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A TAXONOMY FOR THE VULNERABILITY/LETHALITY ANALYSIS PROCESS

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An important aspect of the formulation of any scientific process is the definition of the mathematical framework within which that process is considered. It is quite common for analytical processes to evolve over a long period of time before the underlying mathematics are fully understood and illuminated. This is the case with Vulnerability/Lethality (V/L) analyses, long considered more an art than a science. This paper defines a mathematical framework for V/L analyses, demonstrates how each part of a well-known process fits into this framework, and to identify parts of this analytical process which are in error and/or require additional research. It is shown that this taxonomy allows a rational scientific approach to the V/L analysis process.

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I. Introduction

An important aspect of the formulation of any scientific process is the definition of the mathematical framework within which that process is considered. This mathematical basis defines the limitations of the process, provides the means for conducting analyses, and helps ensure uniformity and consistency of results. It is quite common for analytical processes to evolve over a long period of time before the underlying mathematics is fully understood and illuminated. This is the case with Vulnerability/Lethality (V/L) analyses, long considered more an art than a science. It is the purpose of this paper to define the mathematical framework for V/L analyses, to demonstrate how each part of a well-known process fits into this framework, and to identify parts of this analytical process which are in error and/or require additional research. It will be shown that this taxonomy allows a rational scientific approach to the V/L analysis process.

II. Background

Traditionally, the V/L analysis process for armored fighting vehicles has been that of inferring some loss of effectiveness, or combat utility, from damage inflicted by a munition on a military system. The association of remaining utility with damage has been accomplished by a wide variety of means, from intuitive inference to empirical correlations to Monte Carlo simulations on computers. Among the numerous difficulties with this process is defining "effectiveness" or "utility," since these terms tend to be related to particular mission or combat scenarios. Conclaves of experts in military science have been convened for the purpose of providing estimates of utility, generally expressed as a percent, given the loss of certain combinations of components or subsystems on a particular vehicle.[1] Such estimates, or Damage Assessment Lists (DALs), use intuitive inference to link component damage to loss of combat utility. These estimates represent a kind of average over all possible missions for the vehicle, and are therefore devoid of detail about specific system capabilities. The most common interpretation of these estimates (an incorrect one, as emphasized by Starks[2]) is as a probability of complete "kill," in either mobility or firepower or both.

In the late 1950s, a series of tests at the Canadian Armament Research and Development Establishment (CARDE) represented the first modern attempt at extensive collection of empirical data to relate damage to loss of function.[3] From these CARDE Trials came a number of correlation curves relating hole sizes in armor to loss of capability. Extensions of these curves are still used today, even though in many cases the combat systems to which they are applied bear little resemblance to those tested at CARDE. The unfortunate effects of this extrapolation are pervasive, even infecting computer codes written thirty years after the tests.

In the cases of aircraft and ships, although current analytical practices are different, many of the same shortcomings apply. For aircraft, vulnerability analyses have long included performance-oriented measures of effectiveness

[1] G.A. Zeller and B.F. Armendt, *Volume X: Vulnerability Models; Part 1A: Update of the Standard Damage Assessment List for Tanks: Underlying Philosophy and Final Results.*, ASI Systems International, HQS Armament Division Report No. AD-TR-87-65, November, 1987

[2] Michael W. Starks, *New Foundations for Tank Vulnerability Analysis*, **The Proceedings of the Tenth Annual Symposium on Survivability and Vulnerability of the American Defense Preparedness Association.** Naval Ocean Systems Center, San Diego, CA, 10-12 May 1988

[3] *Tripartite Anti-Tank Trials and Lethality Evaluation, Part I*, **Canadian Armament Research and Development Establishment**, November 1959

(MOE); examples of these include "Forced Landing", "Time-dependent Crash Landings", etc. However, along with additional mission-oriented MOEs such as "Mission Abort", aircraft V/L analyses traditionally suffer from similar logical disconnects between weapon effects and target response. In the case of ship analvses, several shortcomings apply. Therefore, although the language of this report is cast in terms of armored vehicles, the applicability of the concepts is universal.

Computer models which have evolved to assist in this analysis process are a reflection of the level of understanding the analysts have of the various physical and engineering phenomena involved. The lumped-parameter model known as the Compartment Model, for example, assumes each system consists of "black box" compartments such as ammunition, crew, and engine.[4] A perforation by a munition anywhere into one of these compartments results in a standard type of loss of function; that is, all components in the compartment are "lumped" into a single group for analysis. Point burst type models include more extensive component descriptions and attempt to distinguish between different shot lines by tracing the lines through a detailed target description.

In about 1985, the task of making pre-shot predictions for the Abrams tank live fire tests underscored the widely-known fact that deterministic models fail to represent adequately the uncertainties of projectile impact attitude, armor and component fracture mechanics, spall production, fragment ricochet and numerous other factors involved in damaging a combat vehicle. Stochastic or Monte Carlo techniques were introduced in an attempt to provide more realistic estimates of damage to vehicles.[5] In that paper, Deitz and Ozolins recognized the need to understand more rigorously the analytical processes and relationships by introducing the concept of spaces for V/L analysis. These spaces and the mappings between them have been used in a number of papers

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[4] Bradshaw F. Armendt, Jr., *Methods of Assessing Anti-Armor Weapons Lethality,* Working Paper 51 of Subpanel 3 of NATO AC/225, July 1974

[5] For a historical perspective on vulnerability testing and modeling, see: P.H. Deitz and A. Ozolins, *Computer Simulations of the Abrams Live-Fire Field Testing,* **Proceedings of the XXVII Annual Meeting of the Army Operations Research Symposium,** 12-13 October 1988, Ft. Lee, VA; also, Ballistic Research Laboratory Memorandum Report BRL-MR-3755, May 1989

over the past several years.[6][7][8][9] Although there is no question that the notion of spaces has been heuristically useful, there have been both changes in usage and a lack of mathematical precision in the ongoing dialogue. The authors thus determined that it would be useful to provide, in a single document, the complete taxonomy with definitions, assumptions, and limitations. What follows is a complete description of the spaces and mappings, as well as a detailed discussion of the application of this taxonomy to V/L analyses.

> It must be noted that the use of the terms "space" and "vector" in this report may seem somewhat specious. It is recognized by the authors that these terms imply certain mathematical properties which have not yet been shown to pertain to the entities as used in this report. The use of these terms is historically based (see references). Future work will be directed toward solidifying these concepts.

We are, therefore, under no illusions that the present report will be the last word on the subject. Furthermore, it will be noted that the tenor of this report is theoretical. Applications, however, are obvious. It is anticipated that the framework established in this report will pervade much of the future work in vulnerability and lethality, both theoretical and empirical. In fact, the terminology discussed herein has already become part of the working vocabulary in the community.

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[6]Michael W. Starks, *Assessing the Accuracy of Vulnerability Models by Comparison with Vulnerability Experiments*, Ballistic Research Laboratory Technical Report BRL-TR-3018, July 1989

[7]P.H. Deitz, M.W. Starks, J.H. Smith and A. Ozolins, *Current Simulation Methods in Military Systems Vulnerability Assessment*, Ballistic Research Laboratory Memorandum Report BRL-MR-3880, November 1990

[8]Michael W. Starks, *Improved Metrics for Personnel Vulnerability Analysis*, Ballistic Research Laboratory Memorandum Report BRL-MR-3908, May 1991

[9]Paul H. Deitz *et al.*, Current Simulation Methods in Military Systems Vulnerability Assessment, **Procedings of the XXIX Annual Meeting of the Army Operations Research Symposium**, October 1990, Ft. Lee, VA.

III. V/L Spaces and Mappings

A. V/L Levels and Spaces

The basis for the taxonomy of V/L Spaces comes from the recognition that V/L analyses pass through distinct levels of information in a precise order. These levels are:

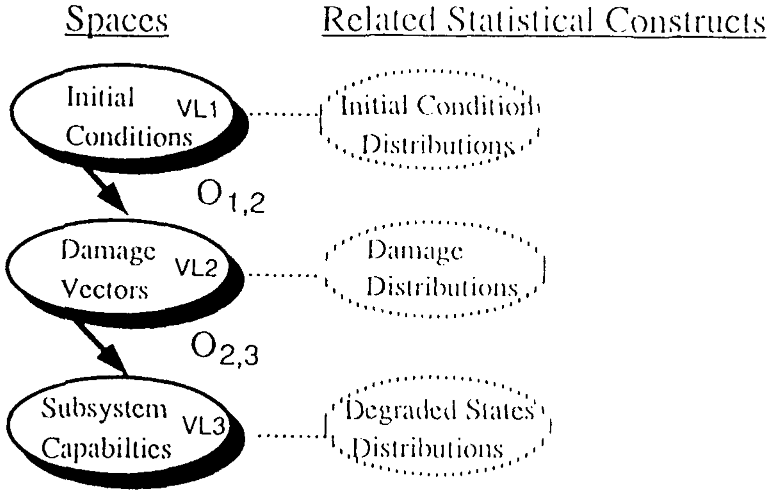
1. Threat-Target Interaction - Initial Conditions,
2. Target Component Damage States, and
3. Target Capability States.

The mappings by which one passes from one level to the next are dependent on different kinds of information at each level. For example, going from Level 1 to Level 2 (threat-target initial conditions to target damage) essentially involves physics; going from Level 2 to Level 3 (target damage to degraded capability) requires engineering measurement. The process can be shown pictorially as in Figure 1.

It is important at the outset to differentiate between "Levels", which are composed only of states of existence, and the "mappings", operators – with the data and algorithms to which they have access – which relate a state at one level to a state at another.

A Level contains all the information required to define the state of the system at the associated stage of a V/L analysis/experiment. At each level, one can define a space of points, each point being a vector whose elements correspond to the status of a particular entity related to the target. For example, in Space 2 (Damage States), each element may refer to the status of a particular component/sub-system. The spaces thus defined are the "V/L Spaces", and represent, at each level, the state of the target system.

A Mapping represents all of the information (physics, engineering, etc.), known or unknown, required to associate a point in a space at one level with a point in a space at the next level. Mappings have access to information such as: fundamental data (penetration parameters [level 1 to level 2], leakage rates [level 2 to level 3], etc.); intermediate data generated by the mapping (line-of-sight thicknesses [1 to 2], temperature rise in an uncooled engine [2 to 3]); algorithms (depth of penetration [1 to 2], fault trees [2 to 3]).



$O_{1,2}$: Weapon-Target Interaction (Physics)

$O_{2,3}$: Damaged Target Capability (Engineering Analysis)

Figure 1: The Vulnerability/Lethality Process

The V/L experimental and analytical processes can then be expressed as a series of mappings which relate a state vector in one space (the domain) to a resultant state vector in a next higher-level space (the range).

Note that at each transition to the next level some detail about the target system is lost: a broken bolt in level 2 may be the cause of degraded mobility influencing mission effectiveness, but at level 3 the bolt is no longer recognized as an entity. It is now widely acknowledged that skipping over levels (such as inferring remaining combat utility directly from the size of the hole in the armor) loses so significant an amount of information that continuity and auditability are lost.

B. Axioms and Definitions

In order to provide a consistent structure to the geometry we are about to define, the following axioms (assumptions) are given:

1. There are 3 levels of information making up the vulnerability/lethality analysis universe; spaces can be defined at each of these levels.

2. The points in each of the spaces are, in principle, observable and/or measurable.

3. The points in each space are vectors, consisting of one or more elements.

4. There exist mappings from each level to the next, and from a space at each level to a corresponding space at the next level.

With these axioms in place, we have then:

Definition 3.1:

1. V/L Space 1, or VL1, is the set of all possible initial conditions for target/munition interaction.
2. V/L Space 2, or VL2, is the set of all possible damage vectors, the elements of which indicate the status of all critical components/subsystems.
3. V/L Space 3, or VL3, is the set of all possible system capability degradation vectors, the elements of which indicate degrees of capability (for movement, communication, firepower – or, at a finer level of resolution, speed, acceleration, etc.)

Definition 3.2: The dimension of a space is the number of elements in a vector (point) in that space.

Definition 3.3: The cardinality of a space is the number of vectors (points) in that space.

Definition 3.4: The mapping from VL1 to VL2 is denoted by O12; similarly, the mapping from VL2 to VL3 is denoted by O23.

It is important to recognize that it is possible to construct many different spaces at any particular level. For example, note that the number of elements in a point (vector) in a space may depend upon the granularity of the target. This appears to be practically unavoidable: a human enumerates the different elements which he will evaluate in deciding what state exists after a single shot. Thus, there may be any number of spaces which could be created to describe the post-shot evaluation. Yet, they could all be "Spaces", as defined in this section. (That is, they can be closed, possess an identity element, be amenable to the defined operators, etc.)

A potentially fruitful area for future study is the relationship between different spaces at the same level that differ only in their degrees of granularity.

This naturally leads to the concept of an "ultimate" space at each level. For example, consider a sequence of spaces of damage vectors (level 2), each succeeding space having more elements in its vectors. Since each element of a damage vector refers to the status of a particular part of the target, such a sequence could result from a progressively finer dissection of the target into successively smaller parts. The endpoint of this sequence is a construct whose discrete elements are replaced by continuously varying ones which detail the infinitesimal, point-by-point status of the target. Ideally, this "endpoint" will also form a space under the same definitions that are listed herein, with the necessary replacement of discrete entities with continuous ones.

The relationship between this "ultimately fine space" and a space of coarser granularity may be of more than academic interest. For example, suppose a predictive result is expressed in terms of a set of damage vectors assembled into space VL2a. An experiment is independently conducted, with results expressed in terms of the damage vectors in VL2b. Consider the task of determining how close the prediction is to the experimental result. Since the spaces are different, comparison of the damage vectors, in a mathematical sense, may be unfounded. However, if both results can be related to their associated points in VL2* (the "ultimately fine space"), a comparison between the points can be made.

C. Example 3.1:

Consider a threat-target system consisting of an arrow attacking a Conestoga wagon. Let the elements in each point (vector) in VL1 refer to:

$$\begin{bmatrix} \text{Arrow velocity in the x-direction} \\ \text{Arrow velocity in the y-direction} \\ \text{Arrow velocity in the z-direction} \\ \text{Wagon impact x-coordinate} \\ \text{Wagon impact y-coordinate} \\ \text{Wagon impact z-coordinate} \\ \text{Arrow mass} \end{bmatrix}$$

In this case, with 7 critical parameters identified, the dimension of VL1 is 7. If we assume a continuum of possible values for velocity, location and mass, then the cardinality of VL1 is infinite. One could, of course, allow only discrete values for these parameters within a certain range of values: this would reduce the cardinality but not the dimension of VL1.

Proceeding to Level 2, we construct a hypothetical space of possible damage vectors. Assume that the Conestoga wagon's critical components have been identified as driver, rifle, right front wheel, left front wheel, right rear wheel, left rear wheel, hull, tang, right ox, left ox, harness, and reins. There are 12 critical components, making the dimension of VL2 = 12. If we further assume only binary damage states for these components (i.e., damaged or undamaged, with no intermediate levels), then the cardinality of VL2 is 2^{12}. Each point in VL2 is a vector with 12 elements, each having possible values 0 and 1 (dead/not dead). Let the elements be arranged as follows:

$$\begin{bmatrix} \text{driver} \\ \text{rifle} \\ \text{rf wheel} \\ \text{lf wheel} \\ \text{rr wheel} \\ \text{lr wheel} \\ \text{hull} \\ \text{tang} \\ \text{r ox} \\ \text{l ox} \\ \text{harness} \\ \text{reins} \end{bmatrix}$$

At Level 3 (Capability Degradation), we choose to analyze three capabilities, the ability to move, shoot and perform other crew functions. Through an engineering analysis, we group the critical components into three critical subsystems: Mobility, Firepower and Crew.

- Mobility
  - driver
  - rf wheel
  - lf wheel
  - rr wheel
  - lr wheel
  - tang
  - r ox
  - l ox
  - harness
  - reins
- Firepower

  - driver
  - rifle

- Crew

  - driver

(Note: Strictly speaking, the number of surviving crew members is a Level 2 metric. However, the ability to do crew functions is a capability and rightly belongs at Level 3.)

The points in VL3 are therefore 3-element vectors like:

$$\begin{bmatrix} \text{M (degradation level)} \\ \text{F (degradation level)} \\ \text{C (degradation level)} \end{bmatrix}$$

where degradation level is an indicator of the performance capability of the subsystem; this might be expressed as a percent of full capability. The dimension of VL3 = 3; the cardinality of VL3 depends on the number of degradation levels assigned to the subsystems. For a continuum of degradation values, the cardinality is infinite. In the case of discrete levels of performance degradation, the cardinality is the product of the possible number of levels of degradation of each subsystem.

We shall return to this example in the following sections.

D. Relationships Between Spaces at Different Levels

a. Mappings Let us next consider the mappings, the association of points from a space at one level with those in a space at another level. As described above, the points in the spaces are determined by system design, construction, and application (mission); specifically excluded are the physical and engineering factors that relate points in one space - for example, a set of initial conditions - to points at the next level - for example, the resultant damage. Rather, such factors are incorporated in the mappings, either actually, if the mapping is accomplished by a field experiment, or algorithmically, if the mapping is accomplished by analysis or simulation.Analytical mappings are characterized by empirical or theoretical relationships such as penetration algorithms, fracture mechanics, etc., in the case of the mapping from VL1 to VL2. When going from VL2 to VL3, an analytical mapping may consist of a series of fault trees. Thus, in this taxonomy, knowledge gaps are quite clearly linked to the ability to construct a mapping from one space to another.

There may also be a certain variability inherent in the processes of penetration, fracture mechanics, and so on. If it exists, such variability would be a characteristic of the mapping function; that is, two applications of a mapping function to the same point in its domain could result in two different image points in its range.

b. Repeated Mappings and Probability Distributions Consider the following procedure: We construct spaces at Levels 1 and 2 (VL1 and VL2) as described above. We also construct a "scorecard" at Level 2 which allows us to count how many times each damage state point in VL2 is reached. We then select only one set of initial conditions (a fixed point in VL1) and iterate the mapping O12, counting the number of times each point in VL2 is reached. It is clear that, following a large number of mappings, the information in the scorecard provides an indication of the likelihood that a certain damage state point in VL2 will occur from a given set of threat-target initial conditions in VL1. In fact, it is straightforward to interpret the scorecard information as a probability distribution associated with the mapping and the initial conditions. Some common interpretations of this kind are included in Figure 1.

In principle, the process could be repeated for several sets of initial conditions. In this way, one can arrive at an understanding of the stochastic nature of the physics or engineering underlying the O12 and O23 mappings.

Once the spaces are defined at each level and the mappings (O12, O23) are known for a particular vulnerability or lethality problem, then the analysis process can proceed. Selecting a set of initial conditions for threat-target interaction, one applies the O12 mapping to determine a damage state vector in VL2. Using that damage state vector as the domain point, one then applies the O23 mapping to determine a loss-of-capability vector in VL3. By repeated application of the O12 mapping from the same initial conditions, one can infer the likelihood of occurrence of each of the damage state vectors. Similarly, by repeated application of the O23 mapping to the same damage state vector, one can infer the likelihood of occurrence of each loss of capability.

It is essential to appreciate two points:

1. These likelihoods, or probabilities, are functions of the mappings, and not of the spaces: if the mappings are changed, the probabilities which

they associate with the vectors in the spaces will change.

2. The mappings have their domains and ranges in the V/L spaces, not in the sets of probabilities. (A forthcoming paper will make clear some of the problems which can result from not properly maintaining the distinction.)

c. Non-invertibility It is also important to realize that the mappings O12 and O23 are not, in general, invertible. That is, given a capability state vector in VL3, it is not possible to determine which damage state vector in VL2 was mapped into it by O23. In fact, there will generally be numerous damage state vectors which could produce, under O23, a given capability state vector. A similar relationship holds for the mapping O12.

To see this more clearly, consider the arrow-wagon problem. A capability state vector in VL3 could be (M=0,F=1,C=1), indicating full firepower and crew capability, but no mobility. Notice that this piece of information by itself tells us nothing about why there is no mobility. Were both oxen killed? Were all or some wheels lost? Was the entire wagon destroyed and both oxen killed, leaving the driver (C) and the rifle (F)? Since one has no way of knowing just from the capability state vector, the mapping O23 is clearly not invertible. Stated another way, the O23 mapping is "many-to-one" (or "many-to-many").

Similarly, O12 is not invertible. Continuing the above example, suppose the corresponding damage state vector in VL2 was:

$$\begin{bmatrix} 0 & \text{(driver)} \\ 1 & \text{(rf wheel)} \\ 1 & \text{(lf wheel)} \\ 0 & \text{(rr wheel)} \\ 0 & \text{(lr wheel)} \\ 1 & \text{(tang)} \\ 0 & \text{(r ox)} \\ 0 & \text{(l ox)} \\ 0 & \text{(harness)} \\ 0 & \text{(reins)} \end{bmatrix}$$

For this case, only the two front wheels and the tang were damaged. One can easily postulate a number of ways in which such damage could occur. For example, arrow hits lf wheel, causing the wagon to tip, breaking tang and rf wheel. Or, perhaps the arrow hit the rf wheel, causing the wagon to tip, breaking the tang and the lf wheel, and so on. Again quite clearly, O12 is not invertible; it, too, is many-to-one or many-to-many.

The consequences of this non-invertibility can be significant, particularly impacting the development process for military equipment (the subject of a forthcoming paper). For the purposes of the present paper, it suffices to point out that non-invertibility of the mappings O12 and O23 translates into an absence of unique solutions for military hardening problems.

E. Impact of Cardinality

It has been implied by the previous paragraphs that a combination of testing and modeling can be used to characterize system performance. As was noted in the previous section, the cardinalities of VL1, VL2, and VL3 could be finite or infinite. If the cardinality of VL2 is finite, it may be possible (though very expensive) to examine, through testing and simulation, the full spectrum of images of VL2 in VL3 under the O23 mapping. If the cardinality of VL2 is infinite, this is simply not possible.

Similarly, if the cardinality of VL1 is infinite (which is quite certainly the case in the real world of continuously-varying coordinate systems, masses and velocities), then it is clearly impossible to analyze every aspect of O12. Thus, the best which can be hoped for is to identify a reasonable approximation to O12, and to O23 as well. This is where the introduction of stochastic simulation into the process can pay off handsomely.

IV. Relevance of the Taxonomy to the Vulnerability/Lethality Analysis Process

A. Initial "Set-up" of Problem

Given a completely defined threat and target, how does one construct the appropriate V/L spaces for a given problem and determine and/or approximate the mappings between them? It is instructive to "walk through" an example; we will again use the arrow-wagon problem.

The first step in any analysis process is to determine the required precision. This requirement will dictate the level of detail required in computer target descriptions, the level of precision needed in test instrumentation and data reduction, the number of components identified as critical, and the level of performance capability testing to be done. (It seems reasonable that precision in the results of an analysis depends upon the level of detail in the target description. However, the quantification of this dependence is most difficult in practice.) For this example, assume that the particular V/L problem to be analyzed is to determine the vulnerability of the M7 Conestoga Wagon to the M328 fin-stabilized arrow. Suppose it has been determined (by some unspecified means) that no significant feature of the target has a presented area of less than one square foot. It is therefore reasonable to form a grid over the target description at the appropriate aspect angle with one foot between grid lines, and presume that a hit by the arrow at one point in a one-foot-square box is identical to a hit anywhere else in that box. Additionally, one might define a likely attack velocity and mass for the arrow. These assigned numbers and the target grid coordinates populate VL1.

Similarly, having identified the critical components and having decided to specify the damage states in terms of those components, it is possible to construct a VL2.

The elements of the VL3 vectors must reflect the capabilities to be evaluated for the M7 Conestoga. In this example, these vectors have three elements, corresponding to Mobility, Firepower and Crew Function. (Note: The "granularity" of these elements is arbitrary, as was that of the elements in VL1 and VL2. For example, it would have been possible to have subdivided "Mobility" into "Ability to Go" and "Ability to Stop". This decision is again a reflection of the required precision with which we began this section. If it is somehow determined that greater precision is required, the dimensions will need to be increased appropriately, by decreasing grid size and adding components/subsystems and capabilities.)

At this stage, the spaces are populated with vectors and their dimension has been set based upon some anticipated level of detail necessary to satisfy the requirements of the analysis. These spaces and the vectors in them represent the total universe of states for the problem; no initial conditions, damage states or capabilities outside these spaces will enter into the analysis.

It remains to characterize the mappings. For the O12 mapping, one needs such things as penetration algorithms for the M328 arrow into ox hide, iron-rimmed wheels, etc.; if these are unknown, penetration testing is required to provide the necessary data for development of such algorithms. If the M328 arrow can be equipped with a flaming tip, fire start/spread algorithms are required. If the arrow tip can be coated with toxic substances found lying about the prairie, then toxicity algorithms may be needed. Continuing in this manner, all pertinent damage mechanisms must be identified and modeled, using a mix of empiricism and theory as appropriate. Essentially, the O12 mapping is characterized by the physics of the threat-target system.

In order to characterize O23, engineering measurements and/or modeling must be used. In this case, one must determine the effects of losing the rf wheel, the lr wheel, both, and any and all combinations of wheel losses, losing one ox, breaking one harness, and numerous other capability questions. While the loss of both oxen or of all four wheels would seem to cause a full loss of mobility, loss of one ox would only reduce mobility, and perhaps losing one or even two wheels would not preclude movement. Such questions are not easily answered theoretically, and may thus require extensive testing for full and adequate characterization of the mapping in order to quantify the capability loss relative to the system's baseline performance.

It is worth reiterating that the spaces can all be formulated without anything more than a complete knowledge of system design and threat attack parameters. Defining the mappings requires testing and physics or engineering judgment. This points out yet another benefit of this V/L taxonomy: The sharp delineation made between the conditions (state-vectors) and the damage/degradation phenomenology (mappings) helps to focus attention upon the areas in which the essential shortcomings lie.

B. Extraction of Results for End-Uses

Our discussion thus far has had to do with particular shots and particular consequences of those shots. For various analytical purposes we must also be equipped to make more general assertions concerning the military utility of actual or hypothesized weapon systems. These general assertions are typically stated in terms of various statistical aggregates.

Figures 2 and 3 provide a notional scheme which shows how these statistical aggregates are formed for both item and force-level modeling. For both of these levels of modeling, the nature of the particular statistical aggregate formed depends on two things.

The first determinant is the manner in which specific weapon-target engagement conditions are chosen in the item/force-level model and the specific fashion in which they are used to drive loops through the V/L spaces. The second is whether or the extent to which the item or force- level model aggregates the subsystem capability information from VL3. Both the details of the looping and the specific methods of aggregation are developed in a large number of different ways in practice. It is not part of our aim to spell out these variations here; the point is that the Spaces concept we have presented here is sufficient to support traditional down-stream uses of V/L information.

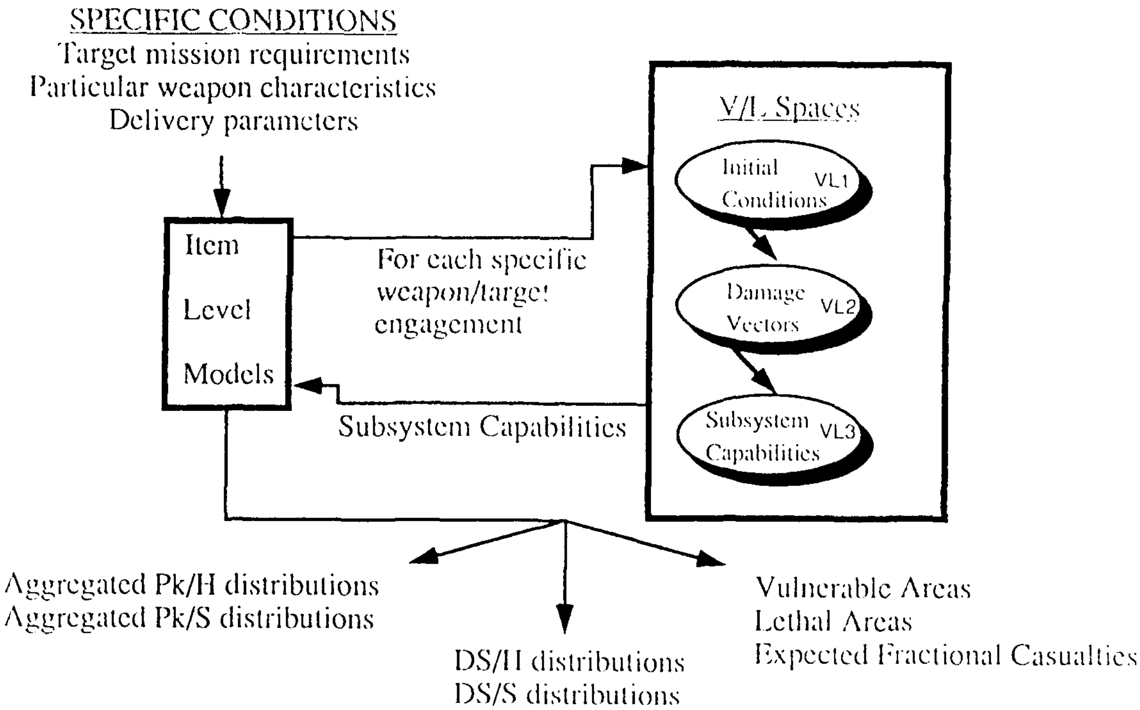


Figure 2: V/L Modeling in the Context of Item-Level Modeling

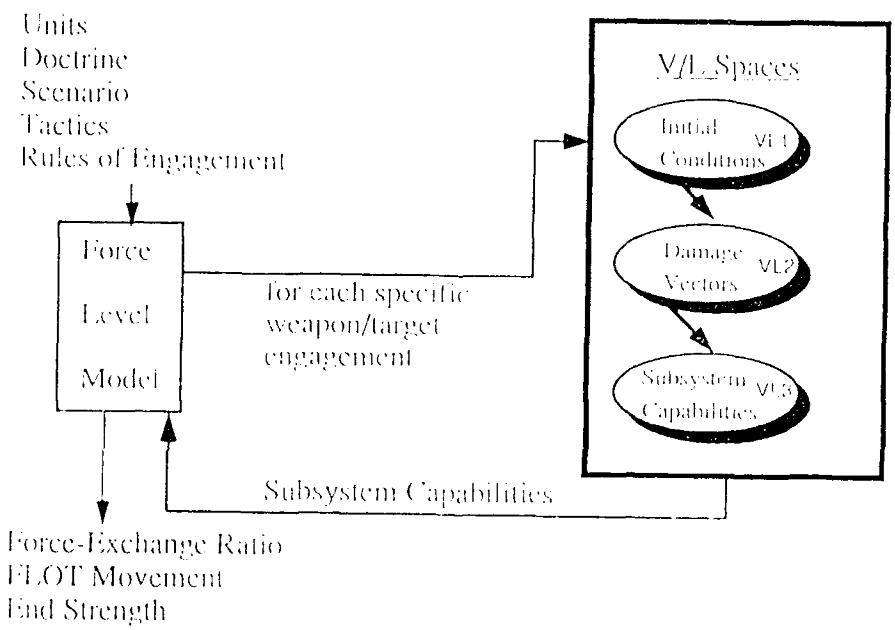


Figure 3: V/L Modeling in the Context of Force-Level Modeling

V. Conclusions and Recommendations

A taxonomy has been developed for the vulnerability/lethality analysis process. It has been shown that this taxonomy represents an appropriate and internally consistent mathematical foundation for vulnerability science, providing a framework for analytical processes and a means for identifying knowledge gaps.

The astute reader will have surmised that there is likely an algebra of the vectors in the spaces which can be defined, with a "norm" or distance, and a binary operator for combining two vectors. This algebra is being pursued, and is the subject of a report now in progress.

At this time it is impossible to predict the degree to which such a formal algebra, with rigorously defined entities, will be able to be fitted to the mathematical structures described above. However, if nothing else ever comes out of the exercise, the taxonomy and associated vocabulary that have been developed have already proven to be extremely useful to those who now routinely use it. The Levels of results, the meaning of a Space of state vectors, the constituents of a mapping - these concepts have considerably sharpened information and idea exchange in a wide range of vulnerability applications, including managerial and operational issues, as well as methodological developments.

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