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A V/L TAXONOMY FOR ANALYZING BALLISTIC LIVE-FIRE EVENTS

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ABSTRACT

Beginning with World War II and its aftermath, the area of ballistic vulnerability/lethality (V/L) was first defined as a specific discipline within the field of ballistics. As the field developed, various practices and metrics emerged. In some cases metrics were developed which were abstractly useful but, for example, bore no direct relationship to field observables. In the last decade, as the issues of live-fire strategies and model VV&A have gained importance, increased attention has been focussed on V/L with the intent of bringing greater rigor and clarity to the discipline. In part this effort has taken the form of defining a *V/L Taxonomy*, which, in essence, is a method of decomposing a series of concatenated complex processes into separable, less-complex ones, each with certain properties and relationships, one to another. This paper attempts to summarize these efforts and illuminate their relevance to the V/L endgame activities so critical to modern weapons analyses.

1. Purpose

Insight into the processes of vulnerability and lethality can be gained through use of what is now called the *Vulnerability/Lethality (V/L) Taxonomy.*[∞] It was first generated[1] as a by-product of a program to improve the quality of Live-Fire (LF) Abrams vulnerability modeling. In essence, the V/L Taxonomy provides a method to decompose the elements of V/L into a sequence of simpler constituent parts. As we will see, the parts relate to each other in a specific processing order, but are fundamentally different, one from the other, and each has its unique and appropriate use in the general scheme of V/L assessment.

2. V/L Taxonomy *via* a Combat Analogue

The V/L Taxonomy can probably best be introduced *via* a description in terms of its physical and engineering processes. Figure 1 illustrates such a view of the Taxonomy. The process structure is illustrated with a missile attacking an aircraft, although this process is applicable for any ballistic threat against any target.[†] The cartoons at the center of Fig. 1 represent alternately *Levels*, indicated on the left, connected by *Transformation* processes, indicated on the right.

We start with an explanation of the process of Vulnerability using Fig. 1. In conventional vulnerability, it is normal practice to assume a warhead hit (or ballistic interaction) with a target *as a given*. It is useful to think in this context of a LF test. **Level 1]** represents a complete geometric and material description of a threat (here a missile), a target

∞ See Appendix A for standard definitions of Lethality, Vulnerability, and Survivability.

1. Paul H. Deitz and Aivars 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.

† It will be noted later that this notion can be applied as well to non-ballistic threats such as Directed Energy and Chemical Weapons analyses.

(here an aircraft), and the relevant kinematics as the two just begin to interact. The event may be signaled by the instant an unguided bullet begins to collide with a target or, as implied by the illustration, a fuze triggers an explosive mechanism in the vicinity of the target. The process of a LF test is to transform an undamaged target at **Level 1]** to a damaged target at **Level 2]**. The transformation process is the LF event itself, and is characterized by all the physical mechanisms of destruction. They may include main penetrators, fragments, blast, shock, fire, fumes and even synergistic effects. As a consequence of the LF transformation event, target damage may have occurred at **Level 2]**. We choose to think of **Level 2]** as characterized by a list of killed components; sometimes this is called a damage vector.

A target which has received damage may likely not continue to operate as before damage. In the case of a damaged aircraft illustrated here, parts of the control surfaces may be removed, hydraulic lines severed and electronic boxes impaired. In a test which might be performed, the rate-of-climb might be measured to see how this key performance property may have been reduced. The performance test is the transformation process which takes target damage at **Level 2]** and transforms it to reduced capability at **Level 3]**. The transformation from **Level 2]** to **Level 3]** can be thought of as characterized by engineering relations. It is important to note that the metrics of **Level 1]**, threat-target initial conditions, **Level 2]**, damaged components, and **Level 3]**, measures-of-capability are all measureable and objective metrics.

The capability state of **Level 3]** should be characterized by all capability measures which cause a military platform to have military utility or worth in a particular mission. For example, if the platform can move, the metrics might include measures of speed and agility. If the platform has a gun, the metrics might include time-to-acquire a target, rate-of-fire and hit dispersion.

The final transformation occurs as a platform with reduced measures-of-capability is exercised in a particular mission scenario. If the particular reduced measures-of-capability are unimportant to the mission at hand, then the utility of the platform may remain high. If not, the utility may be reduced, even drop to zero. The notion of measures-of-effectiveness or utility is illustrated as a **Level 4]** metric and would be reached through an operational test or war experience. Given the complexity of this transformation and the lack of real-world repeatability, we claim that **Level 4]** metrics are essentially not observable, but rather must be inferred through war games or developed *via* subjective processes.

One of the key insights provided by the V/L Taxonomy is that the discipline of vulnerability ranges over three distinct kinds of metrics, *damage*, *capability* and *utility*, and great care must be exercised to see that these metrics are not confused, incorrectly calculated or improperly applied.

In contrast to vulnerability, in which a threat interaction with a target is normally assumed, lethality often includes the process of getting the threat to the target. This is generally true in the assessment of direct-fire weapons such as tank-fired rounds. By contrast, studies of indirect-fire weapons, such as warheads delivered by artillery or rockets, generally begin with warhead initiation in the neighborhood of the target. Thus Fig. 1 includes a **Level 0]**, which represents the initial conditions for the launch of a direct-fired threat. The transformation of the threat at **Level 0]** to the arrival at the target (**Level 1]**) would occur here as the firing of the missile. In a set of repeated experiments, a distribution of threat arrival conditions could be generated. One particular condition at a time might be chosen to use for a given initial threat-target interaction at **Level 1]**.

3. V/L Taxonomy *via* a Mapping Abstraction

The V/L Taxonomy is useful in developing the mathematical abstractions needed for V/L modeling. Each of the levels of the process can be thought of as a mathematical space. As illustrated in Fig. 2, the cartoons in the middle of Fig. 1 describing the Levels have been replaced with ellipses representing these spaces.

The information at **Levels 0]** through **4]** can each be described by vectors within these spaces, here represented as bullets; however, the properties of the vectors are completely different from one space to the next. As mentioned above, the metrics of damage, capability and utility are not interchangeable.

As noted above, a LF test can be thought of as a mapping from **Level 1]** to **Level 2]**. If the LF shot were repeated it is likely that random physical processes could lead to a different damage vector; thus a different vector would result. LF tests and modeling efforts have shown[1] that the outcome for many LF tests can exceed 10^6 individual damage vectors. The high dimensionality of **Level 2]** space is at the core of the difficulty in validating V/L models.

The transformation processes listed at the right of Fig. 1 have been reproduced in Fig. 2 as well. It is useful to think of the transformations as mathematical operators. These operators operate on information on one level to yield information at the next. A nomenclature which has been adopted is to use a capital **O** (for operator), followed by subscripts indicating the input and output levels. Thus the $\mathbf{O}_{0,1}$ Operator represents the mapping of the threat from launch to the arrival at the target. The $\mathbf{O}_{1,2}$ Operator represents the the damage mapping process of a LF test. The $\mathbf{O}_{2,3}$ Operator represents the transformation to reduced capability of a target following damage. And the $\mathbf{O}_{3,4}$ Operator represents the transformation from reduced capability to military utility for a particular mission profile.

4. Granularity and the V/L Taxonomy

In addition to the delineation of the V/L Levels as discussed in **Section 1** and the nature of the mapping operators described in **Section 2**, the character and utility of a V/L code is further determined by the *granularity* reflected in its levels. For a particular level, granularity describes the extent to which a metric is amalgamated (*i.e.* integrated into larger elements) *vice* refined (*i.e.* subdivided into smaller elements). The former tendency is referred to as *lower* granularity while the latter is *higher* granularity.

This issue may be illustrated most easily by discussing its effect at **Level 1]**, where granularity relates directly to the resolution embodied in the target description.[2] Particularly in the early days of V/L analysis, target descriptions were not highly detailed. Only principal volumes of the target were modeled, major compartments and components, certainly not individual wires and hydraulic lines. One of many subjective areas of judgement that a V/L analyst invokes is a decision as to what level of detail to describe the geometry of the target.

Granularity is a part of **Level 2]** metrics as well. As damage is predicted, it is typically applied to the geometry explicitly described at **Level 1]**. For example, if a GPS (Gunner's Primary Sight) is modeled simply as a box at **Level 1]**, there are only very limited ways to predict damage at **Level 2]** to yield information about which circuit or optical element within the unit might now be dysfunctional. One such way might be via empirically derived distributions of the associated subcomponents or functionalities.

So too at **Level 3]**, the capability to fire a gun might be described simply as a Bernoulli trial (binary outcome) or, with greater detail (granularity), utilizing specific descriptors of gun rate-of-fire, time-to-acquire targets, hit dispersion, etc.

The issue isn't simply that each Level can have an arbitrary granularity, but that the granularity of a particular level *requires* a minimum granularity at the prior level. Using the previous example, the high-resolution description of gun performance at **Level 3]** can not be performed without the support of a sufficiently detailed damage vector at **Level 2]**. And the adequacy of the damage vector at **Level 2]** is in turn enabled by the detail of the geometry at **Level 1]**.

The configuration of a V/L model in terms of the granularity invoked must be based on the set of desired metrics which it is to support. The desired metrics may typically be distributed over a number of levels, and a sufficiency check must be made to ensure that the resolution required at a given level is adequately supported at each prior level.

5. Insights Provided by the V/L Taxonomy.

There are a number of important aspects of the taxonomy, particularly for understanding the definitions for vulnerability, lethality and survivability.

- The V/L metrics associated with each of the **Levels 0]** through **4]** are fundamentally different, one from another. That is to say, component damage across a weapon platform is different from (potentially diminished) capability of the platform is different from the (possible reduction in) military utility of the platform. Both vulnerability of a platform or the lethality of a weapon can be *defined* in any combination of metrics from **Levels 2]**, **3]**, and/or **4]**.
- The five levels are sequential, orthogonal and non-permutable.
- Modern V/L modeling schemes must track the taxonomy so that **Level 2]** and **3]** metrics can be compared with the results of field tests.

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2. Paul H. Deitz and Keith A. Applin, *Practices and Standards in the Construction of BRL-CAD Target Descriptions*, **Army Research Laboratory Memorandum Report ARL-MR-103**, September 1993.

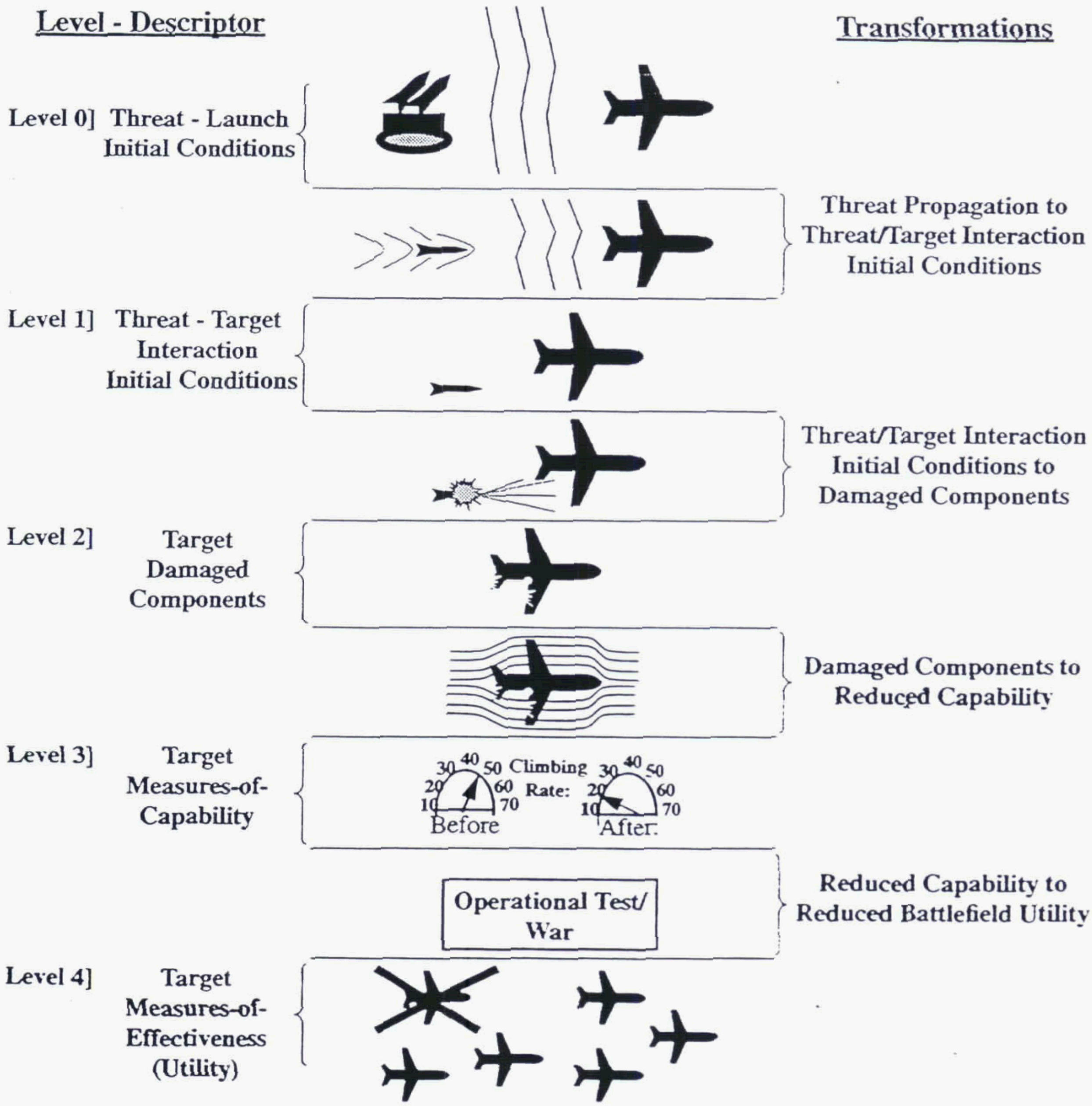

Fig. 1. V/L Taxonomy illustrated with physical and engineering processes in the center column. The Levels 0] through 4] are described on the left. The transformation processes between the Levels are described on the right.

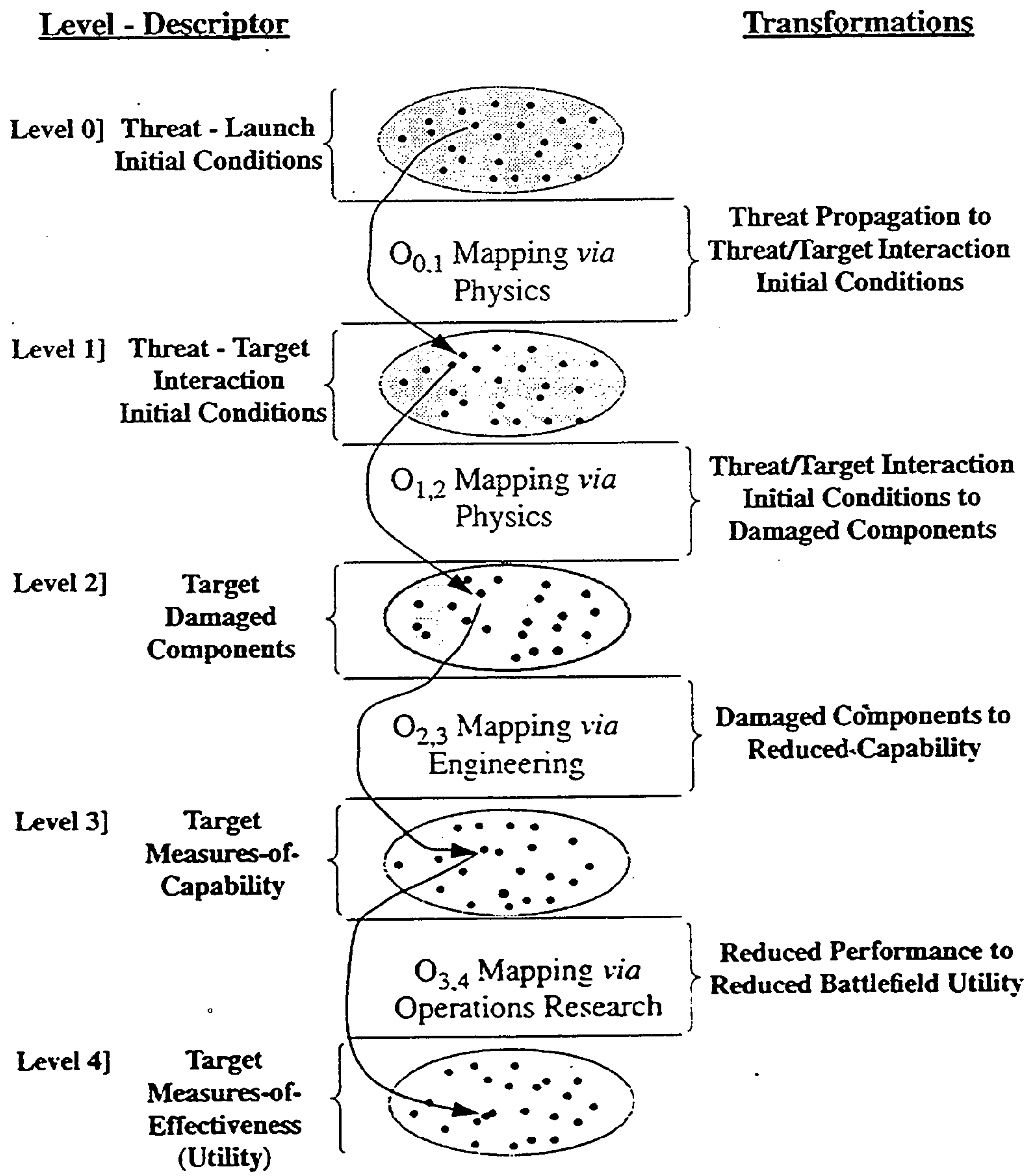

Fig. 2. V/L Taxonomy illustrated *via* a Mapping Abstraction. The ellipses in the middle column represent mathematical spaces. The points contained within represent vectors. The arrows represent mapping operators which take a vector at one level and perform a mapping to the next lower level.

- The operators are generally stochastic and non-linear; therefore the transformations are not invertible, and multiple levels (*e.g.* Level 2] to 4]) cannot be properly mapped in a single process.
- In certain V/L modeling tasks, the mathematical mapping operators must utilize stochastic processes to yield accurate results. This is most notably true in the damage operator, $\mathbf{O}_{1,2}$, where expected-value transformations lead to incorrect results.
- The effect of target damage, whether simultaneous (*e.g.* the striking of two or more artillery fragments), time-ordered (*e.g.* a volley of impinging rounds), or caused by multiple physical mechanisms (*e.g.* blast and/or shock and/or fire) must be aggregated at Level 2], the damage vector level. Clearly if, for example, a personnel carrier were struck by two artillery fragments which each happened to kill the same component(s), then the damage at Level 2] from both fragments would be no greater than the damage from either fragment individually. However the standard method for computing artillery effectiveness for the past 30 years has been to compute an approximation of a damage vector (Level 2] metric) for each fragment, map the resulting damage directly to a Loss-of-Function (Level 4] metric), and then to combine each of the system LoFs (using a formula resembling the survivor rule for combining probabilities) to get an overall vehicle LoF. The merging of individual damage mechanisms at Level 4] rather than at Level 2] is a major difficulty in a substantial amount of today's battlefield simulations. A corollary to this observation is that whenever a battlefield threat is played against a particular target, that target should not be assumed to be pristine, but reflect all prior aggregated damage except that which may have been repaired.
- Level 4] metrics, essentially battlefield utilities, cannot be observed through testing. In addition, to get to Level 4] *via* the $\mathbf{O}_{3,4}$ mapping operator requires the incorporation of tactics, doctrine, threat systems and battlefield environment; this division of labor is clearly in the province of the force-on-force modeler, not the vulnerability analyst.
- Each level of the taxonomy as it is applied in a given V/L model reflects a certain level of granularity (or resolution). The ability to perform adequately a computation at one level in the taxonomy requires a particular minimum level of granularity at the preceding level. The granularities of a V/L model metrics are critically related to the applicability of that model to a particular analysis purpose.

6. Applications of the V/L Taxonomy

Since the original notion of the V/L Taxonomy was generated, many extensions have been made. Delineations of what belong at the levels *vice* what constitute operators, the role of the process structure in V/L model accuracy and the properties of operators have been made clear.[3-6] The V/L Taxonomy has been used to propose Live-Fire Test strategies[7] which, to the maximum extent known, yield predictive metrics compatible with field observables and are also amenable to statistical validation procedures. It has been applied to the description of personnel vulnerability[8] and the description of Reliability, Availability and Maintainability (RAM).[9] It is used across ARL/SLAD for couching metrics and transformation operators in clear and unambiguous ways, not just for ballistic threats, but for Electronic Warfare and Chemical Threats [10] as well.

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3. Michael W. Starks, *Assessing the Accuracy of Vulnerability Models by Comparison to Vulnerability Experiments*, Ballistic Research Laboratory Technical Report BRL-TR-3018, July 1989.
4. Paul H. Deitz, Jill H. Smith and John H. Suckling, *Comparisons of Field Tests with Simulations: Abrams Program Lessons Learned*, Proceedings of the XXVIII Annual Meeting of the Army Operations Research Symposium, 11-12 October, 1989, Ft. Lee, VA, pp. 108-128; also Ballistic Research Laboratory Memorandum Report BRL-MR-3814, March 1990.
5. J. Terrence Klopcic, Michael W. Starks, James N. Walbert, *A Taxonomy for the Vulnerability/Lethality Analysis Process*, Ballistic Research Laboratory Memorandum Report BRL-MR-3972, May 1992.
6. James N. Walbert, Lisa K. Roach and Mark D. Burdeshaw, *Current Directions in the Vulnerability/Lethality Process Structure*, Army Research Laboratory Technical Report ARL-TR-296, October 1993.
7. Paul H. Deitz, Michael W. Starks, Jill H. Smith and Aivars Ozolins, *Current Simulation Methods in Military Systems Vulnerability Assessment*, Proceedings of the XXIX Annual Meeting of the Army Operations Research Symposium, held 10-11 October 1990, Ft. Lee, VA; also 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. Lisa K. Roach, *Fault Tree Analysis and Extensions of the V/L Process Structure*, Army Research Laboratory Technical Report ARL-TR-149, June 1993.
10. William J. Hughes, *A Taxonomy for the Combined Arms Threat*, Chemical Biological/Smoke Modeling & Simulation (M&S) Newsletter, Vol. 1, No. 3, Fall 1995.

7. V/L Taxonomy and Survivability

A number of times we have emphasized the importance of not confounding the different kinds of V/L metrics associated with Levels 2], 3] and 4]. The data associated with a Level 2] metric is straightforward— it is simply an accounting of damaged or killed components. At Level 3], the metrics are capability. Capability measures can be defined clearly in terms of measureables such as top speed, minimum speed, rate of acceleration, rate of fire, etc. Level 4] metrics may best be thought of as *utilities* and therefore are dimensionless. It may be helpful to review a hypothetical example of an aircraft performing a military mission. With a view to Fig. 1, let us assume that a missile attack has led to severing a fuel line to one of two engines on the aircraft. The damage vector at Level 2] is damage vector of one element, one killed fuel line. Applying the capability operator $\mathbf{O}_{2,3}$ to the damage vector gives the following result at Level 3]; the aircraft is able to fly straight and level, but not climb. Now we examine the Military Utility Operator, $\mathbf{O}_{3,4}$. To apply this operator, a number of missions must be defined. In one mission, it might be necessary to climb rapidly to avoid ground ordnance. In mission two, it might only be necessary to maintain level flight. Thus we could define two $\mathbf{O}_{3,4}$ mapping operators. In the case of the first, the damaged aircraft could not fulfill the mission and would have a utility of zero. In the case of the second mission, the mission could be supported, giving a utility of one. One can envision missions which when applied against partially performing platforms would result in partial utility $[0.0 < U < 1.0]$. Given some set of mission utilities, it is then possible to develop an expected utility, averaged over some set of missions.

Often utilities, averaged or otherwise, are used by the community of war gamers. The utilities are often simply *defined* to be probabilities of a certain class of kill. The utility, on the same interval as a probability, is used in the war game to make a draw, assuming a ballistic encounter. Based on the outcome, the platform may be removed from the conflict. Potentially three errors are committed by this practice.

1] Binning a vulnerability metric in a war game scenario which has already been binned by a vulnerability analyst: The war gamer should take the capability information from Level 3] and play that characterization of the platform in his mission encounter. The war game will then *define* the utility of the (damaged) platform.

2] Averaging two or more utilities: Often averages are performed over the outcomes of multiple binning processes. This is legitimate mathematically. However a major problem occurs when an average utility is applied to a specific mission. They may in fact be very different numbers leading to highly inaccurate conclusions.

3] Turning a utility into a probability: A practice which has seen widespread use in the ground arena has been to argue that an average battlefield utility is equivalent to the probability of total loss of the modeled capability.

This third practice has been shown wanting for many years,[11,12] but the numbers provided by the V/L community to its customers are still referred to as "probabilities of kill" or "expected loss-of-function", even if at their foundation, they may suffer from some or all of these three serious problems.

Finally, if a series of utilities is derived as a function of ballistic threats introduced at Level 1] and played against a number of missions in the $\mathbf{O}_{3,4}$ utility mapping, it would appear that we have proper measures for what might be called *ballistic survivability*. We have ignored all other factors in survivability including the probability of detection at various wavelengths, agility, etc. One can think of *overall survivability* as the combined output of an $\mathbf{O}_{3,4}$ utility map utilizing not only the Level 3] capability metrics of ballistic measures, but using the similar capability metrics from all of the other disciplines which affect survivability.

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11. James R. Rapp, *An Investigation of Alternative Methods for Estimating Armored Vehicle Vulnerability*, Ballistic Research Laboratory Memorandum Report ARBRL-MR-03290, July 1983.

12. Michael W. Starks, *New Foundations for Tank Vulnerability Analysis (With 1991 Appendix)*, Ballistic Research Laboratory Memorandum Report BRL-MR-3915, May 1991.

In the Army, there is now movement to repair these logical lapses. Recent work with battlefield modelers[†,‡] has shown that a war game is the singular place where battlefield utility should be estimated, and this in a robust situation where tactics, doctrine and appropriate stochasticism can be properly played. Thus the **Level 3]** to **4]** mapping for vulnerability/lethality must be played along with all of the other relevant platform metrics outside of the pure V/L milieu.

Appendix A

Definitions of Lethality, Vulnerability and Survivability[□]

Vulnerability

The characteristics of a system that cause it to suffer a degradation [loss or reduction of capability to perform the designated mission(s)] as a result of having been subjected to a hostile environment on the battlefield. It is generally an assumption in vulnerability studies that the threat warhead has engaged the target.

Lethality

The ability of a system to cause the loss of, or a degradation in, the ability of a target system to complete its designated mission(s). Often for direct-fire weapons, the delivery of the warhead from launch to target impact is integral to the lethality analysis. For indirect-fire weapons, studies often begin with warhead initiation in the neighborhood of the target.

Survivability

The capability of a system (resulting from the synergism among personnel, materiel, design, tactics and doctrine) to avoid, withstand or recover in hostile (man-made and natural) environments without suffering an abortive impairment of its ability to accomplish its designated mission. If the two facets under control of a weapons designer, materiel and design, are lumped into *System Characteristics*, and the effects of personnel are distributed appropriately over the three remaining variables of *Characteristics*, *Tactics* and *Doctrine*, then Survivability can be written functionally as:

$$
\begin{aligned}
\text{Survivability} = f\,[&\text{Threat (Characteristics, Tactics, Doctrine)},\\
&\text{Battlefield Environment},\\
&\text{System (Characteristics, Tactics, Doctrine)}]
\end{aligned}
$$

† Private communication with personnel at TRAC/WSMR. War Gamers at TRAC are modifying a version of CASTFOREM so as to accommodate ballistic inputs at Levels 2] and 3]. These war games, as a consequence of their outputs, provide a Level 3] to Level 4] mapping (*i.e.* utility weighting).

‡ Private communication with W. J. Brooks, Jr., of AMSAA. A DMSO-funded ATTD Program directed by Mr. Brooks is being configured so as to accept Level 2] (disabled components) and Level 3] (degraded capability) metrics from V/L models.

□ Consistent with *Defense Acquisition Management Policies and Procedures*, DoD Instruction 5000.2, February, 1991.