Development of New Standard Vulnerability Metrics for Training and Analytical Combat Models & Simulations

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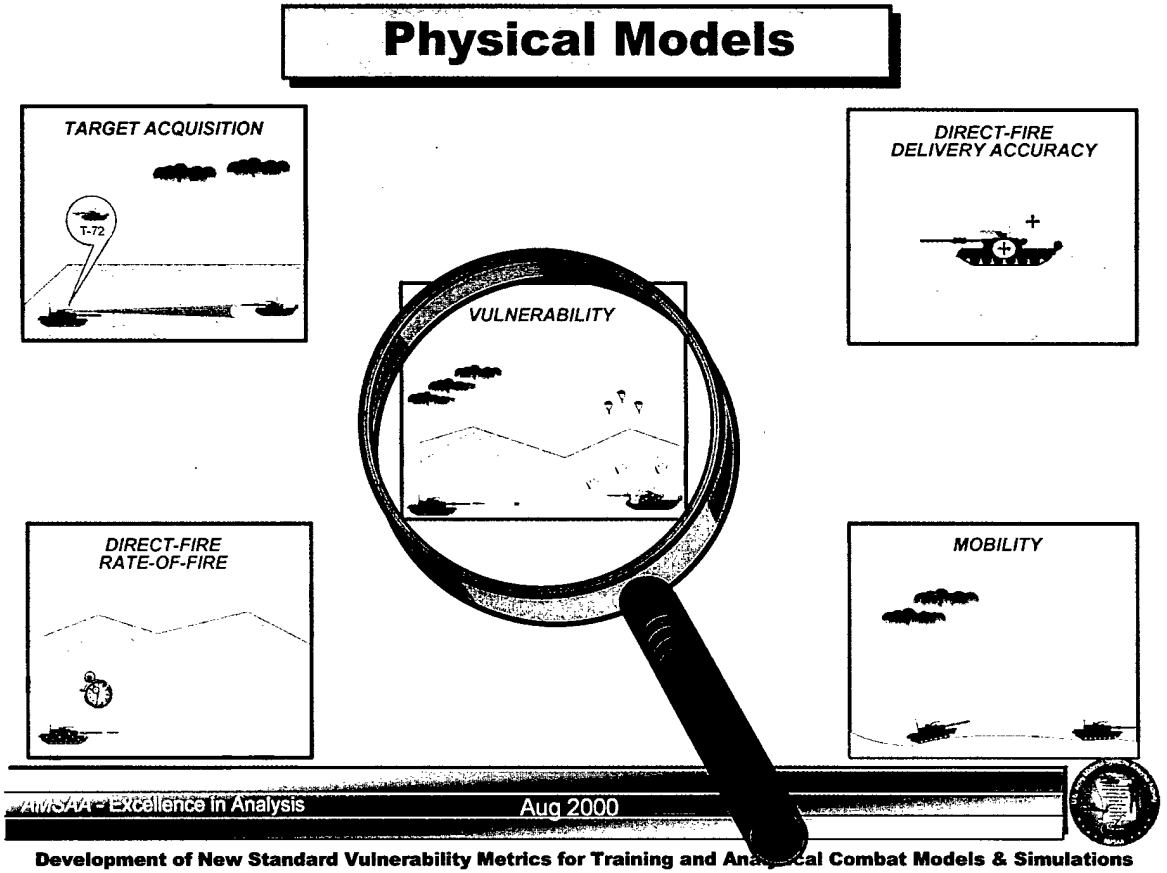
This handout describes the rationale for development of new standard vulnerability metrics for training and analytical combat models and simulations. It covers the current traditional vulnerability metrics and the present status of proposed new vulnerability metrics. It also compares current and proposed vulnerability metrics, including a theoretical perspective. First, an overview is provided on the development of the traditional vulnerability metrics, including its implementation in Army combat simulations. Second, an overview of the vulnerability taxonomy, developed by the Army Research Laboratory (ARL), is provided as insight into how vulnerability should be modeled from a theoretical perspective. Third, an overview of the new vulnerability metrics projects is provided, including objectives, proposed vulnerability metrics, FY00 accomplishments, and future activities.



Most Army combat models and simulations have physical models to estimate the performance of a weapon system in each of the areas of systems performance shown above. This handout focuses on the methodology and fidelity of the vulnerability metrics used in most entity-level combat models and simulations in the Army.

Current Combat Simulations*

Combat Simulation*	Primary Applications TEMO	ACR	RDA
BEWSS		X	X
CASTFOREM	X		
CCTT	X		
GWARS		X	X
ITEMS		X	X
JANUS	X	X	
JCATS	X		
JCS	X		
JTS	X		
ModSAF		X	X

* Entity Level Resolution

All current combat simulations use the same standard vulnerability metrics and data and model/assess vulnerability similarly with varying degrees of resolution.

With few exceptions, all current entity-level combat models and simulations use the same vulnerability metrics, with varying degrees of resolution. These combat models and simulations are used for various purposes within the training, research, and acquisition management domains. These combat models and simulations use vulnerability metrics at different levels of resolution because of the impact of these metrics on model/simulation outcome and design limitations of the model/simulation. Unit-level combat models and simulations use different vulnerability metrics that typically combine vulnerability metrics with other areas of systems performance, such as delivery accuracy.

Component Damage/Failure

To help understand how vulnerability should be modeled, the following pages illustrate a different phase of the engagement process starting from the point of a threat impacting a target vehicle. In the real world, when a vehicle is impacted by a threat, the explosion of the threat directly or indirectly causes damage to components of the vehicle.

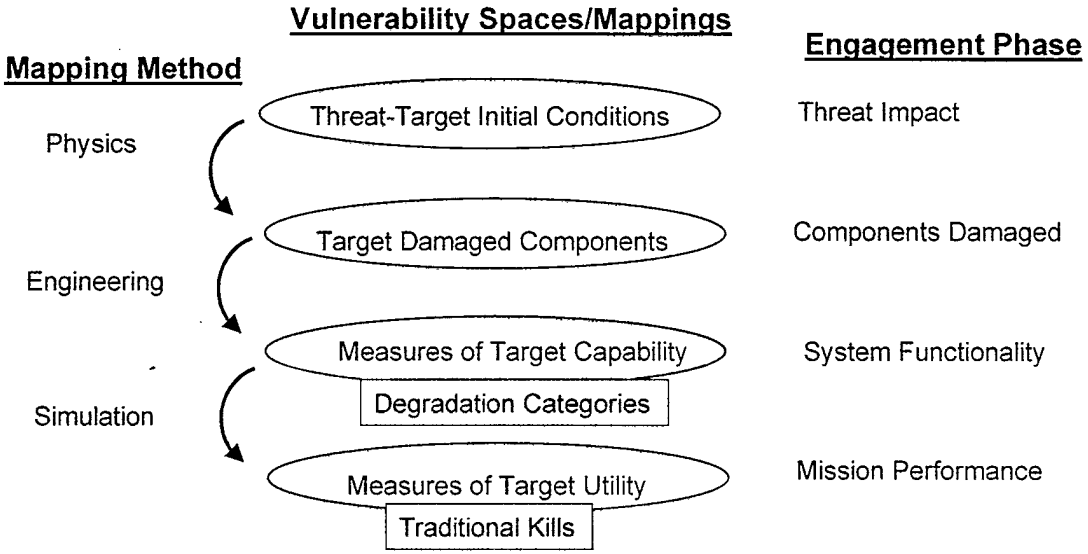
System Functionality/Capability

The failure of the damaged components will directly or indirectly result in the lack of one or more vehicle capabilities.

Mission Utility/Performance

Finally, the vehicle must perform in a mission role that might require some of the non-functioning capabilities.

Vulnerability Taxonomy Mapping Abstraction



Source: "The Generation, Use, and Misuse of "PKs" in Vulnerability/Lethality Analysis", Dr. Deitz, Dr. Starks, ARL/SLAD

This is a pictorial abstraction of the vulnerability process, or taxonomy, developed by ARL for a typical engagement as discussed in the preceding slides. From the events or phases that exist in an actual engagement, we can utilize modeling and simulation to estimate the data to represent the damage state of the vehicle at each step of the engagement phases. Physics models can estimate the damaged components given specific threat-target conditions. Through an engineering process, such as fault trees, the target capabilities can be assessed from the condition of those components that are still functioning. Finally, combat simulation can use the target capability assessments to simulate the vehicle's performance in a specific mission role.

Since the traditional vulnerability metrics don't address target capabilities and directly map damaged components to mission utility via the Damage Assessment List (DAL) process, the traditional vulnerability metrics have several inconsistencies. The development of new standard vulnerability metrics follows the vulnerability taxonomy by developing vulnerability data at the target capability space, allowing simulations to model the target utility space.

Traditional Kill Category Background

- Limited computer technology
  - Limited data storage
  - Limited processing speed
- Simple combat models & simulations
  - Limited behaviors
  - Limited visual effects
  - Limited performance degradation
- Limited vulnerability models
  - Unknown physical effects
  - Simplistic target descriptions (Blue & Ret)
  - Few damage mechanisms

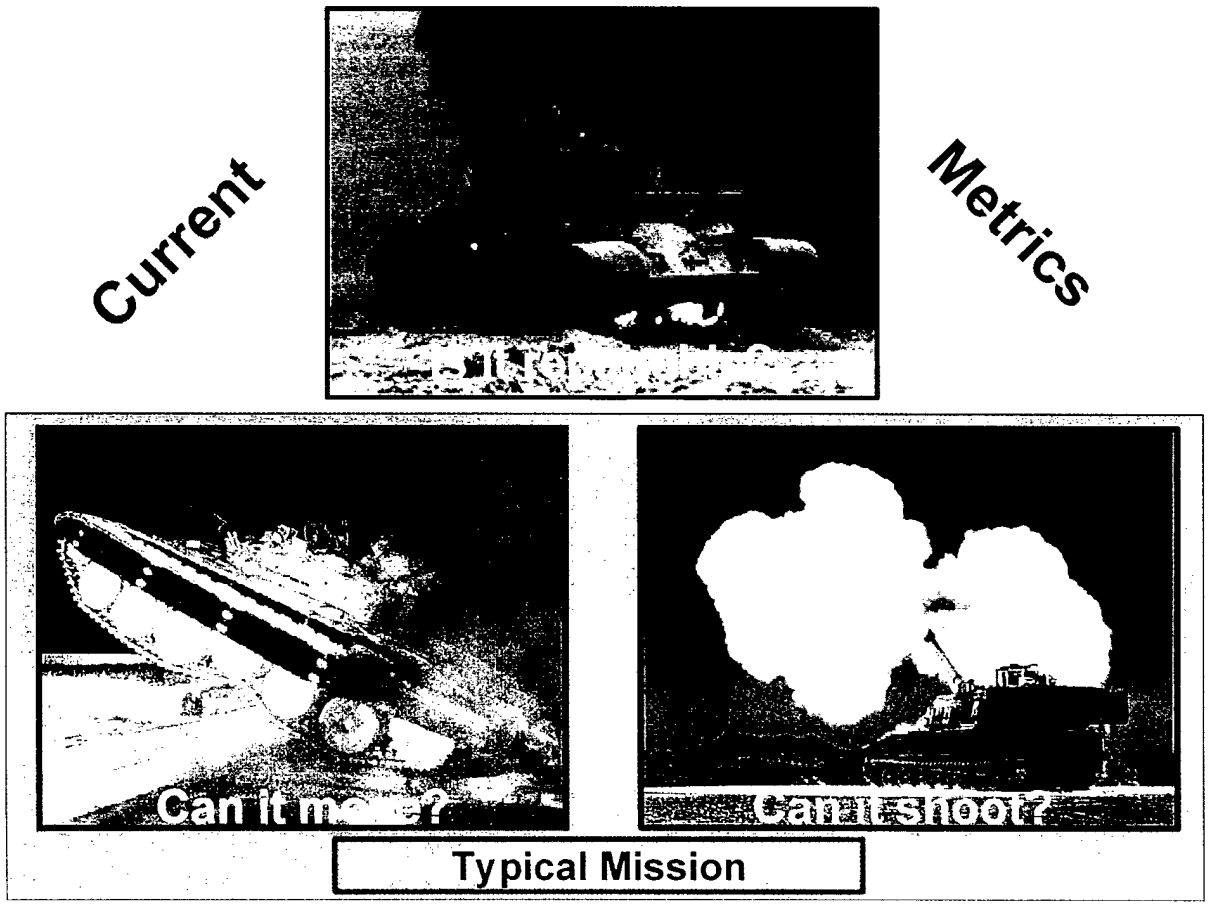
1950's - 1980's: Traditional kill categories developed.

1980's - present: Live-Fire Program and technology have driven changes in modeling and simulation. Users prefer higher resolution of vulnerability data.

The traditional vulnerability metrics were first developed by ARL in the late 1950's and early 1960's. The development of vulnerability data used relatively simplistic, compartment-level vulnerability models primarily because of limited computer technology and limited understanding of the physical effects of weapon performance. Hence, the vulnerability metrics were designed to model the vulnerability of weapon system as it directly related to the system's performance in a typical combat mission at the system level.

In the early 1980's, the live fire program drove changes to improve the accuracy and fidelity of vulnerability models still in use today. These changes included improved representation of the physical effects of threat weapons and modeling targets at a component-level.

Today, combat simulation users desire to model vulnerability at a higher resolution and computer technology has made this change feasible.



These pictures illustrate the kill categories represented in the current vulnerability metrics. The kill categories include catastrophic (repair), firepower (shoot), and mobility (move). Note that some vehicle functions seem to be ignored. Some vehicle functions are missing, such as combat service support. However, vehicle functions, such as communications, are included as indirect effects on one or more of the kill categories. In most of these cases, the behaviors of the crew must be predicted to determine their indirect effect on the kill categories.

Current vulnerability data are developed **prior** to use in a combat simulation using military experts who make subjective estimates on the impact of damaging **each** component on the mission performance of the damaged vehicle. Hence, a typical mission is assumed, and the interoperability of components are ignored. The result of such a process is the generation of data that represent the expected loss of mission utility for each kill category.

Note in the illustrations that the answers to all the questions are either "yes" or "no". Once implemented in a combat model/simulation, the vulnerability data represent the probability of complete loss of function. Hence, a weapon system attacked by a threat is either non-functional or completely functional for each of the kill categories, i.e. no degraded states are possible.

Current Vulnerability Metric Issues

- Representative of an average scenario/mission
- Do not represent all combat vehicle functions of interest, e.g., communications, surveillance, CSS
- Subjective estimates for component mission utility
- Component interoperability is ignored
- Damage is accumulated at the mission utility level (not component level)
- Partial loss of capability is not modeled
- Expected loss of function data are treated as probability of complete loss of function

This chart shows the design and implementation issues with the traditional vulnerability metrics. Most of these issues have already been discussed. There are two remaining issues not previously discussed.

First, since the vulnerability metrics represent damage at the mission level in combat simulations, vehicle damage is accumulated at the mission level, instead of at the component level. This can result in an overestimation or an underestimation of the damage after several shots. For an example of overestimation, suppose a tank suffered damage to a roadwheel (mobility kill) on the first shot and a machine gun (firepower kill). The result using the traditional vulnerability metric methodology would be a mobility kill after the first shot and a mobility-and-firepower kill after the second shot, which would result in the tank being unable to move or shoot. In reality, the overall system damage would be minimal. For an example of underestimation, assume the same first shot as before, but suppose the second shot damaged the radiator (mobility). The result using the traditional vulnerability metric methodology would be a mobility kill after the first shot, which would result in the tank being unable to move. The second shot, although additional mobility loss, would be modeled as no additional damage effects since it was already immobile after the first shot.

Modeling & Simulation Perspectives

- It would seem that the four-level (risk-to-utility assessment) structure has been with us for > 50 years. Since 1954 and the establishment of the DAL, military utility and platform capabilities have been linked.
- Various workers have considered the linkage to military utility.
- The existence of stochasticism in particular mappings has been ignored.
- Granularity, driven by military utility, a major issue:
  - Connectivity between levels
  - Premature averaging/washing out critical detail
- Given the new world order, definitions of mission outcomes/success should probably be revisited and redefined.

ARL researchers have known about the four-level vulnerability taxonomy since the beginning, but were limited to the computer technology and real world test data sufficient to characterize and model the vulnerability taxonomy. Hence, ARL had to make assumptions about some vulnerability effects and ignored other aspects. Unfortunately, the granularity of vulnerability metrics that has developed because of such limitations and assumptions, including the DAL process that prematurely averages critical detail. In the modern era of lighter, more versatile weapon systems and modern computer technology, modeling vulnerability at a more detailed level is not only feasible but necessary. However, since the combat simulation results are heavily dependent on the traditional vulnerability metrics, the measures of effectiveness or mission success in combat simulations must also be reviewed.

Project Overview

- Purpose: Develop, implement new vulnerability / lethality metrics as standards for future analytical and training combat simulations
- Participants: AMSAA, ARL-SLAD, TRAC-WSMR
- Status:
  - Two-year effort, began 1Q FY00
  - First Year Focus on Tanks, IFVs
    - Develop V/L metrics & definitions
    - Develop V/L data
    - Conduct fidelity analysis using CASTFOREM scenario
  - Second Year Focus on Artillery, Air Defense, Aviation
    - Develop V/L data
    - Conduct fidelity analysis using COMBAT^{XXI} scenario
  - Implement metrics/rules into CASTFOREM (FY00), COMBAT^{XXI} (FY01), OneSAF (FY03-04)
  - Assessment for ModSAF, CCTT SAF & Simulators (FY01)

The purpose of this project is to develop and implement new vulnerability metrics that can represent all combat systems (tanks, artillery, helicopters, etc) in such a manner as to permit various analytical and training combat simulations (present and future) to model vulnerability in a similar and realistic manner.

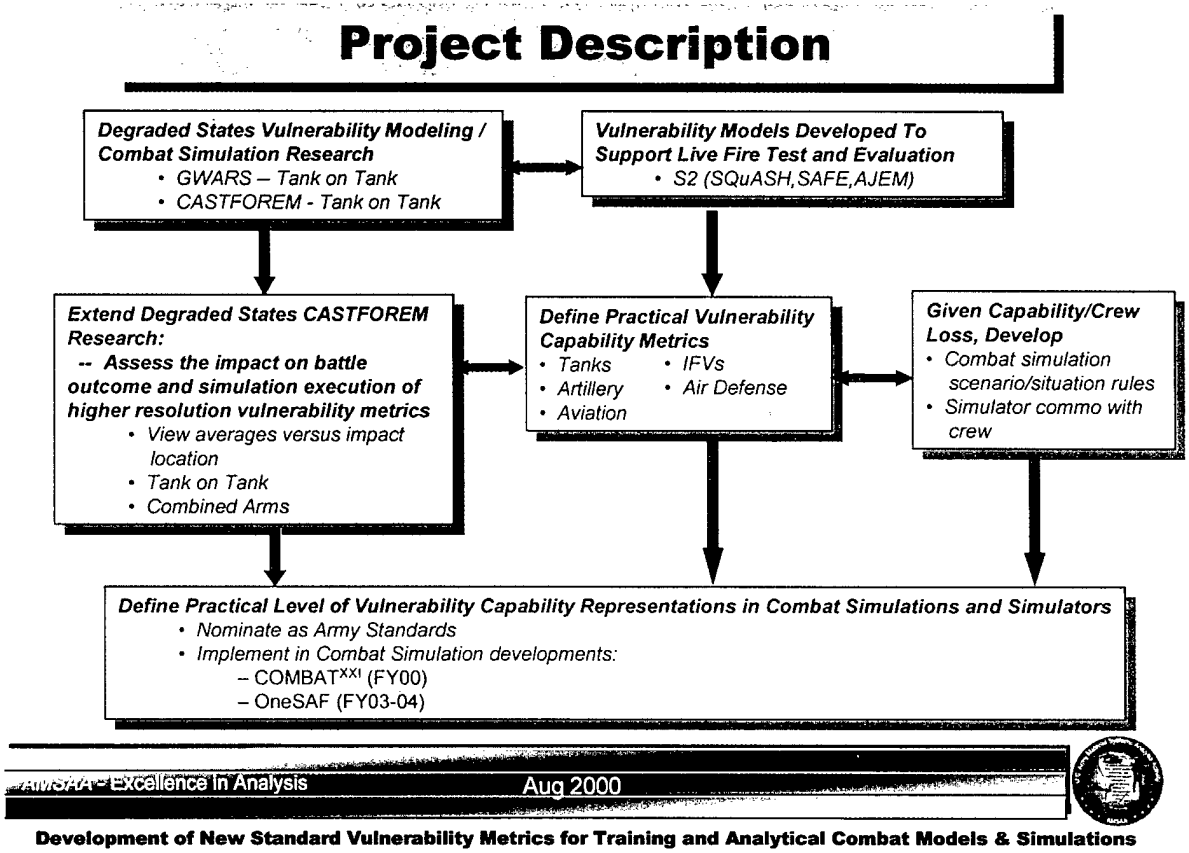
The Army Materiel Systems Analysis Activity (AMSAA) leads the development and testing of new vulnerability metrics, with technical support from the Training and Doctrine Command's Analysis Center at White Sands Missile Range (TRAC-WSMR) and the Army Research Laboratory's Survivability and Lethality Directorate (ARL-SLAD). Financial support is provided by the Live Fire Test and Evaluation (LFT&E) office.

The project is a two-year effort which began in 1Q FY00, but did not start development of vulnerability metrics until March 2000 because of programmatic issues.

Project Objectives

- Define practical set of platform capability states for classes of targets based on S2 (SQuASH/SAFE/AJEM) output
- Assess impact of high resolution metrics on battle outcomes by mapping platform capabilities to mission effectiveness
- SAF - Develop scenario/situation rules for systems that suffer loss of platform capability / crew
- Simulator - Determine damage symptoms & cues for displaying damage to crew members
- Define the practical level of vulnerability capability representation for SAFs and manned simulators
- Allow for partial functional capability states
- Increase fidelity & granularity of vulnerability estimates
- Implementable in Army combat models and simulations
- Capability to mix and match metrics (limited target descriptions)

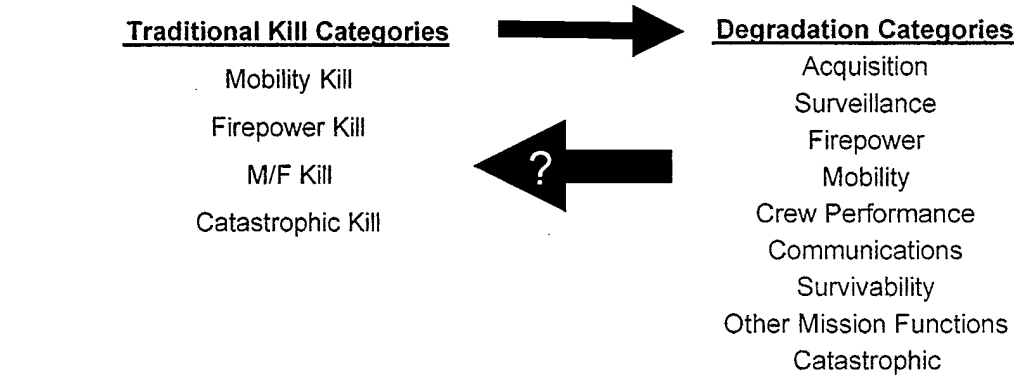
The development of new standard vulnerability metrics should utilize the current ARL S2 vulnerability estimation model, assess the impact of high resolution metrics on battle outcome (probably developing a new set of measures of effectiveness), develop rules and cues for Semi-Automated Forces and manned simulators, respectively, determine the most effective & practical level of resolution, be implementable in current Army Simulations, such as CASTFOREM & COMBAT^{XXI}, and maintain the capability to mix and match levels of metrics. Since some targets have limited target descriptions in the current S2 model, the methodology should be capable of using both low and high level resolution vulnerability metrics in a single combat simulation.



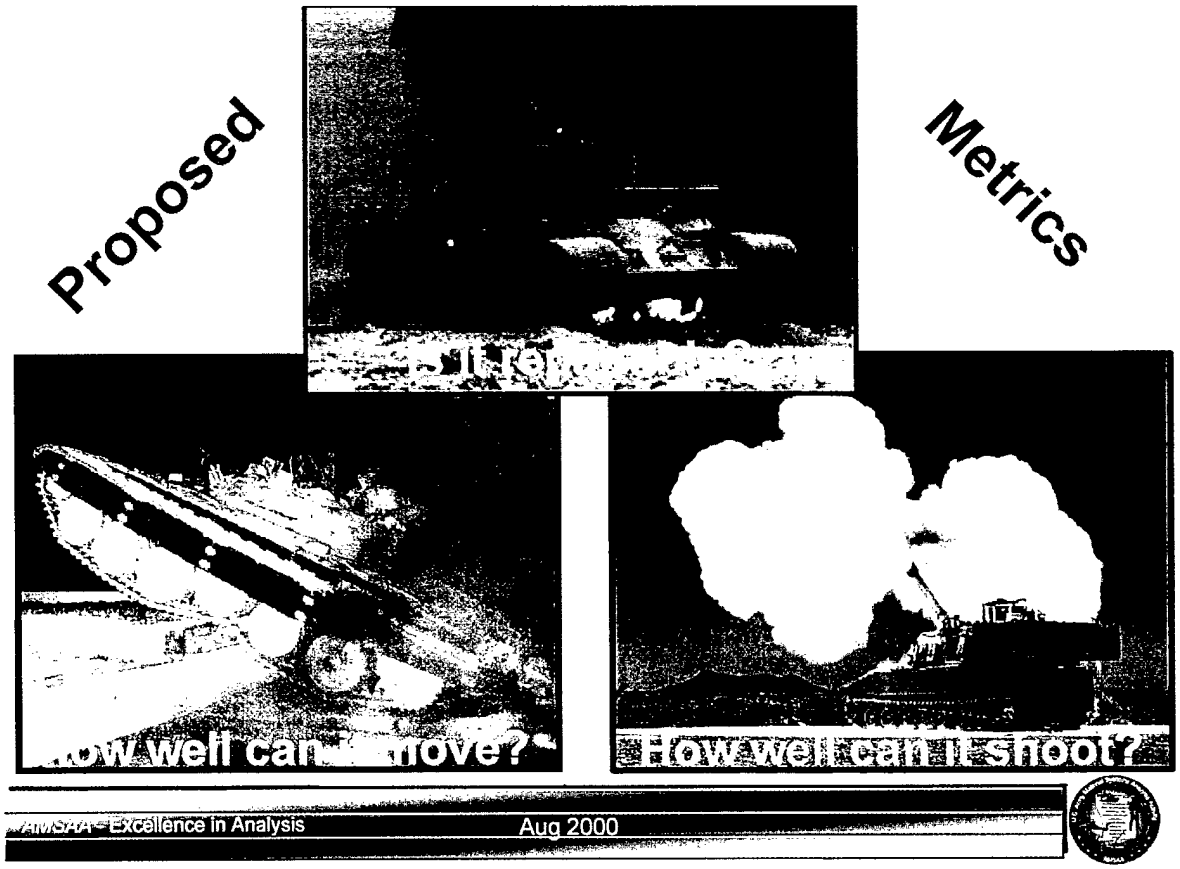
In the early 1990's, ARL initiated an effort called "degraded states", which was the forerunner to the new standard vulnerability metrics. The degraded states effort developed tank vulnerability metrics and developed fault trees for utilization in the current S2 vulnerability model. This project will extend the initial research by including other systems and analyzing the effect of various levels of granularity of the vulnerability data estimates on battle outcomes. This project will develop a single set of vulnerability metrics useable for all types of Army systems. This project will develop a set of metrics/rules for implementation into SAF and manned simulators. The final methodology will be nominated into the Army Standard Repository System (ASTARS) and implemented into COMBAT^{XXI} and OneSAF.

Degradation Categories Concept

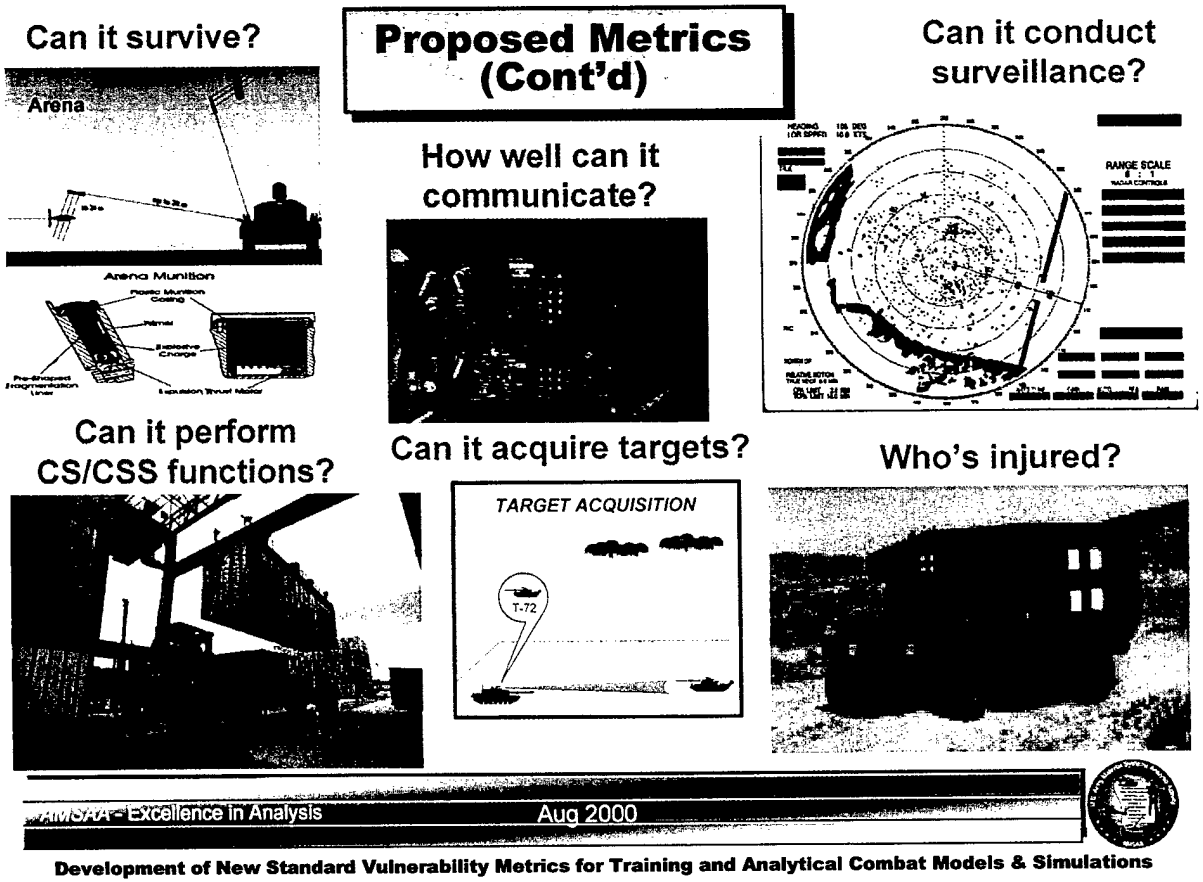
- Information Sources
  - AMSAA DSWARS Degraded States for Abrams
  - ARL Degraded States for Bradley
  - Army Standard Platform Object (July '98)



The first step in developing new vulnerability metrics was to develop a completed set of degradation categories that encompass the previous degraded states effort, traditional kill categories, and other mission functions. These degradation categories were developed using the previous degraded states efforts and the Army standard platform object, developed by the M&S community as a general approach for modeling a platform, while not precluding a mapping between the degradation categories and the traditional kill categories. This mapping has not yet been defined, but is necessary for accomplishing the capability to mix and match vulnerability metrics. It is envisioned that the vulnerability data at the degradation category level can be "rolled up" to a traditional kill category level. Note that this "rolled up" data will not have the same representation as the traditional kill metrics, since it does not utilize the DAL process.

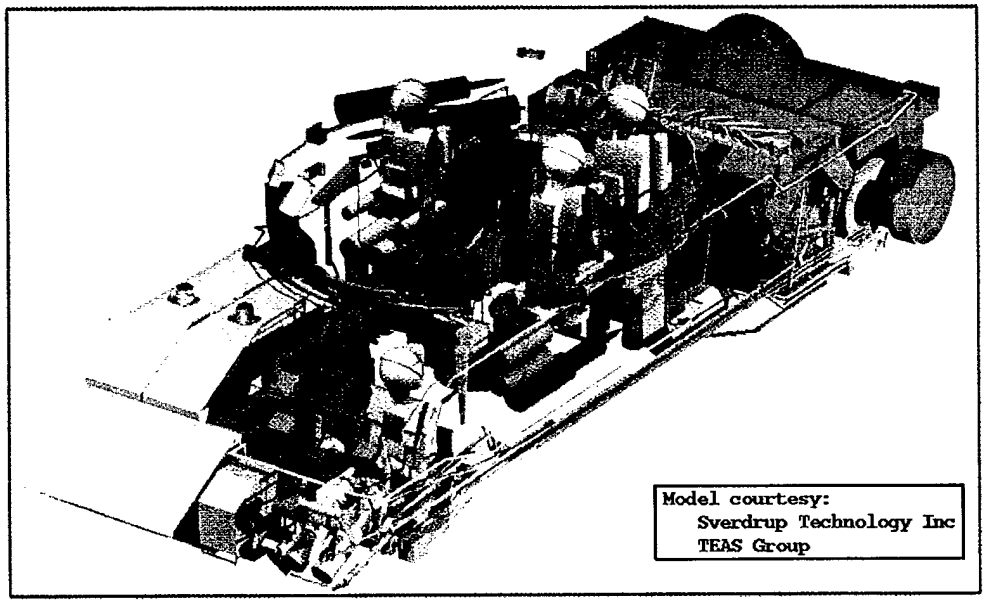


The following two charts show the proposed vulnerability metrics. This chart shows the new counterparts to the traditional kill categories: catastrophic, mobility, and firepower degradation categories. Note the questions for mobility and firepower relate to a relative measure of performance degradation or capability outside of a mission context. This is drastically different from the questions and focus of the traditional kill categories.



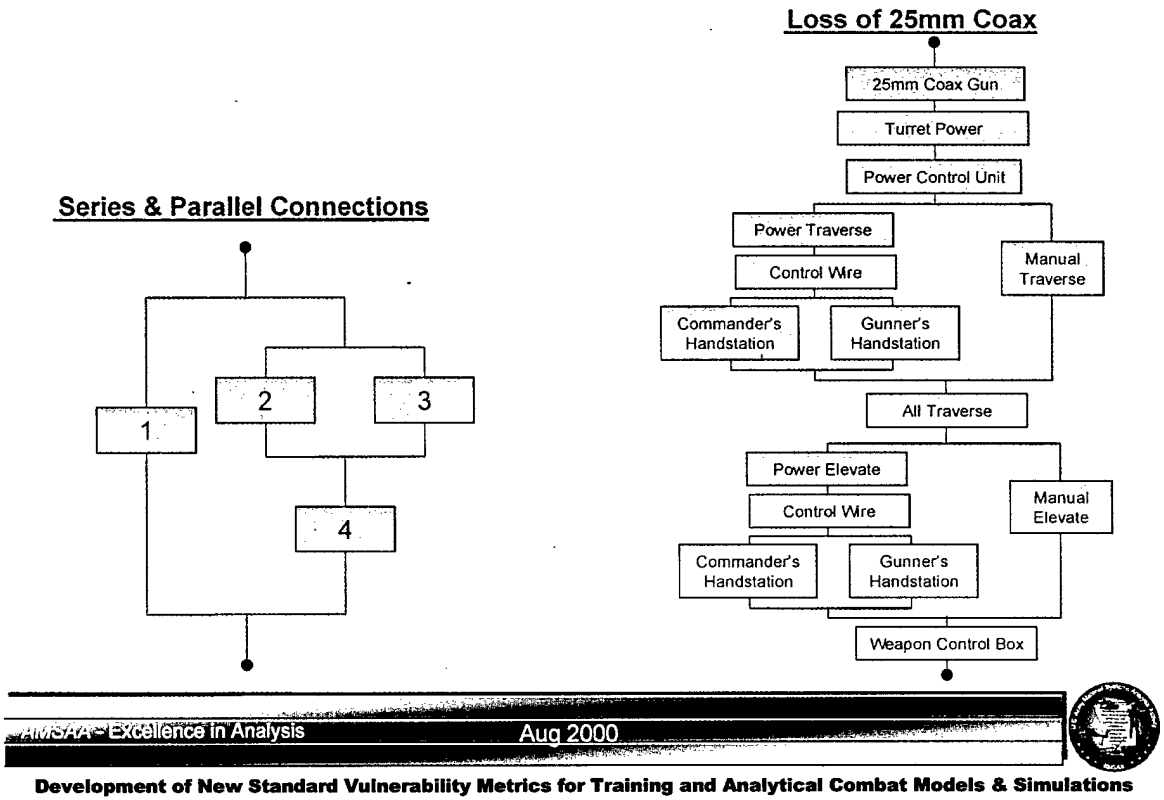
This chart shows the other degradation categories of the new standard vulnerability metrics. Some of the degradation categories will focus on the level of performance degradation or capability, while some categories are limited to a functional/non-functional level. The present M&S community believes these categories are sufficient to adequately represent the damage states that occur on the battlefield and impact the outcome of a battle.

Component-Level Vulnerability Modeling



At the core of the new standard vulnerability metrics is ARL's S2 vulnerability model. The S2 model utilizes a detailed description of a target, down to the component level. In some cases the number of components ranges in the tens of thousands. Using ballistics and physics equations and detailed data on the threat and impact conditions, the S2 model estimates the components damaged at various impact points along the vehicle. The damage data can then be averaged by 4" square area, called a cell, or averaged over an entire view, or aspect angle.

Fault Trees: Component to Capability Mapping



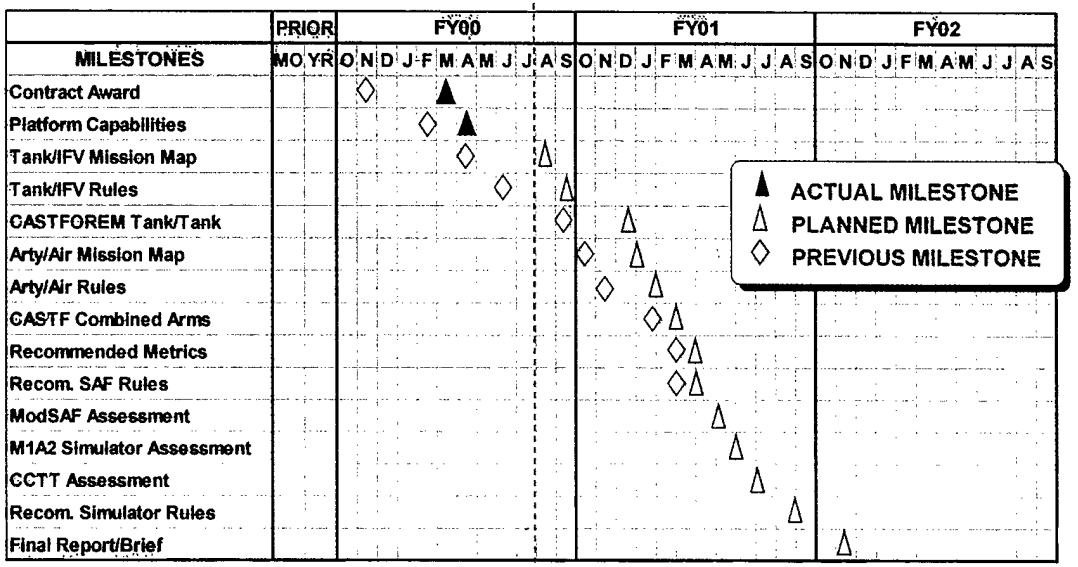
For the traditional vulnerability metrics, the damage data described on the previous slide is averaged using the DAL values as weights to develop an overall mission utility value. For the proposed vulnerability metrics, fault trees are developed which relationally connect the functionality of each component to determine the status of various degraded capability states. These degraded capability states are subdivisions of the degradation categories to model the vulnerability at a higher level of fidelity, consistent with M&S user requirements and quantifiable performance parameters. This chart shows the theory of fault trees and a theoretical example of a fault tree for the 25mm coax on the Bradley Fighting Vehicle.

New Vulnerability Metrics Benefits

- ✓ Models partial & complete system functionality loss
- ✓ Has a functional area focus across all areas
- ✓ Estimates objective probabilities of damage
- ✓ Maps component damage directly to system capabilities
- ✓ Accumulates damage at the capability-level
- ✓ Models interoperability of components
- ✓ Standardizes vulnerability metrics across various system types
- ✓ Applicable to future combat systems (FCS)

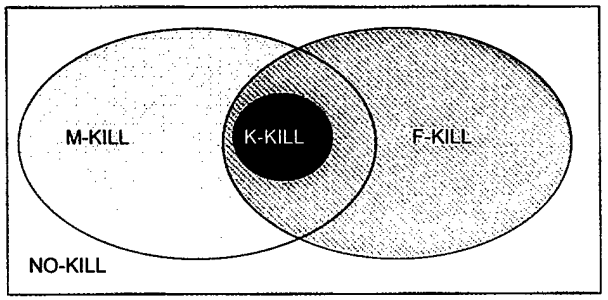
This chart summarizes the benefits of the new vulnerability metrics. Since the new vulnerability metrics methodology utilizes fault trees instead of the DAL, the vulnerability estimates are objective and focused on system capabilities independent of mission context, which follows the vulnerability taxonomy. Since the new vulnerability metrics methodology models damage at the subsystem or degraded capability states level, instead of at the mission utility level, the vulnerability estimates realistically accumulate damage over several damage events, realistically model partial damage conditions, and the interoperability of components. Since the new vulnerability metrics methodology is a general approach to systems performance, the degraded capability states can be applied in a similar manner to various types of combat systems, including future combat systems.

Project Schedule



This chart shows the current (August 2000) project schedule. Some slippage in the project has occurred due to unforeseen programmatic issues. The current slippage is not expected to impact the final completion date. NAWCSTD has funded this project through FY01.

Vulnerability Metric Comparison

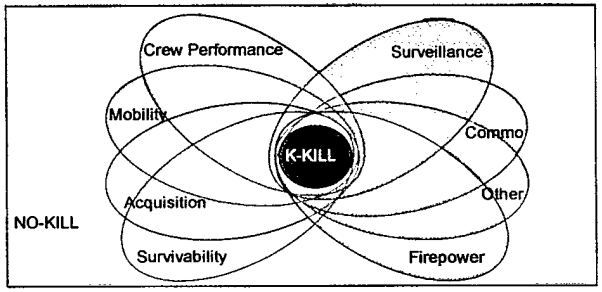


Traditional Vulnerability Metrics

- Simplified Functional Categories
- No Degraded States (all or nothing)
- Subjective Estimates
- Simplified Mission Functionality
- Interoperability of Components Ignored

Degraded Capability States Metrics

- Functional Area Focus
- Objective Estimates
- Maps Component Damage to Capabilities via Fault Trees
- Higher Fidelity of Mission Functionality



This chart summarizes, using venn diagrams, the differences between the traditional and proposed vulnerability metrics. It is clear that model users desire more fidelity of vulnerability in combat simulations. It is yet unclear as to how the higher fidelity will impact the battle outcome, although it is expected that higher fidelity modeling will result in more realistic behaviors and tactics. In order for all the M&S domains to utilize the new vulnerability metrics, significant testing and analysis must be accomplished to verify and validate the differences between the various implementations of the two sets of vulnerability metrics.

FY00 Activities

- Develop vulnerability methodology (AMSAA/SLAD)
  - ✓ Define degradation categories and degraded capability states (AMSAA/SLAD)
  - ✓ Refine degraded capability states for M1A2, M2A3 data (AMSAA)
  - ✓ Identify data structures (AMSAA/SLAD)
  - ✓ Develop dummy vulnerability data sets (AMSAA/SLAD)
  - ⊠ Develop fault trees for DCS of M1A2, M2A3 (AMSAA/SLAD)
  - ⊠ Develop system functionality mappings (AMSAA/SLAD)
  - ⊠ Develop vulnerability data for M1A2, M2A3 (SLAD)
- Implement vulnerability methodology (TRAC)
  - ⊠ Data structures in CASTFOREM (TRAC)
  - – System functionality mappings in CASTFOREM (TRAC)
- Conduct sample sensitivity model runs & analysis (TRAC/AMSAA)
  - – Initial vulnerability metrics comparison
  - – Level of resolution

This chart shows the status of the FY00 activities. The ✓bullet indicates completed activities, the ⊠ bullet indicates on-going activities, and the - bullets indicate activities not yet started. Basically, definitions have been developed for the degradation categories and degraded capability states for the Abrams Tank and Bradley Fighting Vehicle. Sample vulnerability data has been developed to illustrate the data format and initiate the data structures in CASTFOREM. ARL is presently developing vulnerability data based on the traditional and proposed vulnerability metrics using current target and threat information in the S2 model. Once these data are developed for the Bradley and/or Abrams, sensitivity model runs and analysis will be conducted later this CY using CASTFOREM.

Level of Resolution of Vulnerability Metrics

Assess the impact on battle outcome and simulation execution of higher resolution vulnerability metrics

- View averages versus cell-by-cell

FY00 Program

- Extended CASTFOREM DS Research
  - Tank vs Tank Runs
- Combat^{XXI} Development
  - Implement new vulnerability metrics for tanks and IFVs

FY01 Program

- Combat^{XXI} Runs with new vulnerability metrics for tanks and IFVs
  - View average versus cell-by-cell
  - Mix and match level of resolution metrics
- Combat^{XXI} Development
  - Implement new vulnerability metrics for artillery, air defense, aviation

The focus of the initial sensitivity model runs and analysis will be to asses the impact of vulnerability metrics resolution, cell-by-cell versus view average, on battle outcome. This effort will effectively be conducted using CASTFOREM research. However, these runs will also be conducted using Combat^{XXI} to ensure consistency across simulations. Combat^{XXI} is planned to replace CASTFOREM.

CASTFOREM DCS Research

Purpose: Identify level of resolution of vulnerability metrics

Scenario (Maneuver Units)				Vulnerability Metrics			
Red		Blue		Degr. Cap. States		SDAL-M,F,M/F,K	
Tank	IFV	Tank	IFV	Cell	View Avg	Cell	View Avg
+	+	-	+	X	X	X	X
-	+	+	+	X	X	X	X
-	+	-	+	X	X	X	X
+	+	+	+	X	X	X	X
+ Overmatching - Tank KE & CE							
- Undermatching - Tank KE & CE							

The Degraded Capability State research will include red & blue tank & infantry fighting vehicles that use overmatching & undermatching rounds, as depicted in the above chart. It is expected that overmatching and undermatching rounds may have different effects on the traditional versus degraded capability states and cell-by-cell versus view average modeling issues.

Project Transition

- Transition Plan
  - Nomination as new standard in Standards Nomination and Approval Process (SNAP) at the end of FY01
  - Operational version of new V/L metrics in COMBAT^{XXI} in FY01
  - First use of new metrics in FCS Phase 2 (FY02-FY05)
  - Implementation in OneSAF in FY03-FY04
- DoD Customers:
  - Analysis Community - ACR/RDA
  - Training Community - TEMO

After the development, implementation, and testing of new standard vulnerability metrics, they will be nominated into the Standards Nomination and Approval Process (SNAP) and placed in the ASTARS. Also, the new vulnerability metrics will have been incorporated into COMBAT^{XXI} for use in the FCS during phase 2 of the development program. Finally, the new vulnerability metrics will be implemented into OneSAF. As a result, all three management domains (RDA, ACR, TEMO) will benefit from the development and implementation of new standard vulnerability metrics the wide variety of models and simulation applications. If the testing phase of the development of new vulnerability metrics is successful, i.e. has significant impact on battle outcome, then we expect significant improvement in all Army combat models and simulations.