in open air or within buildings and whether they cause collapse of a building or other structure.

There are numerous objects to consider in close environments that can either increase the casualty/injury toll by working as flying debris, or decrease the toll by providing a shield to humans. Close environments also needs to entertain the refraction waves. A blast wave can also amplify in close environments by refraction and less number of ventilations. Ventilation, refraction waves and non-human objects are out of scope of this tutorial paper.

There are nine different settings a user can choose from the simulation main screen to estimate the outcome of an attack for a particular crowd formation. There are formations for Conference, Market, Street, Bus, Concert, Hotel, Shopping Mall, Mosque and University Campus. These nine settings were derived from the findings of Mark Harrison, where the majority of the suicide bombing attacks from November 2000 to November 2003 in Israel, occurred on the Streets, Cafeterias, Buses or other open spaces [3]. Users can also define number of participants (victims), number of attackers (suicide bombers), bomb strength (TNT weight in pounds), and bomb-timer (if any). Figure 7 shows the selection menu for crowd formation styles, Figure 8 displays the input menu for agents’ properties like height, weight, age, gender etc., and Figure 9 shows the display after the blast is simulated with the circular blast zone for each explosion/bomber.

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

The display depicts the casualties by red colored icons, those with injuries in green colored icons, and those who remain unharmed in the attack are shown in blue colored icons. Thus, there are three states of victims after the blast: dead, injured and unharmed (but in panic and contributing in stampede).

V. CONCLUSIONS AND FUTURE WORK

This paper provides a tutorial of modeling explosions for civil settings. Paper has also discussed basic physics of an explosion, scaling laws, TNT equivalence, and characteristics of a good explosion model. A practical example is given in the last section to demonstrate the development of proposed model in C#. The model can be used to develop a real-life simulation for situation awareness, resource management, automatic handling and recommendations for people in dangerous environments, and to perform forensics investigations for a suicide bombing or an explosion event.

REFERENCES


