Smart Munitions Effectiveness Model

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ABSTRACT

Conventionally, the US ARMY evaluates smart munition performance through a mix of dated low-fidelity M&S that is validated against limited physical testing. Ideally, all munition development would be backed by a coupling between high-fidelity digital twins executed and validated against relevant physical testing; this is rarely feasible. The cost and complexity of M&S inputs, models, run-time, and data analysis is directly proportional to the involved model's fidelity. A solution to these issues is a new smart munition effectiveness model that implements both low and high-fidelity modeling. This model is a collection of C++ modules that allow for rapid parametric analysis of a smart munition effectiveness across the system design and employment space. This development is a timely and necessary achievement due to the increased need for the US ARMY to possess improved smart munition effectiveness models. Going beyond the available legacy models, this provides increased capability, improved input and output interfacing, and is developed within a modern and modular simulation framework. This paper documents a notional yet realistic use case assessing the effectiveness of three munitions against two target formations to touch on the model capabilities and highlight the model's power. Results show how the trade-off between lethality and munition delivery accuracy is often counterintuitive, emphasizing the need for robust effectiveness modeling.

ABOUT THE AUTHORS

Evelyn Welling is a Systems Analyst working at Combat Capabilities Development Command – Armaments Center (DEVCOM-AC) in Picatinny Arsenal. Evelyn earned her Bachelor of Science in Chemical Engineering from Brigham Young University in 2021 and presently works within the System Analysis Division.

Antonio Aguirre works for the US ARMY's Picatinny Arsenal in New Jersey as a mathematician, computer scientist, and data analyst. In his 6-year career with the US ARMY, Mr. Aguirre has most notably: selected to serve as the MATLAB Technical POC for Picatinny Arsenal, Watervliet Arsenal, and Picatinny's Armament University; completed a Radar Systems Certification from Georgia Tech; contributes to, developed, and maintains several tools and models that regularly provide critical insights to senior ARMY and program leadership. Prior to Mr. Aguirre's service with the ARMY, he lived in New York City where he earned a Bachelor of Science in Applied Mathematics with the distinction Magna Cum Laude. While in college Mr. Aguirre was selected to work with world class scientist in the field of Remote Sensing at NASA-Goddard Space Flight Center, NASA-Glenn Research Center, and twice at Brookhaven National Laboratory.

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Introduction

Physics-based munition effectiveness modeling is a rapidly growing field of interest but presents consistent challenges. Subject matter expert guidance for the necessary input minutiae to such effectiveness models is often absent or unable to be obtained in a timely manner. When expert guidance is unavailable to provide a single set of values for a series of inputs, each input must instead be assigned an upper and lower bound which span the range of realistic possible values for the simulation; this results in large case matrices and impracticably excessive computational runtime.

A solution to this is to employ a probabilistic model referencing data tables informed by physics-based modeling to evaluate smart munition effectiveness. This can minimize computational runtime while maintaining the integrity of results. This paper presents a Smart Munitions Effectiveness Model (SMEM) as a collection of lightweight C++ modules which simulate a parametric array of variables on a Monte Carlo basis. It includes homogenous and heterogenous target formations, shoot-scoot tactics, munition delivery, sublet dispense, sensor-fuzed scanning and target detection, point and area target aiming strategies, target recognition and prioritization, hit, and lethal effects. Beyond the available legacy models, this novel solution provides increased capability, improved input and output interfacing, and development within a modern and modular simulation framework.

Given current events, there is critical need for the US ARMY to obtain accurate effectiveness measurements of existing munitions against an expansive array of targets under a variety of tactical, environmental, and climactic conditions. The US ARMY also has an immediate need to rebuild its recently depleted munitions stockpile and to identify the specific warhead improvements which will preserve its technological advantage and provide a full range of operational capability in diverse future combat theaters. The research and development, design, and field testing of munitions is time, money, and resource intensive.

SMEM meets demand for increased munition performance data, accepting advanced lethality inputs for weapon-target combinations to output realistic effectiveness data for existing and conceptual warheads in a variety of current and future combat theater scenarios. Data generated by the model can be used to inform critical decision making to accelerate the research and development of future munitions and reduce the time and resource cost involved in the performance evaluation of existing munitions.

The “Model” section of this paper outlines the model methodology and characteristics. The “Scenario” section provides an illustrative use case, simplified to demonstrate the ease and utility of the model. Inputs for the scenario are comprised of notional parameters for targets and weapons in a notional environment to demonstrate SMEM data output and analytical applications. To meet distribution requirements, this paper does not contain data about real targets or real weapons systems, nor does it reference any real tactical environments.

MODEL

Development and Accreditation

SMEM arose from a co-development effort between Combat Capabilities Development Command - Armaments Center (DEVCOM-AC) and Combat Capabilities Development Command - Analysis Center (DEVCOM-DAC). The SMEM modules are C++ based source code controlled and developed by DEVCOM-AC. The SMEM GUI is source controlled and developed by DEVCOM-AC within the open-source Python programing language. SMEM is currently releasable as a zip file and is compatible with Linux and Windows operating systems. The installer provides the SMEM model and the SMEM GUI. SMEM is releasable via email contact to any author.

Guided Artillery Munitions Effectiveness Simulation-Sense and Destroy armor (GAMES-SAD) is a simulation model developed in the early 1990s to evaluate the effectiveness of the Sense and Destroy Armor munition (SADARM). Developed within the FORTRAN programming environment, active maintenance for GAME-SAD no longer occurs. GAMES-SAD went through a successful VV&A process with personnel from Georgia Tech. Initial comparisons of SMEM outputs to GAMES-SAD provide a high level of confidence in the accuracy and precision of the newly developed SMEM model. SMEM is currently undergoing further accreditation efforts.

End users may interact with SMEM to build, execute, and visualize simulations either directly through scenario XML files or through the GUI.

Target Generation and Placement

SMEM Supports a number of target formation types including Lazy-W, Diamond, Wedge, Column, Grid, FromFile, Uniform-Area, Uniform Radial. Any SMEM simulation can contain a heterogeneous mixture of formation types, but each individual formation comprises a homogenous target set. The notional scenario described in further detail later in this paper includes two of these target arrays: Uniform-Area and Uniform-Random.

SMEM allows for the generation and placement of both real and false targets within a simulation. Only sensing munitions differentiate between real and false targets in SMEM, as Pd (Probability of Detection) does not apply to munitions unequipped with sensors. Real targets represent any intended combat target while false targets represent all other diversional objects which could be mistakenly detected as the intended combat target by the munition scanner.

Munition Delivery Errors

The SMEM model simulates the delivery of munitions from gun to aim-point via application of a series of delivery errors. The model allows end-users to define and simulate delivery errors for engagements consisting of one or more surface-to-surface, air-to-surface, direct-fire, or gunship attacks. More specifically, as applicable, SMEM accepts inputs for target location error (TLE), mean point of impact (MPI), fixed bias, burst-to-burst or gun specific errors, precision error or ballistic dispersion, attack azimuth, and angle of fall (AOF).

Munition Dispense

After application of munition delivery errors, munition dispense occurs. SMEM supports three dispense pattern styles: ellipse, explicit, and line.

The ellipse dispense type allows for placing one or more sub-munitions, relative to an aim point at positions uniformly sampled on the circumference of an ellipse defined by its general mathematical properties via a standard SMEM formatted ellipse dispense pattern file. The sampled sub-munition positions are along the circumference of an ellipse centered at the dispense point or can be spaced throughout the ellipse according to the bivariate distribution. Nominally, N-submunition are placed along the circumference of an ellipse, where their position on the circumference follows a uniform random distribution. After nominal placement on the circumference, additional errors can be applied with respect to the nominal positions, where the error follows a bivariate normal distribution. The additional errors on top of the nominal positions account for system and environment state variability at the time of the dispense event such as carrier angle of fall, speed, and rotation rate which results in a perturbed ellipse. This dispense type is used to model Munition C dispense in the scenario.

The explicit dispense type is the most customizable dispense pattern with the possibility of defining any number of dispensed sub-munitions, with each having its own positional offsets relative to the dispense point. Like the ellipse dispense type, positional arguments are reserved for: the minimum number of detections needed before target engagement and simulating dispense pattern variabilities by applying random samples from a user-defined bivariate normal distribution as offsets to the nominal positions of the sub-munitions placed by the user defined offsets. SMEM reserves the first line for comments and disregards the line. This dispense type is used to model Munition A and Munition B dispense in the scenario.

The line dispense type allows for placing one or more sub-munitions, relative to the dispense point shown in at positions uniformly sampled on a line by its general mathematical properties via end-user input to a standard SMEM formatted line dispense pattern file. Nominally, the sampled sub-munition positions are along the line that is centered at the dispense point. The line dispense pattern file reserves positional inputs for specifying: the number of dispensed sub-munitions; the minimum number of detections needed before target engagement, an offset of the line centroid from the dispense point; and bivariate normal distribution parameters, allowing for the simulation of dispense pattern variabilities by applying random samples from a user-defined bivariate normal distribution as offsets to the nominal positions of the sub-munitions place along the line. SMEM reserves the first line for comments and disregards the line. Lastly, each line of the file represents a different line dispense pattern of sub-munitions and requires a standard set of positional arguments. This dispense type is not featured in the scenario included in this paper.

Scan Patterns

Scan pattern input files detail on a line-by-line basis the munition position and a minimum of three x-y vertex pairs forming a closed polygon on the ground plane representing a lethal search basket at a particular altitude. For each line, the munition position represents relative 3D offsets from the initial dispense position. For each target encountered in the lethal search basket, SMEM computes the success or failure in terms of the probability of detection (Pd), probability of recognition (Pr), probability of hit (Ph), and probability of kill (Pk) the target. Pr is set to 1 for all munition-target combinations in the scenario. End-users can make and inspect standard SMEM scan pattern files using the SMEM GUI.

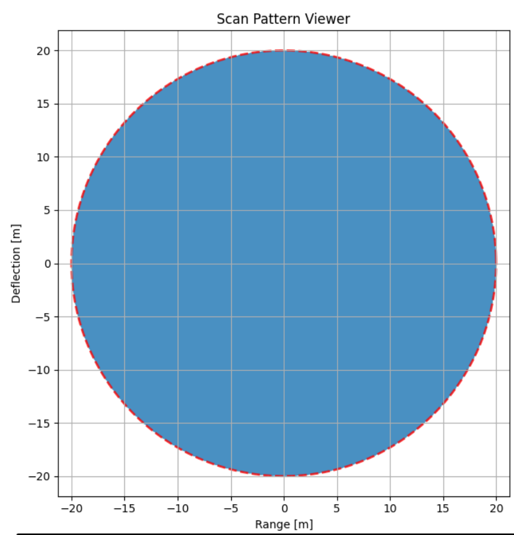
SMEM supports Sensor-Fuzed Munition (SFM) and Automatic Target Recognition (ATR) style scan patterns. SFMs are carrier munitions containing a payload of sensing projectiles which scan the terrain in a series of sequential polygons. SFM submunitions achieve lethality by firing an Explosively Formed Penetrator (EFP) upon detection and recognition of a combat target. ATR style munitions are equipped with devices which allow them to identify objects and targets acquired in real time by comparing the images to a database. ATR munitions achieve lethality through a variety of mechanisms.

For SFMs, the SMEM GUI creates new notional scan patterns customizable by munition altitude resolution, azimuth resolution and scan angle. The altitude resolution changes the number of concentric circles, the azimuth resolution changes the number of circumferential divisions within the scan pattern, and the scan angle represents the munition's sensor boresight up from nadir. Sequential frame-by-frame visualization of each polygon of the scan pattern is available through the GUI and can be saved as a GIF.

SMEM formats ATR scan patterns in the shape of an ellipse or a frustum. The SMEM GUI creates ATR scan patterns customizable by horizontal and vertical field of view, altitude, and scan angle.

Munition B and Munition C in the scenario use notional SFM scan patterns while Munition A uses a notional circular ATR scan pattern and is shown in Figure 1.

SMEM can also represent munitions unequipped with sensors. In these cases, the probability of hit and detect are set to 1 and munition effectiveness is computed by applying the appropriate area of lethal effects around the munition dispense point after the application of its delivery errors. This is further illustrated in the 'Scenario' section of the paper where Munitions B and C use notional scan patterns to engage at maximum one target within the lethal search basket because they represent munitions with unitary EFPs while Munition C which uses a circular ATR scan pattern to engage all items within its lethal search basket because it represents a High Explosive (HE) munition. All scan pattern radii are collectively referred to as the "Effects Radius" in the scenario.



All information regarding targets, munitions, and conditions is **notional**; sample data and analysis generated does not represent any specific system or actual circumstance

Figure 1: SMEM GUI scan pattern plot output for Munition A Baseline and A-3

System Effectiveness Logs

SMEM produces an output file containing data on the cumulative and unique number of kills on a per target, per round, per volley, per Monte Carlo basis. The file can be post-processed to derive the minimum rounds-to-defeat (R2D) a target array(s) at various fractional defeat levels, e.g., N-rounds are needed to defeat 30% of all targets in an array.

Kill-Chain

For SMEM, the JTCG-DEM outputs coordinates representing the nominal aim-points translated as a function of TLE, MPI, and precision errors. From these coordinates, either SFMs or ATR munitions are instantiated into the simulation and lethal search begins. Once lethal search begins, there is an ordered logic for processing encountered targets referred to as the kill-chain. Along the kill-chain, evaluation of multiple probabilities occurs in a particular order. The kill-chain evaluation order is detection, recognition, prioritization, collaboration, hit, and kill. In the case of SFMs, the only relevant processes are detection, hit, and kill. For ATR munitions there are the additional kill-chain evaluations of recognition, prioritization, and optionally collaboration. *Count* and *Random* are kill-chain logic options (KCLOs) implemented in SMEM for munitions of type SFM. The SFM *Count* KCLO processes scan patterns in the order of presentation within the scan pattern file. In contrast, the SFM *Random* KCLO processes scan patterns randomly regardless of presentation order within the scan pattern file. The ATR *Random* KCLO processes scan patterns randomly regardless of their presented order within the scan pattern file.

SCENARIO

All targets, munitions, and their inputs as described in this scenario are fictional, general in nature, and intended for illustrative purposes in this paper only. The sample data and analysis generated should not be relied upon or construed as recommendation regarding any specific issue or factual circumstance. The “Data” subsection details example input and output data for SMEM to illuminate the underlying logic and methodology. The “Results” subsection includes an analysis of the data to highlight a selection of some of the further analytical applications of munitions effectiveness data.

In this example scenario, the US ARMY is attempting to address an urgent materiel release to address specific concepts of operations to counter a defined hard target and soft target threat. Artillery rounds are traditionally fired as a volley of 6 rounds; therefore, firing solutions under 6 rounds are ideal, but solutions less than 6 volleys (36 rounds) are considered operationally acceptable in this scenario. There are three munitions presently in service: Munition A, Munition B, and Munition C.

Table 1 details the three baseline artillery rounds and their associated range-dependent delivery error budgets. Munition A is an HE munition which achieves lethality through a combination of blast and fragmentation effects and has moderate delivery errors. Munition B is a precision munition which achieves lethal effects via dispensing an explosively charged penetrator (EFP) and has negligible delivery errors due to its guidance package. Munition C is an area payload munition with six submunitions, each of which have one EFP, and large delivery errors. Note that this means that in the simulation, Munition A can engage an unlimited number of targets per round, Munition B can engage one target per round, and Munition C can engage at maximum six targets per round.

Mean point of impact (MPI) and precision errors, in the range and deflection directions increase with mission range distance. The addition of guidance, as Munition B always has, is costly but negates these errors. While error data shown in Table 1 are fictional, SMEM has the capability to integrate error data sourced from live fire test data or from firing tables derived from physics-based simulations.

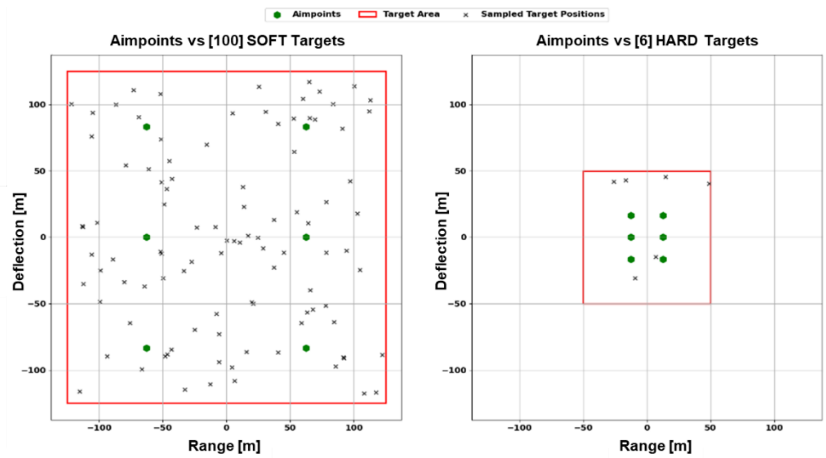
Table 1: Range Dependent Delivery Errors

All information regarding targets, munitions, and conditions is **notional**; sample data and analysis generated does not represent any specific system or actual circumstance

		MPI [m]		Precision [m]	
Munition	**Range (Distance)**	**Range (Direction)**	**Deflection (Direction)**	**Range (Direction)**	**Deflection (Direction)**

A	Short	100	30	50	10
	Mid	150	40	60	20
	Long	200	50	70	30
B	Short	0	0	0	0
	Mid	0	0	0	0
	Long	0	0	0	0
C	Short	150	40	60	20
	Mid	200	50	70	30
	Long	250	60	80	40

The effectiveness of each munition is evaluated against two target arrays (Figure 2) at three range conditions (Short, Mid, Long) by three levels of TLE (50 m, 100 m, 200 m). The Soft target is comprised of 100 targets randomly emplaced in 250 by 250 m area. The hard target is comprised of 6 targets randomly emplaced in a 100 by 100 m area.



All information regarding targets, munitions, and conditions is **notional**; sample data and analysis generated does not represent any specific system or actual circumstance

Figure 2: Notional target arrays for the Soft Target (left) and Hard Target (right)

A vendor has proposed potential upgrades for the munitions, each with their own cost and time schedules. For Munition A, the vendor proposes improvements to increase its blast effect radius and Pk (A-2), add guidance to negate delivery errors (A-3), or to both increase blast effect radius and Pk, and add guidance (A-4). For Munition B, the vendor proposes improvements to increase Pk (B-2). And for Munition C, the vendor proposes improvements to increase Pd, Ph and Pk (C-2); increase effect radius (C-3); or both improve Pd, Ph, and Pk, and increase effect radius (C-4). The baseline munitions and the vendor-proposed improvements are summarized in Table 2; highlighted cells indicate munition enhancements over baseline.

Table 2: Munition Baseline Specs and Vendor-Proposed Improvements

All information regarding targets, munitions, and conditions is **notional**; sample data and analysis generated does not represent any specific system or actual circumstance

Munition	Version	Effect Radius (m)	Pd	Ph	Pk Hard Target	Pk Soft Target	Delivery Errors	Round Cost ($K)	Time to Field (yr)
A	Baseline	20	1	1	0.3	0.8	Range Dependent	2	--
	2	40	1	1	0.7	0.9	Range Dependent	13	2
	3	20	1	1	0.3	0.8	0	13	1
	4	40	1	1	0.7	0.9	0	25	3-4
B	Baseline	200	0.8	0.9	0.5	0.9	0	70	--
	2	200	0.8	0.9	0.6	0.95	0	105	3
C	Baseline	50	0.7	0.7	0.1	0.7	Range Dependent	10	--
	2	50	0.8	0.8	0.2	0.8	Range Dependent	15	1
	3	100	0.7	0.7	0.1	0.7	Range Dependent	20	2

	4	100	0.8	0.8	0.2	0.8	Range Dependent	25	2-3

The lethal effect radius represents the blast radius for Munition A, and the munition engagement basket radius for Munitions B and C. Munitions B and C are sensing munitions and as such conduct a lethal search routine for targets within their respective scan patterns, which functions as their lethal effects radius; if a target is within the scan pattern, the probabilities for Pd, Ph, and Pk are applied sequentially. As munition A is an HE munition and not a sensing munition, Pd and Ph do not apply; these are set to 1 to ensure that any target(s) within the lethal effect radius, which is the munition blast radius here, are engaged by the model and subsequently evaluated for Pk.

These lethality inputs are simplistic and fictional but serve to illustrate model methodology. SMEM can also integrate high fidelity lethality data inputs from advanced physics-based models of 3-D weapon-target interactions to yield corresponding highly accurate outputs.

Data

These data are notional; all parameters selected for data evaluation including the Expected Fractional Causality (EFC) and Monte Carlo levels are standardized metrics nonspecific to any particular program, weapons system, or operational procedure. The cost and time schedules proposed in this section are fictitious and intended to show further applications of effectiveness modeling methodology.

Monte Carlo analysis is a statistical sampling method which uses random number generators to represent the uncertainty inherent in real-life parameters such that following an appropriate number of study specific iterations, the random physical processes of the original problem are reflected in the probabilistic outcomes to mimic real-life results. Conducting a sensitivity analysis to determine the number of Monte Carlo iterations necessary to achieve results convergence is imperative to Monte Carlo analyses. Sensitivity analyses for the munition target combinations detailed in this paper indicated convergence of the mean EFC below 300 Monte Carlos. To ensure result convergence across all cases in the scenario, each R2D solution represents the average of 500 Monte Carlos.

Effectiveness data is evaluated at 0.3 EFC, which signifies the number of rounds required to kill 30% of targets in an array. 0.3 EFC is a widely accepted metric for achieving enough target kills to meet operational requirements. In effectiveness modeling methodology, other EFC levels could be selected to alternatively model neutralization, suppression, or complete kills for targets. Table 3 delineates the number of R2D required to achieve 0.3 EFC, for each munition at three ranges and three levels of TLE. Table 4 represents the product of the cost and R2D solution at 0.3 EFC for every combination of munition, range, and TLE. Users can specify a maximum number of firing missions in SMEM input files so the model ceases to run for cases after an unreasonably high number of rounds are fired; in this scenario the maximum mission number is set to 50 volleys (300 rounds). Cells with “n/a” in Table 3 – Table 4 indicate that the R2D solution is greater than 300 for those cases.

Table 3: R2D Results, Evaluated at 0.3 EFC

All information regarding targets, munitions, and conditions is **notional**; sample data and analysis generated does not represent any specific system or actual circumstance

		SOFT Target									**HARD Target**								
		TLE (m)									**TLE (m)**								
		50			100			200			50			100			200		
		Range (Distance: Long, Mid, Short)									**Range (Distance: Long, Mid, Short)**								
		L	M	S	L	M	S	L	M	S	L	M	S	L	M	S	L	M	S
Munition A	Baseline	72	56	44	92	75	60	164	142	129	111	78	57	179	139	104	n/a	n/a	n/a
	v2	16	13	9	21	17	14	39	34	28	15	12	8	23	19	15	52	44	43
	v3	30			47			116			27			81			n/a		
	v4	6			10			26			5			16			60		
B	Baseline	38			39			55			5			6			10		
	v2	37			38			52			4			5			9		
C	Baseline	35	28	23	41	34	28	64	61	52	49	36	27	71	54	46	128	119	99
	v2	27	22	19	33	27	22	53	45	41	22	17	13	32	25	20	53	53	45
	v3	25	21	18	28	24	21	43	38	36	21	17	13	29	23	19	50	43	41
	v4	19	17	14	23	20	17	34	31	27	11	9	7	13	12	9	26	23	19

Table 4: Cost to Achieve 0.3 EFC

All information regarding targets, munitions, and conditions is **notional**; sample data and analysis generated does not represent any specific system or actual circumstance

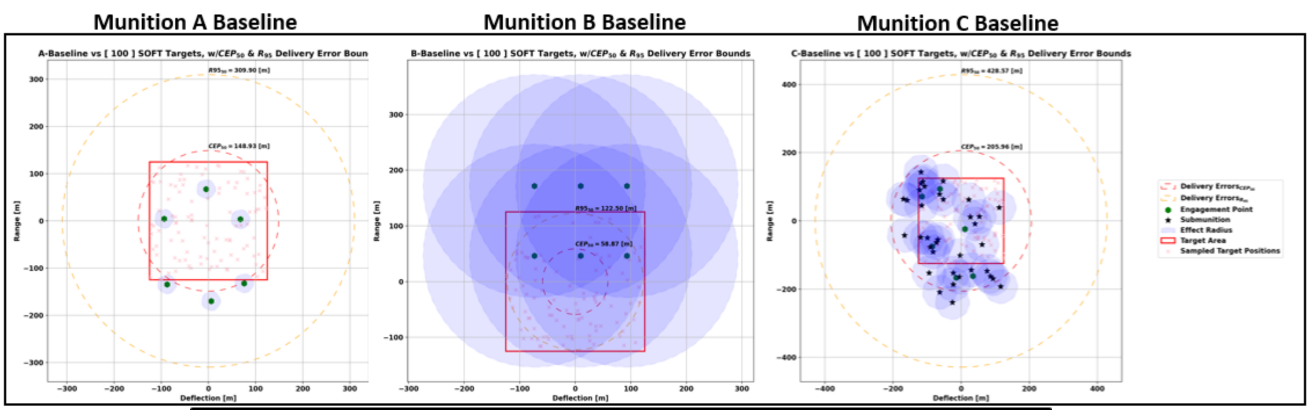
Munition		SOFT Target TLE (m) 50 L	M	S	100 L	M	S	200 L	M	S	HARD Target TLE (m) 50 L	M	S	100 L	M	S	200 L	M	S
A	Base-line	144	112	88	184	150	120	328	284	258	222	156	114	358	278	208	n/a	n/a	n/a
A	v2	208	169	117	273	221	182	507	442	364	195	156	104	299	247	195	676	572	559
A	v3	390			611			1508			351			1053			n/a		
A	v4	150			250			650			125			400			1500		
B	Base-line	2660			2730			3850			350			420			700		
B	v2	3885			3990			5460			420			525			945		
C	Base-line	350	280	230	410	340	280	640	610	520	490	360	270	710	540	460	1280	1190	990
C	v2	405	330	285	495	405	330	795	675	615	330	255	195	480	375	300	795	795	675
C	v3	500	420	360	560	480	420	860	760	720	420	340	260	580	460	380	1000	860	820
C	v4	475	425	350	575	500	425	850	775	675	275	225	175	325	300	225	650	575	475

Range (Distance: Long, Mid, Short)

Results

This data is notional; results and analysis generated from fictitious data input likewise inherit the fictitious quality and conclusions are unrepresentative of reality. The purpose of the results discussion and data analysis is twofold: first to illustrate, by way of a notional scenario, how users can employ effectiveness modeling techniques to isolate which munition parameters drive target specific lethality and effectiveness in the "Results" subsection; and second, to show further applications of the methodology in assessing effectiveness data conjointly with other parameters like cost and environment to determine the best operational solutions in the "Analysis" subsection.

Soft Target



All information regarding targets, munitions, and conditions is **notional**; sample data and analysis generated does not represent any specific system or actual circumstance

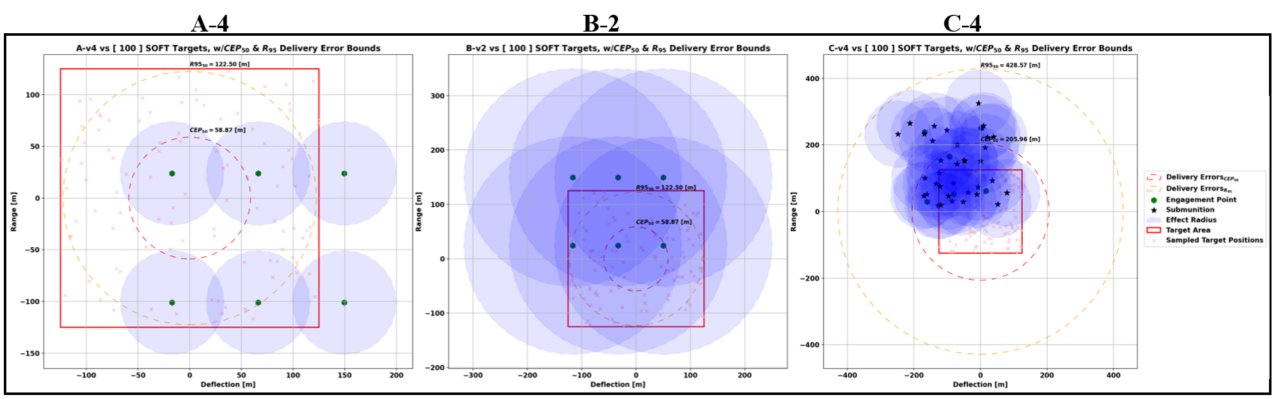
Figure 3: Monte Carlo visualization of Munition A, B, and C Baseline at Short Range delivery errors and 50m TLE

The Circular Error Probable 50 (CEP_{50}) is the radius in which 50% of munitions land given a particular error budget. Likewise, the R_{95} represents the radius in which 95% of munitions fall given the cumulative effects of an error budget. In the visualizations provided by Figure 3 – Figure 5, the CEP_{50} and R_{95} inscriptions represent the resultant areas in which a respective 50% and 95% of munitions fall given cumulative MPI, Precision errors, and TLE for each munition. The locations of the engagement points and submunitions, and their lethal effects, are single Monte Carlo representations as a function of TLE and range dependent delivery errors. Figure 3 depicts a Monte Carlo visualization of Munition A, B, and C Baseline cases versus the soft target given the minimum TLE and range dependent delivery errors for this scenario.

Munition A baseline ostensibly provides the best solution against the soft target overall from a pure cost analysis perspective. Without examining R2D output data from SMEM, incentive to pursue munition upgrades to counter the soft target is absent. However, additional factors must be considered. Munition A baseline against the soft target has a very high R2D solution: from 44 rounds (short range, 50m TLE, shown in Figure 3) to 164 rounds (long range, 200m TLE). This presents challenges logistically, as it is difficult to store and transport an inflated number of rounds to kill a single soft target array. And operationally, R2D solutions as high as this are impractical if not impossible. Typically, rounds are fired as 6-round volleys; 44-164 rounds cannot be fired simultaneously and must instead be fired 6 rounds at a time with time to cool down in between each instance to avoid overheating. As soon as the first volley is fired, the enemy is alerted to artillery positions and may commence movement or counterbattery fire. Thus, while inexpensive, the legacy Munition A baseline case is no longer fieldable. Analysis of effectiveness results in addition to munition cost is necessary to determine best operational solutions.

Versus the soft target, Munition B is exorbitantly expensive and fails to provide a R2D solution under the operationally acceptable benchmark of 6 volleys (36 R2D) for this scenario. Munition C is the only baseline case able to meet the sub-6 volley operational requirements in the scenario for lower levels of TLE and shorter range combinations. This is a current operational limitation in the scenario: there is no acceptable R2D or cost solution among the baseline munitions to counter the soft target at the 200 m TLE level at any range, and at the 100 m TLE level at long ranges. This is not the type of limitation that would be first identified by effectiveness analyses; the US ARMY would already be aware of the performance capabilities and limitations of munitions in service. Effectiveness analyses can however be used to illuminate the space representing potential munition upgrades, rapidly generating data to predict the effectiveness of next-generation warhead concepts, to inform decisions as to which concepts provide the greatest capability enhancements for the lowest cost.

Munition ability to engage many targets per round drives effectiveness against the soft target. As shown in Figure 4, increasing munition effects radius from 20m to 40m for Munition A notably decreases R2D for this munition, but the 200m effects radius of Munition B is not significant enough, especially given that the original 100m effects radius is large enough to cover the entire target area, to overcome limitations as a unitary engagement round against a numerous target set. Munition B has the largest effects radius and near total lethality against the soft target, but because it only dispenses one projectile per munition it can never kill more than one soft target at a time; to achieve 0.3 EFC against an array of 100 targets, a R2D solution under 30 is impossible. Therefore, this munition never presents an acceptable R2D or cost solution against the soft target.



All information regarding targets, munitions, and conditions is **notional**; sample data and analysis generated does not represent any specific system or actual circumstance

Figure 4: Monte Carlo Visualization vs the Soft Target of A-4, B-2, and C-4 at short range and 50m TLE

Upgrades to Munition C, limited by a six target engagement per round and low kill chain probabilities, never present a competitive cost or R2D solution compared to Munition A upgrades. Based on these data, the analyst could return to the vendor and propose that investigating upgrades to instead increase the number of submunitions or increase Pd, Ph, and Pk may make upgrades for Munition C a more worthwhile investment for use against the soft target.

Hard Target

Of the Munition A, B, and C Baseline case, Munition B Baseline initially provides the most cost and round effective solution against the hard target at all TLEs. However, analysis of munitions effectiveness data of the potential munition upgrades from SMEM shows that with the vendor-proposed upgrades to develop A-4, an equivalent 5-R2D solution at 50m TLE can be achieved for half the cost. However, data show that this cost and performance improvement of A-4 against the hard target does not continue at the 100m and 200m TLE levels.

Munitions with submunition payloads are more resilient against increased TLE because the carrier dispense of submunitions covers a larger target area to begin with compared to the smaller lethal area of unitary rounds. The effect of TLE is also more pronounced against a sparsely populated target, like the hard target array in this scenario. This is evidenced by the effectiveness data, with R2D solutions increasing more rapidly for Munition A than Munition C as TLE increases. While Munition B also has a unitary round dispense, its large scan pattern mitigates the impact of increasing TLE.

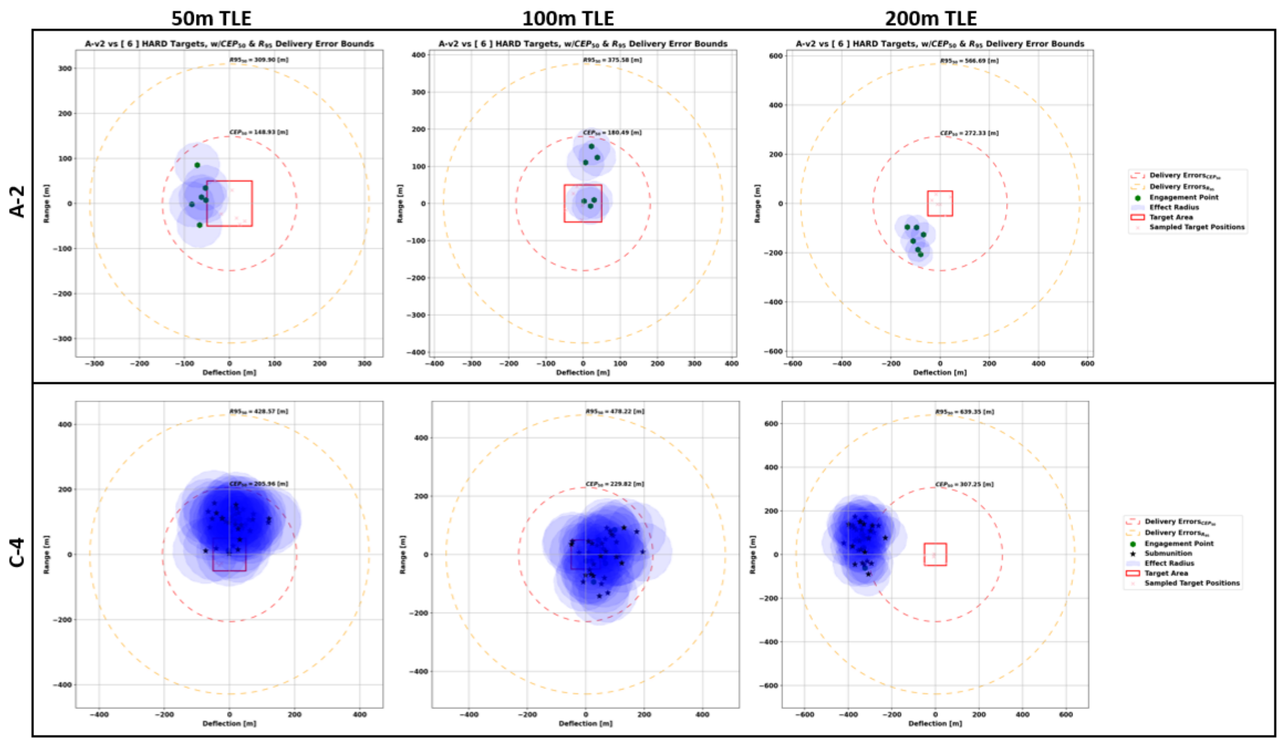
Guidance environment agnostic, while Munition C does show less sensitivity to increased TLE and munition delivery errors over Munition A, neither Munition C nor any of its upgrades stand out over Munition B Baseline or A-4 as worthwhile cost or R2D solutions in addressing the hard target.

Analysis

Effectiveness modeling methodology can be further applied to inform decisions about munition upgrade investments, and current and anticipated future operational scenarios. While this analysis is notional, it serves to provide examples of some of the advanced implementations of munitions effectiveness data: examples included in this section are analyses of effectiveness data to inform operational loadout decisions, and to anticipate the effects of increased enemy electromagnetic warfare capabilities in future combat theaters. Results from SMEM can be used to pinpoint specific munitions improvements with the greatest potential to provide enhanced performance and operational capability to address such items.

Exclusive examination of the baseline munition cases could inform current operational loadout decisions while awaiting the more attractive vendor-proposed upgrades which are one to four years away. Munition B is the only baseline case which provides a viable R2D or cost solution against the hard target. While the Munition A baseline case provides the cheapest cost solution against both the soft target and the hard target, Munition A baseline cannot be fielded due to the logistical and operational challenges discussed in the "Soft Target" subsection. To counter the soft target, Munition C is the only baseline case able to meet the sub-6 volley operational requirements in the scenario for lower levels of TLE and shorter range combinations; currently there is no acceptable R2D or cost solution among the baseline munitions to counter the soft target at the 200 m TLE level at any range or and at the 100 m TLE level at long ranges. Therefore, the data support continuing to field Munition B and C baseline versions in operational loadouts to counter the hard and soft target, respectively, with the caveat that Munition C only provides capability against the soft target at the 50 m TLE level and at the 100 m TLE level at short and mid ranges.

Guidance environment is an essential consideration in munitions effectiveness analyses. Electromagnetic warfare is increasingly common in the modern combat theater. This means it is important for the US ARMY to obtain accurate data of munitions performance in environments where guidance is partially or entirely unavailable. In the scenario presented here for Munition A in an environment where guidance is unavailable, A-4 performance becomes equivalent to A-2 and A-3 becomes equivalent to Munition A Baseline. Munition B becomes ineffective in a guidance denied setting against either the soft or the hard target, as its guidance package would fail, and significant range-dependent ballistic delivery errors would apply instead. Considering this environment, A-2 stands out as the best solution against the soft target at all TLEs and against the hard target at close range and low TLE while C-4 is the most suitable to counter the hard target at increased range and TLE. Figure 5 illustrates the how the submunition dispersion of C-4 provides increased lethal area coverage provided to overcome greater range dependent delivery errors and resulting CEP_{50} to emerge as the best candidate munition versus the hard target at high TLE.



All information regarding targets, munitions, and conditions is **notional**; sample data and analysis generated does not represent any specific system or actual circumstance

Figure 5: Monte Carlo Visualization comparing short range 6-round volley dispersion of A-2 (top) vs C-4 (bottom)

Therefore, these data support investing in A-2 and A-4 for improved effectiveness and reduced cost against the soft target in unguided and guided scenarios, respectively. The vendor-proposed lethality enhancements for B-2 yield marginal effectiveness improvements for a high cost; data does not support investing in this upgrade. The data also back investing in C-4 to address the hard target in guidance denied environments.

In future operational loadout decisions anticipating uncertainty regarding guidance availability, data support providing A-4 and A-2 versus the soft target for guided and unguided environments, respectively. To counter the hard target, results recommend a loadout including Munition B Baseline, A-2, and C-4. When guidance is available, Munition B Baseline provides the most cost and round effective solution against the hard target. However, in anticipation of environments where guidance is unavailable, A-2 is the most cost and round effective solution at close range and low TLE while C-4 provides capability at long range and increased TLE.

CONCLUSION

SMEM meets critical demand, heightened by current world events, for accurate performance assessment of existing munitions against an extensive array of targets under a variety of tactical, environmental, and climactic conditions. The research and development, design, and field testing of munitions is time, money, and resource intensive. And while effectiveness models should never be used to replace live safety and performance testing, SMEM can be used to inform critical decision making to accelerate the research and development of future munitions and reduce the time and resource cost involved in the performance evaluation of existing munitions. The example scenario included in this paper emphasizes the importance of comprehensive analyses and illustrates the pertinence of munitions effectiveness data to a variety of engineering, operational, and fiscal decisions. Development of powerful and flexible effectiveness models like SMEM is of particular significance to the US ARMY given critical objectives to rebuild a recently depleted munitions stockpile and to identify specific warhead improvements to maintain its technological edge and provide a full range of operational capability in diverse future combat theaters.

ABBREVIATIONS AND ACRONYMS

AJEM	Advanced Joint Effectiveness Model
AOF	Angle of Fall
ATR	Automatic Target Recognition
DEVCOM-AC	Combat Capabilities Development Command - Armaments Center
DEVCOM-DAC	Combat Capabilities Development Command - Data & Analysis Center
CEP	Circular Error Probable
EFC	Expected Fractional Casualty
EFP	Explosively Formed Penetrator
FOV	Field of View
GAMES_SAD	Guided Munitions Effectiveness Simulations – Sense and Destroy
GUI	Graphical User Interface
JTCG-DEM	Joint Technical Coordinating Group – Delivery Error
KCLO	Kill-Chain Logic Options
LoFi	Low Fidelity
LSPP	Lethal Search Pattern Polygons
MPI	Mean Point of Impact
Pd	Probability of Detection
Ph	Probability of Hit
Pk	Probability of Kill
Pr	Probability of Recognition
PRISM	Performance Related and Integrated Suite of Models
R2D	Rounds to Defeat
SFM	Sensor-Fuzed Munitions
SMEM	Smart Munition Effectiveness Model
TLE	Target Location Error
VMAP	Vulnerability MAPs
VV&A	Verification, Validation & Accreditation