Simple Physical Models in Support of Vulnerability and Lethality Data for Wargaming and Simulation Environments

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Abstract. Combat Simulations require appropriate vulnerability and lethality data in order to adjudicate military engagements involving human and vehicle targets. While typical modeling provides an excellent depth of knowledge when conducted at the item level, it is extremely resource intensive and does not necessarily provide suitable data required by Combat Simulations. We present a methodology for generating vulnerability and lethality data from simpler abstract models which require minimal set of parameters and are able to produce data for many weapon-target combinations and different combat simulation environments. In building models we focus on essential physical properties of weapons, targets and their interaction without simulating high fidelity effects. The results are compared with the limited empirical data available and adjusted accordingly. In this paper we describe the problem of wargaming and simulation data, similar work on the same problems by other groups, general solution ideas, mathematical models and their results, and the future work. Core work so far includes ballistics, error dispersion, blast effects, and armour penetration and propagation, along with methods for converting generic result data such as vehicle probability of kill models into simulation-specific input data.

1. WARGAMING AND SIMULATION DATA

Combat Simulations are part of a suite of tools and methods used by Land Operations Division (LOD) to support Army decision makers and have been used to support many studies, for example (Bowden, et al., 2009; Bowley, et al., 2004; Coutts & Dexter, 2008). They allow the analysis of the effects of modifying or introducing different equipment, force structure or tactics to a land force.

In order to represent combat effectively, these tools require an enormous amount of input data. Such input data may include both pre-calculated values and plug-in algorithms. Different types of input data correspond to different aspects of the simulation, such as detection and identification, behavioral decision making and weapon-target interaction. The topic of this paper is LOD's approach to generating weapon-target interaction data.

Simulation of combat requires the probabilities of outcomes of particular weapon and target engagement given a particular environmental situation. Weapon-target engagement is a well defined and well studied topic of any military organization. In the majority of cases the interest is focused on a particular weapon and target, or a particular type of weapon and a particular type of targets. Thus the most advanced models are invented to simulate physics as close as possible to reality. New weapon systems and ammunition, new targets, and modifications to any of those make the matrix of interactions (weapon-target pairs) large. This approach, with a focus on the depth of analysis, is common and adding more weapons or targets to a study can quickly explode the level of effort required to simulate and analyse the problem.

Wargames and Simulations require representations of many types of weapons and targets, along with the complex interactions between them. Depth-based data generation approaches are unsuited to this task because populating the whole matrix of interactions is more important than populating data for any particular pair. In addition, experiment designers may require a weapon or target to be added to a simulation at short notice, perhaps weeks or even days before a study commences.

Therefore there is a need for simple and generic models that can generate data in short time frames. The fidelity of these models can be adjusted depending on timeframes or availability of physical data, representing a trade-off between the speed of data generation and the accuracy of resulting information.

LOD supports several Combat Simulations which share this requirement for data. While these tools represent combat in broadly similar ways, their data requirements are all slightly different, adding to the data generation challenge. Our goal is to develop a framework that generates reliable, consistent, timely data to all of these tools.

This paper in particular focuses on methods for determining the probability of hit and kill between pairs of entities. It describes our overall data generation approach along with descriptions of our models for generating direct and indirect fire vulnerability and lethality data.

2. SIMILAR WORK

In the last decade, LOD has devoted some effort to generating input data for combat simulations, with mixed success. The concept for a common database was developed and designed to store input data for a number of Combat Simulations that LOD has used. However, there has been comparatively little effort in developing reliable data.

LOD has also attempted to use other experts in the field of vulnerability and lethality, such as those in Weapons Systems Division (WSD) or Land Engineering Agency (LEA), to generate this input data. However, the goals of these agencies are divergent from the requirements of LOD. While we require rough order of magnitude data on a broad range of interactions, they conduct extremely detailed, but narrow research into selected areas of interest.

The Centre for Operations Research and Analysis (CORA), a part of Defence Research and Development Canada (DRDC), has made significant strides in developing a more complete data generation methodology. This approach combines simple, fit-for-purpose physical models with a limited, clearly stated goal of developing data for the Joint Conflict and Tactical Simulation (JCATS) wargame.

Key areas of research include ballistics and penetration (Cazzolato & Roy, 2006), probability of hit (Roy & Cazzolato, 2007), probability of kill (Cazzolato, et al., 2007) and fragmentation (Cazzolato, 2008). In addition, they have iteratively improved upon their processes and source data (Cazzolato & Roy, 2010; Cazzolato, et al., 2011). The work covered in this paper is based on some aspects of CORA's efforts.

SimR (Angel, et al., 2011) is a repository for combat simulation input data that is under development within LOD. Its goal is to provide a common database for storing characteristic and performance data required by a number of combat simulations. The goal of this work is to provide a bridge between the data stored in SimR and the combat simulations themselves.

3. APPROACH

Our approach focuses on the generation of interaction data between entities within a Combat Simulation, specifically the determination of the probability of hit and kill between any pair of entities. Combat Simulations represent such information using vast lookup tables, which define these probabilities depending on a number of factors such as range and angle of shot, the speed of shooter and target and whether the target is obscured.

When adding a new weapons system or vehicle platform to a combat model, one needs to provide some basic information about it, such as the size and speed (for a vehicle) or rate of fire and time of flight (for a weapon), along with many other characteristics. More importantly, one must define how this system interacts with every other system in the combat model.

Therefore this matrix of interaction data can become extremely large. Our approach to generating this matrix relies on a number of principles and draws heavily from the data generation methods developed by CORA.

Firstly, at no point do we attempt to permanently store interaction data, which has the effect of limiting the amount of data that needs to be verified. We rely heavily on simple, fit for purpose algorithms to build the data required either by a Combat Simulation or by other algorithms. For example, instead of storing detailed penetration data on munitions, we use basic information such as the length and diameter of the projectile, along with appropriate penetration equations, to generate this information as required.

These algorithms range from fundamental models which generate ballistics and penetration data, to more detailed interaction models that determine the probability of hit and kill of a weapon/target combination. Each model is designed to be as simple as possible, with an emphasis on reducing data generation requirements instead of increasing them.

Empirical data is often used to feed input data to a Combat Simulation. For example, field trial data measuring a particular munition trajectory might be used to populate trajectory tables within a simulation. We feel this approach introduces two problems. Firstly, it increases the amount of data that is stored, increasing the validation requirements. Secondly, empirical data is typically not available for all situations. Thus, data generation algorithms are necessary anyway, in order to fill these gaps. Rather than taking a hybrid approach, where a combination of empirical and generated data is used in a Combat Simulation, we use empirical data only as a verification and validation tool across the data generation process.

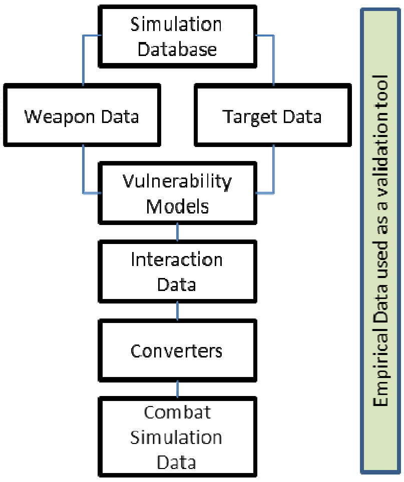

Figure 1: Workflow view of our approach

A simple view of our approach is illustrated in Figure 1. A simulation database carries basic physical data regarding relevant weapons, targets and environmental factors. Vulnerability models, which are explained in the next section, determine the probability of various outcomes from a particular engagement. The resulting generic interaction data is then converted into specific data required by a relevant Combat Simulation. Available empirical data is used throughout the process to verify results at each stage of the data generation process.

This approach offers a number of advantages. Verifying the characteristics of weapons and targets is much simpler, as this is typically simple physical data. The use of simple algorithms allows reliable and consistent extrapolation of more detailed characteristics from basic data. However, these algorithms are only models, hence the use of available empirical data to validate their output.

4. IMPLEMENTATION

This section, describing the algorithms and models used to generate combat simulation input data, is split into three sub-sections. Firstly, we describe some fundamental models that are common to several applications. Then, we will describe two specific models that generate vulnerability and lethality data – for direct and indirect fire, respectively.

4.1 Fundamental Models

Fundamental models are those that produce data required for other models. In some cases, they may also produce data required by combat simulations themselves. Fundamental models are used as a precursor to more detailed vulnerability models and sit within the weapon and target data objects of Figure 1. Our framework contains two fundamental models, described in 4.1.1 below.

4.1.1 Ballistics & Penetration

Ballistics data is required by vulnerability and lethality models to calculate the angle of fall and penetration power of a weapon when striking a target. Ballistics data may also be required by combat simulations to model the trajectory of a munition and determine times of flight.

Industry-standard software like Projectile Rocket Ordnance Design and Analysis System (PRODAS) provides excellent trajectory data for a wide range of munitions. However, the user must know a great deal of information about the munition to get an accurate solution. CORA have developed a model (Cazzolato & Roy, 2006) that produces results within 1% of PRODAS (more than accurate enough for our purposes) using a far simpler model that only requires two inputs – muzzle velocity and ballistic coefficient. Thus, detailed, reliable trajectory data can be generated with limited input.

As an addition to this model, CORA also developed a set of fit-for-purpose armour penetration models. These simple models do not take into account detailed concepts such as ricochet or projectile shattering, but do provide reliable armour penetration data that matches stated penetrations and other empirical data.

4.1.2 Error and Dispersion

All weapons have some kind of error, related to either the weapon itself and/or its operator. Combat simulations require error data to adjudicate the probability of hitting a target.

CORA have developed a model of dispersion (Roy & Cazzolato, 2007), which divides error into a set of factors related to the weapon, mount and targeting system. This approach allows for the simple categorisation of classes of weapons systems, although it lacks the level of detail to compare systems that are very similar. Despite this, the model is built for and is appropriate for combat simulation data generation as it adequately describes the differences between disparate weapons systems.

4.2 Direct Fire Model

Combat simulations adjudicate direct fire combat using sets of lookup tables, which must be generated prior to a study. Therefore, there is a need for an external model to judge the effects of munitions against targets. CORA has created such a model for the JCATS wargame (Cazzolato, et al., 2007), which we have expanded on to suit the needs of LODs suite of combat simulations.

The following sub-sections describe how a target is represented, how we use the concept of Kill Grids to determine behind-armour effects and how we apply weapon error to determine what areas of a target are struck.

4.2.1 Target Representations

Targets are represented as simple 3D models, with the geometry broken up into the various parts of the vehicle. These models represent both the external and internal components of a vehicle, albeit in a rough manner compared to tools such as Weapon Target Interaction (WTI) (Cernis & Hasall, 2007).

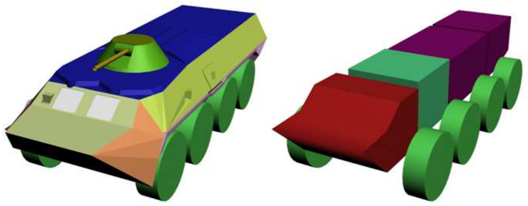

Figure 2: Example vehicle, external and internal model

Metadata is attached to each vehicle component, defining the Rolled Homogenous Armour Equivalent (RHAe) level of protection along with the probability and type of damage to the vehicle if that component is penetrated.

4.2.2 Kill Grids

A Kill Grid is a rectangle that is overlaid on a target from a particular aspect angle. This rectangle is divided into a grid. A chosen projectile is then applied to each of the cells and the result is calculated. Figure 3 shows an example Kill Grid, where each colour represents a different type of effect on the target.

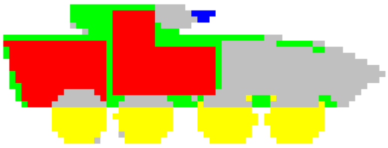

Figure 3: Kill Grid showing different types of kill as different cell colours

The Kill Grid concept is inline with other vulnerability tools such as Mavkill and WTI. Its generic nature allows for the simple conversion of vulnerability data to a variety of formats.

4.2.3 Aim Points

An aim point is an imaginary point on the Kill Grid used as a reference point for weapon error distribution. This point has to be defined in order to calculate the overall kill probability by integrating the weapon's dispersion over the target.

Simulations which use the Army Materiel Systems Analysis Activity (AMSAA) standard format (such as OneSAF or Combat XXI) use separate tables to calculate probability of hit and probability of kill. In these cases, the simulation determines the aim point of the shooter and uses a kill table to determine the probability of kill, taking into account weapon error.

Other simulations, such as the Close Action Environment (CAEn), require a single table with a combined probability of hit and kill (thus the probability of kill given a shot). In this case, an aim point must be selected during the data generation process.

CORA data generation experts select aim points manually. However, since our problem space is much larger, we required an automated solution. This takes into account the Kill Grid and the dispersion of the firer's weapon when determining the point aim. One simple way is to select the centre of mass as the aim point. This however is not always the optimal solution. When the weapon' round-to-round dispersion is smaller than the target, and the centre of mass presents a low kill probability (perhaps due to heavier armour in such an area), then the probability of destroying a target may decrease as range decreases, which is counter-intuitive.

Therefore we have devised other methods to select aim points, such as artificially increasing dispersion at short ranges and having the firer pick an aim point based on the chance of killing the target. However, such solutions also raise other questions regarding the perceived tactical skill of a firer and their knowledge of the target.

4.2.4 Overall Direct Fire Model

Figure 4 illustrates the overall direct fire model, if applied to a single weapon, target, aspect angle and range. A blank Kill Grid is overlaid on the target. For each cell, the terminal characteristics of the projectile are calculated, along with the effect of the projectile on the target. This effect is represented through four mutually exclusive probabilities: Mobility Kill, Firepower Kill, Mobility and Firepower Kill, and Catastrophic Kill.

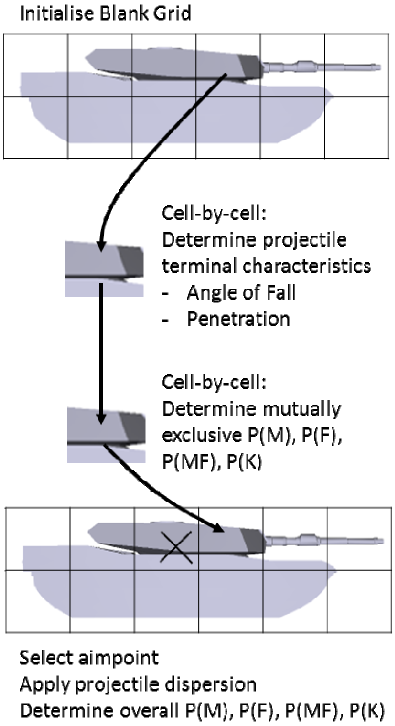

Figure 4: Direct Fire Model

After the cell-by-cell calculation is complete, the model calculates an aim point and applies the projectile's dispersion to obtain an overall probability of kill. This process is repeated for each combination of range, aspect angle, level of cover and firer/target movement combination. The resultant data is therefore multi-dimensional, but Figure 5 shows a small example of the output data. It gives the probability of kill over range for a 25mm APDS round fired at an exposed BTR-80 from the front, with a stationary firer and target.

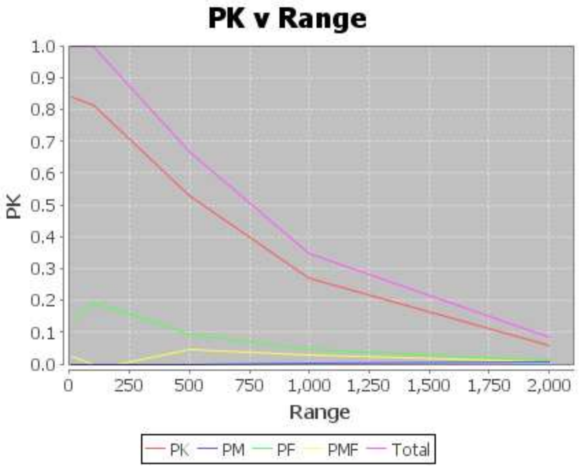

Figure 5: Single Shot Probability of Kill vs Range - 25mm APDS vs BTR-80, front aspect

4.3 Indirect Fire Model

The indirect fire model deals with detonation effects of high explosive weapons. Three main types of effects are identified:

1. Primary, air blast: air pressure damages people and objects.
2. Secondary, fragmentation: thrown solid fragments damage people and objects by penetrating them.
3. Tertiary, translation: air kinetic energy is passed to objects as momentum; objects can be damaged by hitting the ground or colliding with other objects.

4.3.1 Air Pressure

If the blast air pressure can damage a vehicle, then very specific data is required for what pressure each component of the vehicle can withstand. This effect is considered to be small since the high air pressure required to damage equipment requires a detonation point so close to the target that the effect of fragmentation is orders of magnitude greater.

For air pressure effects on humans, empirical data is available (Australian Army, 2005). Depending on simulation requirements different levels of incapacitation can be selected. Such data can be presented as a curve of probability of incapacitation depending on pressure. The pressure can in turn be obtained from empirical data based on scaled distance and physical properties of the explosion.

4.3.2 Blast Hit

If the kinetic energy of the air is passed to a vehicle, the vehicle may turn over. This effect may also be negligible for common weapon rounds and military vehicles, but it is very easy to make an estimate by comparing the kinetic energy passed to a vehicle and the potential energy required to pull up the centre of mass to the highest point of turning over the vehicle.

Blast air impulse passed to a human body may cause damage to a person if they are thrown against a hard surface and the velocity gained by the human body exceeds some threshold value. Empirical data can be used for estimation of the probability of damage (Australian Army, 2005). For example, the head hitting a surface with 5.5 m/s is considered to be lethal 50% of the time. As above, depending on simulation requirements different levels of incapacitation can be selected and the pressure necessary for calculation of kinetic energy can be obtained from empirical data tables.

4.3.3 Fragmentation

Calculation of probabilities of damage caused by fragmentation is a top-down hierarchy of values where each is derived from others.

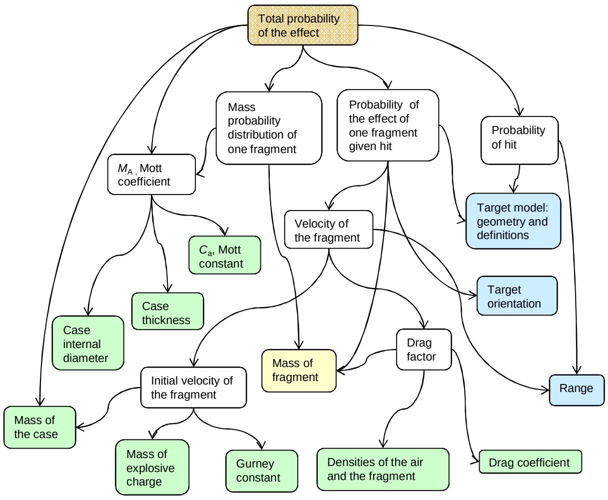

Figure 6 Probability of kill due to fragmentation calculation hierarchy.

Figure 6 shows the logic of calculating fragmentation. White items are intermediate values, green items are final values obtained from tables of known characteristics. Blue represents environmental variables. The mass of a fragment (yellow) is the integral parameter: for every set of blue and green values, the yellow parameter runs through all possible values to calculate just one result.

The total probability of effect can be calculated with a simple model given some basic physical parameters of the explosive device and the target. We distinguish several types of effects on vehicle vulnerability: mobility, firepower, and catastrophic kills. Each of those effect types or incapacitation effect on humans can be calculated independently. In our model the total probability of kill depends on the hit probability of fragments, probability of the effect of one fragment given a hit and the distribution of mass for fragments. We use Mott's model (Mott, 1943) for the distribution of mass, which requires mass of the external case of the explosive device, internal and external diameters, and a specific Mott constant defined empirically for different types of explosive charges and metal cases.

Probability of hit and effect depends on situational parameters such as the target geometry, distance from the point of detonation, orientation of the target, and physical variables at the moment of contact between the fragment and the target. The final velocity of the fragment can be calculated by a drag differential equation, which in turn requires initial velocity, drag coefficient and other physical properties of moving the fragment through the air. Initial velocity is calculated by Gurney's model (Baker, 1983), which depends solely on characteristics of the explosive device.

4.3.4 Kill Events

To combine the effects caused by explosion into one probability a binomial sum of the independent probabilities is calculated. All three effects are considered when determining the probability of incapacitation of a person. For vehicle vulnerability, blast air pressure is not considered, but similar to the direct fire model, four distinct kill types are calculated: Mobility Kill, Firepower Kill, Mobility and Firepower Kill, and Catastrophic Kill. The target representations described in Section 4.2.1 can be used to calculate these probabilities. A vehicle roll over is considered to be a Mobility Kill. Table 1 summarises these considerations.

Table 1 Blast Effects and Kill Events calculated as probabilities. P stands for personnel incapacitation probability, M, F, MF, and K are Mobility, Fire, Mobility-and-Fire, and Catastrophic Kill respectively. Subscripts represent individual probabilities of the same type which are combined to form a final probability.

	Pressure	Fragmentation	Blast hit
Personnel	P_1	P_2	P_3
Vehicle	-	M, F, MF, K	M_3

5. FUTURE WORK

This data generation system is being developed with an eye towards supporting the SimR Database, which is also under development within LOD. We are currently at the stage where this system can generate critical files and data for a number of wargames and simulations within the LOD suite. However, the bulk of a simulation study (creating weapons, ammunitions, entities, etc) must still be done by hand, a process which remains time consuming and error prone.

We envisage a system where SimR can, with limited input from a user, produce a complete, working simulation study, from which scenarios can immediately be built and run. In addition, we envisage a system that produces interaction data that is functionally the same (or as similar as possible) across multiple simulations.

Our current approach proposes solutions for two main data requirements of Combat Simulations, namely direct and indirect fire vulnerability. A similar approach is envisaged for other data requirements. For example, LOD is developing a concept for a generic behavior repository, which would define actions (such as a section assault) in a common language, allowing similar implementation across multiple Combat Simulations.

Finally, our existing components will be subject to continual scrutiny and improvements, in terms of both input data and internal models. Collaboration with key partners will be important in validating our models, data and design decisions.

6. ACKNOWLEDGEMENTS

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