2020 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM
SURVIVABILITY TECHNICAL SESSION
AUGUST 11-13, 2020 - NOVI, MICHIGAN

ARMOR AND SYSTEM WEIGHT IMPACTS TO PROCUREMENT, TRAINING, AND SUSTAINMENT COSTS

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ABSTRACT

In monolithic protection materials, a threat increase correlates to an increased material thickness. This is evident in V50 armor material specifications, such as Rolled Homogeneous Armor (RHA) MIL-DTL-12560K. This relationship translates to combat system level weight; the higher the performance, the higher the material weight, the higher the system weight. For ground combat systems, the total platform weight indicates relative protection. Hence, the M1 Abrams weight and protection level is greater than the Bradley Family of Vehicles, and the Bradley weight and protection level is greater than the M113. The weight procurement dollarization impacts are known during developmental efforts, but weight relationships also impact training and sustainment costs. Thus armor based weight changes have at least three cost relationships: procurement, training, and sustainment. These cost relationships are useful to understand in the context of the Army's annual budget cycle.

Citation: RA Howell, "ARMOR AND SYSTEM WEIGHT IMPACTS TO PROCUREMENT, TRAINING, AND SUSTAINMENT COSTS," In *Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium* (GVSETS), NDIA, Novi, MI, Aug. 11-13, 2020.

1. INTRODUCTION

The background for understanding and defining armor cost relations has traceability all the way up through statute. Cost considerations for a defense acquisition program are required by law [1] within Title 10, United States Code 2434. This law requires the Secretary of Defense to produce cost estimates prior to system development or production and deployment approval. A flow-down of the statute is the Department of Defense (DoD) policies, such as the DoD 5000 [2], that require program cost estimation calculations. The Army Cost Position is computed per the Army Cost Analysis Manual [3] with terms and boundary conditions tied to weapon types found in MIL-STD881D [4]; the Work Breakdown Structure (WBS) for Defense Systems [4]. It is important for engineers to understand these legal and policy requirements because these documents drive many of the questions and information sought by government officials from equipment

DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited manufacturers. The law and policies require program offices to use deliberate processes and checklists to acquire cost information in a consistent manner. This required submission information must be addressed in order to be both compliant with the law and allow funding execution for programs to proceed.

Per the Army Cost Analysis Manual [3, p.3], cost estimation accuracy at the start of a program is limited due to "an imperfect understanding of the technical merits and limitations" of the system under study. Cost estimation is intended to be flexible and tailored to the problem set. Per the manual, two cost estimating methods can inform armor and protection analysis. First, an "engineering (bottom-up) approach" [3, p.33] can provide precise cost data for a well-defined armor component that has a known bill of materials, known processes to produce, and known integration costs. When those details are not fully defined or there is need for Size, Weight, and Power plus Computing (SWAP-C) trades, a second methodology, the parametric analysis [3, p.33], is employed. This method relates the attributes relative to the system.

What is not in the manual, though, is a defined set of conditions to dollarize the weight as an individual contributing variable in the larger cost calculation. Instead, the manual descriptively acknowledges weight and its influence in several locations throughout the Army Cost Analysis Manual [3, pp. 3, 33, 38, 41, 84, and 147]. The nature of cost estimating, then, is not a simply defined universal equation with prescribed variables accounting for all inputs, specifically system weight. In order to better inform capability cost calculations and affordability, the following qualitative analysis was conducted to assess weight impacts on procurement, training, and sustainment costs.

2. DATA SOURCES AND ANALYSIS METHODOLOGY

Three data sets provide the primary source of information for this study's analysis. The three data sets are: ballistic acceptance information from MIL-DTL-12560 REV K for RHA [5]; the Operations and Sustainment (O&S) database for weapon system cost per mile [6]; and the O&S database for depot repair cost [7]. Other contributing sources were based on World Wide Web sources for United States Army tracked vehicle weights [8-17].

Table A-II from MIL-DTL-12560 REV K is the first data source [5]. This particular material source was referenced because armor mass efficiency is always related to this steel's material performance. A simple corollary analysis of Table A-II illustrates the relationship of material weight to cost that is borne out by tracked combat systems. This is done in three steps. First, simple cost material equations are shown in relation to a commodity price variable, material density, and material volume. Second, material performance is shown to relate material thickness by plotting the V50 acceptance limit and corresponding RHA thickness in Table A-II. Third, since thickness changes corresponding to performance equate to volume and weight changes, Figure 2 reflects the material cost-to-weight relationship from Equation (3), rather than cost-to-thickness.

The other two data sources are from the Army's O&S database portal [6, 7]. Within the portal is the replenishment part and fuel unit training cost data set, and the depot cost data set. The unit training and depot cost data sources provide cost information according to platform type. Tracked combat system data was extracted from each table. This included direct fire weapons, such as the M1 Abrams tank, indirect fire systems, such as the M109 Paladin system, and support vehicles, such as the M1068.

The unit training costs are expressed on a per mile basis by weapon system type, and contain costs for repairable subcomponent parts, consumable items, and fuel. There are separate per mile dollar figures for each weapon system for the Active Army, overseas forces, and National Guard, as well as an Army compositional number accounting for all three conditions. This compositional value was the selected value for each system.

Depot repair costs reflect the actual dollar figure in a given year, indicated by repair code type and vehicle quantity that was repaired for the dollar figure. Data was available for the years 2006 to 2019 across common recapitalization and battle damage repair codes. For the depot cost calculation, the average vehicle cost was calculated by dividing the total dollars spent per platform for all codes of consideration by the total number of vehicles processed.

The O&S per vehicle cost data was then correlated to open sourced platform weight values [8-17], normalized to the Abrams data points, and plotted such that cost is made as a function of weight for an individual system. The analysis was further stratified by first removing combat support vehicles and leaving only weapon systems. The second stratification removed indirect fire weapon systems with the remaining category data plot consisting only of direct fire weapons.

The data in each Figure was plotted using Microsoft Excel. A simple linear curve fit was used for each data set. The Figure plots, curve fits, and analysis are qualitative without error bars since the data sources did not have high resolution and only general trend analysis was sought. That is, traceability down to individual serial numbers, associated cost data, total miles driven for each system, individual vehicle weight, and age of each system is lacking. Therefore, the analysis shows an aggregate vehicle type function. The function's impact to cost should not be taken as an exact solution.

3. COST WEIGHT RELATIONS

3.1 Material Procurement

Weight and cost impacts are logically the most understood, particularly with respect to materials. If a metal plate's thickness is increased, the vehicle's weight and cost go up. From this idea, a generic material cost equation is established. The cost of a monolithic material C equals the price per pound, P (\$/lb), times the material density, ρ (lbs/ft^3), times the volume, V (ft^{3,}) as shown in Equation (1).

$$C = P\rho V \qquad (1)$$

Weight (W) of a plate of material equals density times the volume.

$$W = \rho V \qquad (2)$$

By substituting W into Equation 1 the relationship of C equals P times W is shown.

$$C = PW \qquad (3)$$

This simplification assumes negligible changes in material cost per pound associated with changes in thickness due to any delta in processing or other material parameters. The three aforementioned equations simplistically reflect that a growth (or reduction) in weight has linear proportionality to the cost of that material.

Next, Figure 1 shows the minimal acceptance V50 velocity for RHA steel against the 0.30 caliber armor piercing M2 (APM2) projectile.

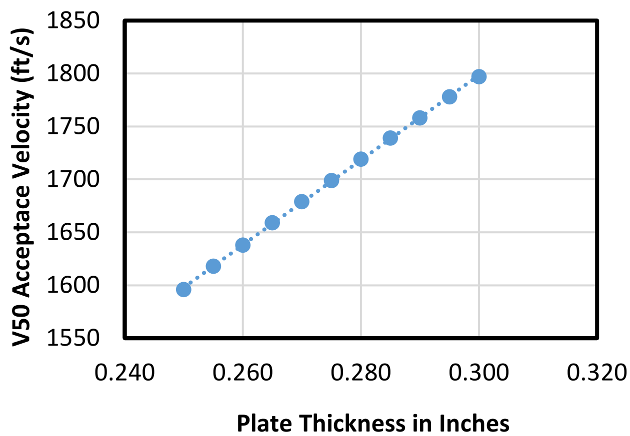

Figure 1: The plot is from Table A-II for RHA Classes 1 and 3, 0.30 caliber APM2 acceptance criteria in MIL-DTL-12560 K.

The data shown in Figure 1 is a subset of the table. Figure 1 is the acceptance velocity for RHA thicknesses from 0.25 inches through to 0.30 inches. Figure 1 shows that in this thickness range, a change in the V_{50} velocity corresponds to a linear proportional change in material thickness (X). This can be written generically as:

$$V_{50} = mX \quad (4)$$

X represents the material thickness and m represents the slope. The value of m in Figure 1 is constant. That is, for changes in projectile velocity, the correlation to thickness is constant and directly proportional to the material's volume. Due to the linearity shown in Figure 1, the weight value per Equation (3) is also linear for a fixed price per pound. This relationship is shown graphically in Figure 2.

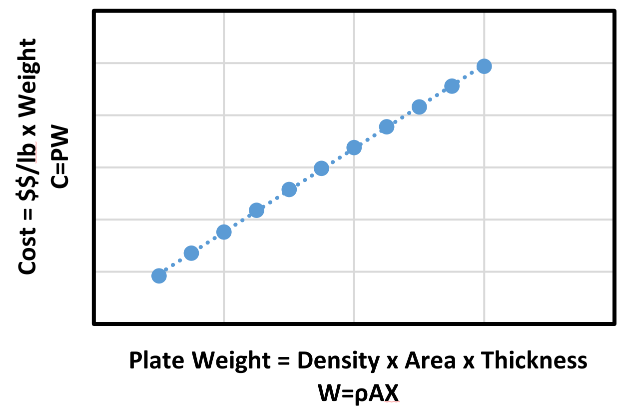

Figure 2: A generic plot is shown that correlates material cost C at a defined weight W.

In this context, for a given cost C, a change in performance equals a direct cost and material weight. At the system level, this can translate to one pound of material equaling one pound of system weight change. This performance-weight-cost trade for material procurement is the first cost-to-armor weight relationship.

3.2 Annual Training

The second cost-to-weight relationship is constructed from the data provided by the replenishment part and fuel cost data [6]. This cost data supports Army analysis for training budget calculations. Figure 3a shows normalized training cost data on a per mile basis for the M1 Abrams, M88 Hercules, M2 Bradley, M109 Paladin, M992 Ammunition Carrier, M270 Multiple Launch Rocket System (MLRS), and the M113 Family of Vehicles (FoV). The data was normalized to the M1 Abrams which is shown with a (1, 1) value.

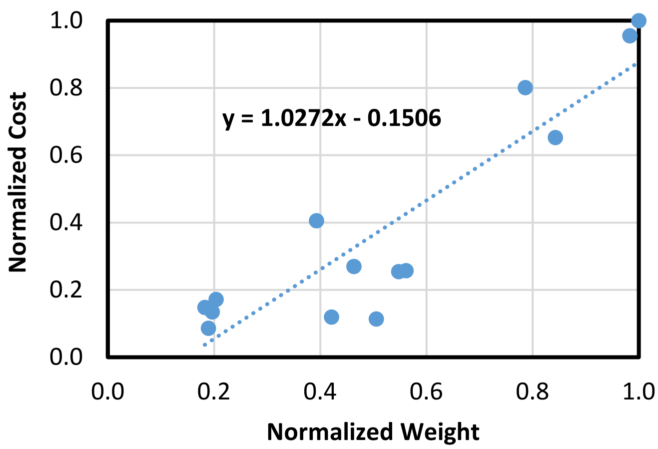

Figure 3a: Normalized per mile training cost data is shown for tracked combat systems.

Also in that location of the chart are data points for the M88. In the center of the chart are training costs for the Bradley FoV, and the lower left are training costs for the M113 FoVs.

Figure 3b removes the non-firing support vehicles, and Figure 3c removes the indirect fire vehicle types from the data set. The linear curve fit for Figures 3a, 3b, and 3c shows consistent trends that for increasing weight, training costs rise in commensurate form.

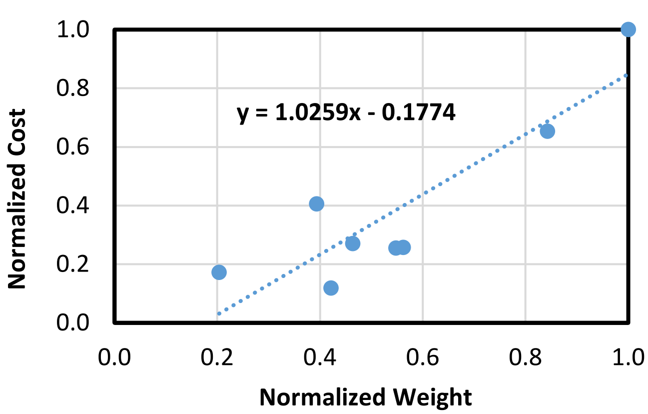

Figure 3b: Normalized per mile training cost data is shown for tracked weapon systems.

From an armor perspective then, every pound of armor increases training cost. The curve fit is not intended to provide precision, but is instead used in follow-on comparisons between the aggregate vehicle trend and fighting vehicles.

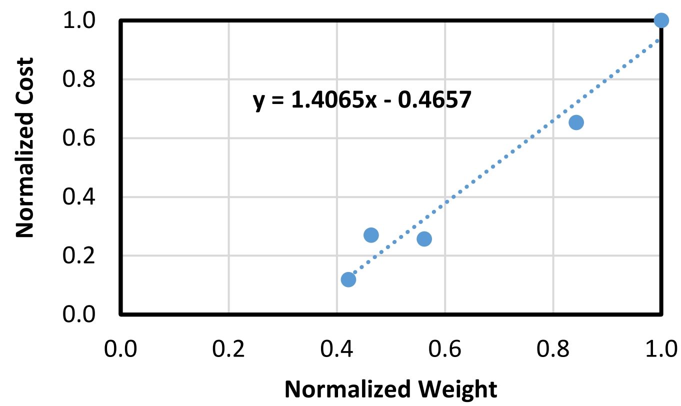

Figure 3c: Normalized per mile training cost data is shown for tracked direct fire systems.

3.2. Sustainment

The third cost weight relationship is shown in Figures 4a, 4b, and 4c for depot cost impacts. Figure 4a is the mixed fleet composition. The data in the upper right for Figure 4a is for the Abrams and M88 vehicles, the middle is the depot costs associated with the Bradley FoV, and the data in the lower left is from the M113 FoV. The data is normalized to the cost and weight of the Abrams tank. Figure 4b removes combat support vehicles and isolates fighting systems only. Figure 4c further stratifies the data by removing indirect fire combat systems leaving only direct fire platform data. All data is weighted equally and is presented on a per vehicle type basis.

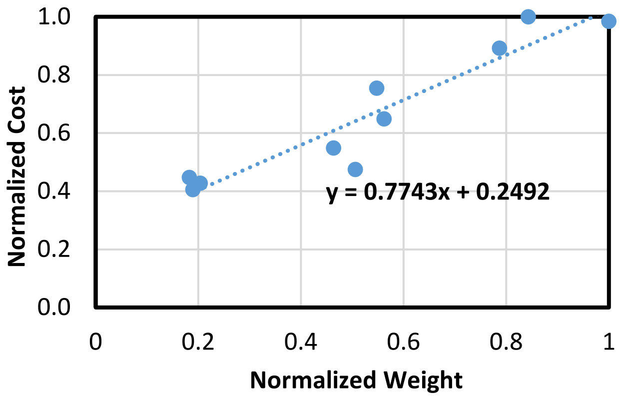

Figure 4a: Normalized depot repair cost data is shown for tracked combat systems.

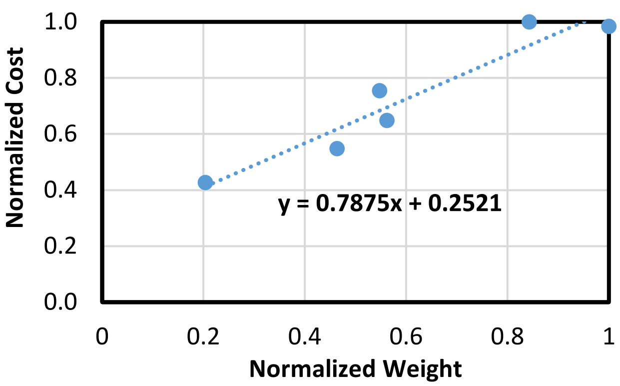

Figure 4b: Normalized depot repair cost data is shown for tracked weapon systems.

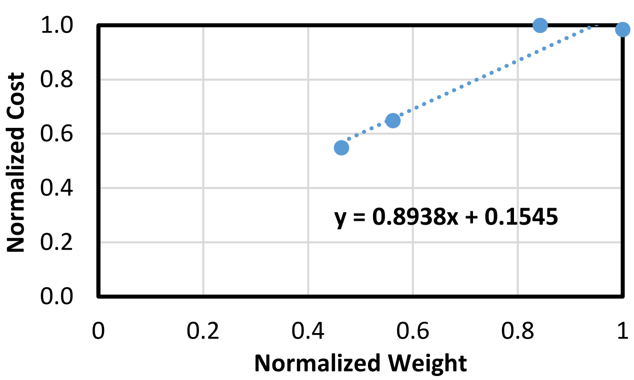

Figure 4c: Normalized depot repair cost data is shown for tracked direct fire systems.

In the same manner as the RHA analysis and the training cost data figures, the trend across Figure 4 is linear and follows that for added weight, an increase in sustainment cost is incurred.

4. DISCUSSION

In each of the three cost-weight impacts for RHA, training costs, and depot costs, a linear cost increase distinction is observed for every unit of weight added. While the Equations and Figures are qualitative, the three increases demonstrate a compounding effect for every pound of mass added to the platform. With respect to monolithic material armor, a nominal change in plate thickness negatively impacts the cost in three ways, not just one.

The direct fire weapon system costs in Figures 3c and 4c have unique characteristics compared to the rest of the data. What the data in these figures show is the weight-to-cost influence is more pronounced than the mixed fleet. In particular, removing the M113 vehicle influence on the plot is the greatest contributor to the change in slope for each relationship. The slope for the training cost increases from a value of ~1 in Figures 3a and 3b to ~1.4 in Figure 3c. The slope value increases ~40% from the normalized data field. This seems logical given that support vehicles lack the complexity of weapons platforms. To be clear, this cost data does not contain ammunition cost differences, so that is not a factor, and all data points are treated with equal weighting on a per vehicle basis only. The metrics are not aligned to brigade combat team fleet composition and density.

The change in slope for the normalized sustainment cost-weight slope figures increases from ~0.8 to ~0.9 from Figures 4a and 4b to Figure 4c or a slope increase of ~13%. The slope change from the mixed fleet to the direct fire systems for sustainment cost analysis is comparably less than the ~40% cost-weight training cost slope increase for the training cost-weight relationship.

The challenge then is to capture protection weight and cost trades as part as a larger cost impact sensitivity to Total Army capability and system budgeting. The cost calculating methods in the

Army Cost Analysis Manual do not align specifically to these impacts in a clean, computational manner. Material trades for reduced weight while maintaining equal protection capability generally drive procurement to more costly solutions. Alternate material and active protection solutions may offset weight, but their cost and integration present other challenges. These technologies have only been in the inventory a short time. Just as armor materials and protection systems can be measured in mass efficiency, active systems may need some other mass equivalency analysis for evaluating impacts on training and depot repair costs. The cost of armor, and weight in general, should be accounted for as cost effects are felt across procurement, training, and sustainment as a part of system trades.

5. CONCLUSION

Weight impacts due to armor affect the Army's costs in three ways. First, the cost of increasing the capability of armor by changing material thickness is directly proportional to procurement costs. The weight change of the armor also affects training costs, and third, armor and system weight impacts depot costs. In all three instances, more protection capability equals more weight and more cost in procurement, training, and sustainment. Thus, as armor weight trades are considered during initial procurement activities, the contributions of weight trades inform total system expense and should produce a dollarized value for each pound added to a combat system. More in-depth, weight-based cost analysis could inform the cost trades of Army decision makers with regard to total item life cycle cost and the affordability of a material solution.

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