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Research on Development and Application of Tools to Assist the OSD Office of Systems Engineering

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About This Publication

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Executive Summary

The Institute for Defense Analyses (IDA) was tasked by the Office of the Deputy Assistant Secretary of Defense for Systems Engineering (ODASD(SE)) Director, Mission Assurance to conduct research on developing high level tools for use by ODASD(SE). The target timeframe within the acquisition process for using these tools is pre-Milestone A and pre-Milestone B. The objectives of IDA's task were to evaluate whether the sponsor's research goals are feasible and to provide a project plan for addressing those research goals.

ODASD(SE)'s first research objective is to understand the extent to which systems engineering (SE) is being under-resourced (funded) and how initial under-resourcing of systems engineering and program-specific factors (e.g., percent software) is related to program outcomes (i.e., additional cost and schedule growth). IDA determined that developing Defense Acquisition Board (DAB)-level systems engineering resourcing rules for DoD weapon systems is feasible.

IDA arrived at this conclusion based on research undertaken by RAND and an evaluation of the Contractor Cost Data Report (CCDR) library and IDA's cost growth data set. The DAB-level resourcing rules envisioned in this research would allow ODASD(SE) to estimate the SE "should cost" for a specific weapon system. Additionally, the resourcing rules would outline the program cost penalty for under-resourcing SE (e.g., 5 percent reduction in SE funding would result in a 10 percent increase in program costs).

ODASD(SE)'s second set of research objectives are to understand:

- if physics-based analysis of cost and capability trade spaces (PACCTS) is feasible,
- what benefits PACCTS provides,
- the process for conducting a PACCTS project, and
- where PACCTS could play a role within the DoD acquisition process.

The purpose of the physics-based analysis is to link capabilities (e.g., key performance parameters) to costs in order to create a map, informed by physics, that graphically shows the relationship between desired capabilities and the required costs.

In the course of this task IDA determined that:

- PACCTS is feasible, as demonstrated by IDA Document D-3744, "Performance Trades for Joint Light Tactical Vehicle."[1]
- Physics-based analysis can expose decision makers to the full range of options (i.e., cost and capabilities) in a simple and communicable manner.
- Developing PACCTS requires linking the cost and capabilities to physical design features, which in turn are governed by physics and engineering principles, thereby implicitly creating a link between cost and capabilities.
- ODASD(SE) has at least three opportunities prior to Milestone B to use PACCTS to inform the acquisition process. The most fruitful and highest leveraged opportunity requires engaging with the initial capabilities document (ICD) stakeholders to ensure that the desired capabilities are mutually compatible.

Potentially, PACCTS's biggest benefit is that it can map out the feasible capability and cost space for a weapon system. In contrast, Analysis of Alternatives (AoA) generally considers several design points and not the entire cost-capability space. Conceptually, PACCTS involves mapping capabilities to physical design features or parameters through the use of physics and engineering relationships. We then cost these physical features or parameters (e.g., inlet area for an engine or diameter of helicopter blades). Since we can link cost and capabilities to physical design features, we can compute the cost and capability trade space.

ODASD(SE)'s best opportunity for improving the acquisition process, with PACCTS, occurs during the ICD formulation stage. During this phase ODASD(SE), with the cooperation of the ICD stakeholders, has the potential to help identify which requirements are compatible or incompatible and how they will drive costs for major acquisition programs. Additional opportunities to engage occur during the AoA and after Milestone A, as outlined in DTM 10-017[2] and an Office of the Secretary of Defense (OSD) memo entitled "Preparation for Defense Acquisition Board (DAB) Meetings, DAB Readiness Meetings (DRM), and DAB Planning Meetings (DPM),"[3] respectively.

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1 David R. Gillingham et al., "Performance Trades for Joint Light Tactical Vehicle" (Unclassified//FOUO), IDA Document D-3744 (Alexandria, VA: Institute for Defense Analyses, June 2009).

2 Under Secretary of Defense for Acquisition, Technology and Logistics, Directive Type Memorandum (DTM) 10-017, "Development Planning to Inform Material Development Decision (MDD) Reviews and Support Analyses of Alternatives (AoA)," September 13, 2010.

3 Principal Deputy Under Secretary of Defense (OSD), "Preparation for Defense Acquisition Board (DAB) Meetings, DAB Readiness Meetings (DRM), and DAB Planning Meetings (DPM)," Memorandum, April 23, 2010.

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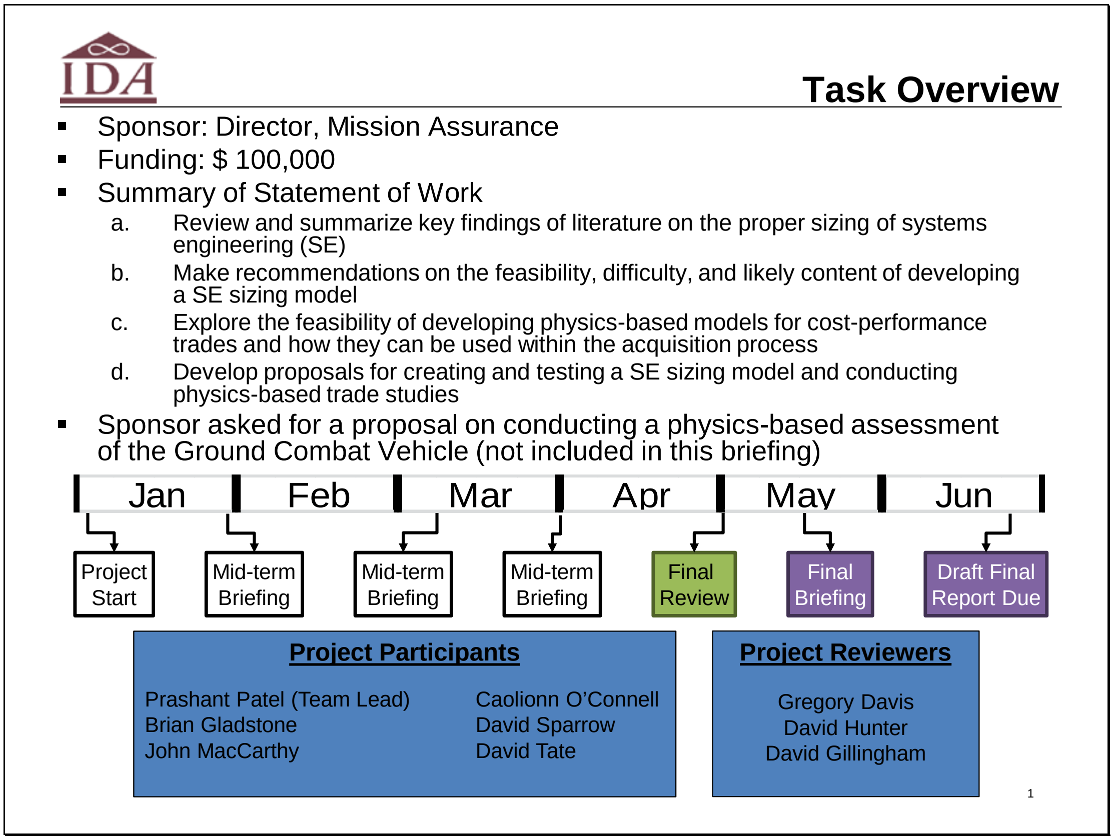

This task is sponsored by the Director, Mission Assurance in the Office of the Deputy Assistant Secretary of Defense (Acquisition, Technology and Logistics) for Systems Engineering (ODASD(SE)). The goals of this task are to review and summarize the key findings of literature on the proper sizing of systems engineering, to propose a project plan for developing a systems engineering resourcing model, and to develop a plan on how to implement and use physics-based analysis of cost and capability trade spaces (PACCTS) in the DoD acquisition process. The project team consisted of members from IDA's Cost Analysis and Research Division (CARD) and Science and Technology Division (STD). During the six-month project, IDA was also asked to provide a plan for implementing PACCTS for the Ground Combat Vehicle (GCV) program. The results of the GCV project plan were provided to the sponsor informally and are not included in this report.

Outline

- ***Literature Survey Results***
- Systems Engineering Sizing
  - Project Objective, Approach, and Notional Results
  - Project Proposal
- Physics-based Analyses of Cost and Capability Trade Space
  - Project Objective, Approach, and Notional Results
  - Project Proposal
- Concluding Remarks

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This document is divided into four parts. The results of the literature survey outline the current state of research on the proper resourcing of SE, programmatic factors that drive systems engineering costs, and system engineering metrics that are perceived to be leading indicators of program outcomes. The systems engineering sizing portion of the document focuses on the analytical questions that can be addressed, the expected results, and the project plan. The PACCTS section of the document focuses on the benefits of conducting physics-based analysis, an overview of how such an analysis could be conducted, a real world example that demonstrates the benefits of physics-based analysis, and, finally, possible places for ODASD(SE) to engage in the acquisition process. The concluding remarks summarize the major points of the document.

Literature Survey Objectives

- Review and summarize key findings of literature on the proper sizing of SE
- Identify some SE-related leading indicators (metrics and processes) of program success or failure

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Findings Reported in SE Literature

- These results are reported in SE literature and are not IDA conclusions
- Proper sizing of SE results
  - The optimal SE effort, to minimize cost growth, appears to be approximately 15-20% of actual RDT&E effort
  - A wide variety of quantitative and qualitative factors are used in SE sizing estimates (e.g., Program Cost/Duration and Type of Item)
- Leading indicators results
  - SE Leading Indicators Guide (v2.0) identified 18 categories and many metrics for evaluating SE (e.g., Requirements trends)
  - Several key SE processes that correlate with program success (e.g., Trade Studies) are reflected in Capability Maturity Model Integration model
- See backup for additional material

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The results of the literature survey represent views that IDA found in literature and do not necessarily reflect IDA's conclusions. When evaluating the issue of how to properly size SE, in one study, Dr. Honour attempted to correlate program outcomes (cost and schedule growth) with SE effort; other studies evaluated specific characteristics of the program. Dr. Honour's research indicates that, on average, cost and schedule growth is minimized when SE effort is approximately 15 to 20 percent of final total program development cost. There were a variety of references that identified parameters that affected the way programs sized their SE efforts. The two most useful references were the National Defense Industrial Association (NDIA)/ Software Engineering Institute (SEI) study and the Constructive Systems Engineering Cost Model (COSYSMO) dissertation. Examples of such parameters included Program Total Cost, Program Duration, and Type of Item. Additional parameters and references can be found in the backup and bibliography, respectively.

Additionally, IDA found numerous reports that identified possible leading indicators of program health. For example, the SE Leading Indicators Guide identified 18 broad categories, with each category containing numerous recommended individual metrics. As an example, the requirements trends category included such metrics as requirement growth and requirements stability. A more complete list of these categories is provided in the backup slides, as are additional references for leading indicators. One particular leading indicator, addressed in the joint NDIA/SEI study, identified a number of key SE processes that appeared to be correlated with program success.

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Caveats of Literature Survey

- Data was primarily voluntary and survey-based (self-selection bias)
- Dataset included a mix of DoD, NASA, and commercial projects
- Very few projects with SE effort > 10%
- Limited confidence on optimal SE effort due to data limitations

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While the literature survey indicated possible avenues for continued exploration, there are several significant caveats that must be considered before applying the results to DoD. The data used for the vast majority of research (e.g., Dr. Honour's, the NDIA/SEI study, COSYSMO, and the Leading Indicators Guide) were based on information that was provided voluntarily, introducing the possibility of a self-selection bias. Additionally, a large portion of the data from these four sources were based on survey responses. While some of these data came from DoD programs, the surveys also included data from commercial sources, NASA, and other government agencies. This is explicitly the case for Dr. Honour's work and the NDIA/SEI work. Furthermore, due to the need to protect proprietary data, we do not know which specific programs were considered. However, given the cost distributions on the programs, it is unlikely that many of them were Major Defense Acquisition Programs (MDAPs). In looking at Dr. Honour's work on the proper resourcing of SE effort, there were very few projects with SE effort greater than 10 percent and the data exhibited a significant amount of scatter. Furthermore, the information was not binned according to like programs, thereby limiting the applicability to specific DoD programs.

Outline

- ✓ Literature Survey Results
- ***Systems Engineering Sizing***
  - ***Project Objective, Approach, and Notional Results***
  - ***Project Proposal***
- Physics-based Analyses of Cost and Capability Trade Space
  - Project Objective, Approach, and Notional Results
  - Project Proposal
- Concluding Remarks

6

In the next section we will discuss IDA's proposal for conducting research on how to properly resource SE. Slides 7 through 11 cover the analytical questions that can be addressed and the long term goals of the research project, and present a plan for empirically addressing the analytical questions.

Project Questions and Expected Results

	1	2	3
Sponsor Questions	Is SE under-resourced?	What metrics and programmatic factors drive SE costs?	
Analytical Questions	Is there a correlation between program performance (cost and schedule) and:		
	planned SE funding	contractor reported SE metrics	programmatic factors (e.g., percentage software)
Results	Correlation between SE funding and program performance	Identification of key metrics and their correlation to program performance	Identification of key program factors (characteristics) and their correlation to program performance
	Top-level cross checks and rules govering SE funding / penalties for underallocation		

Long-term sponsor objective: Cost model that determines Systems Engineering funding for well-behaved programs

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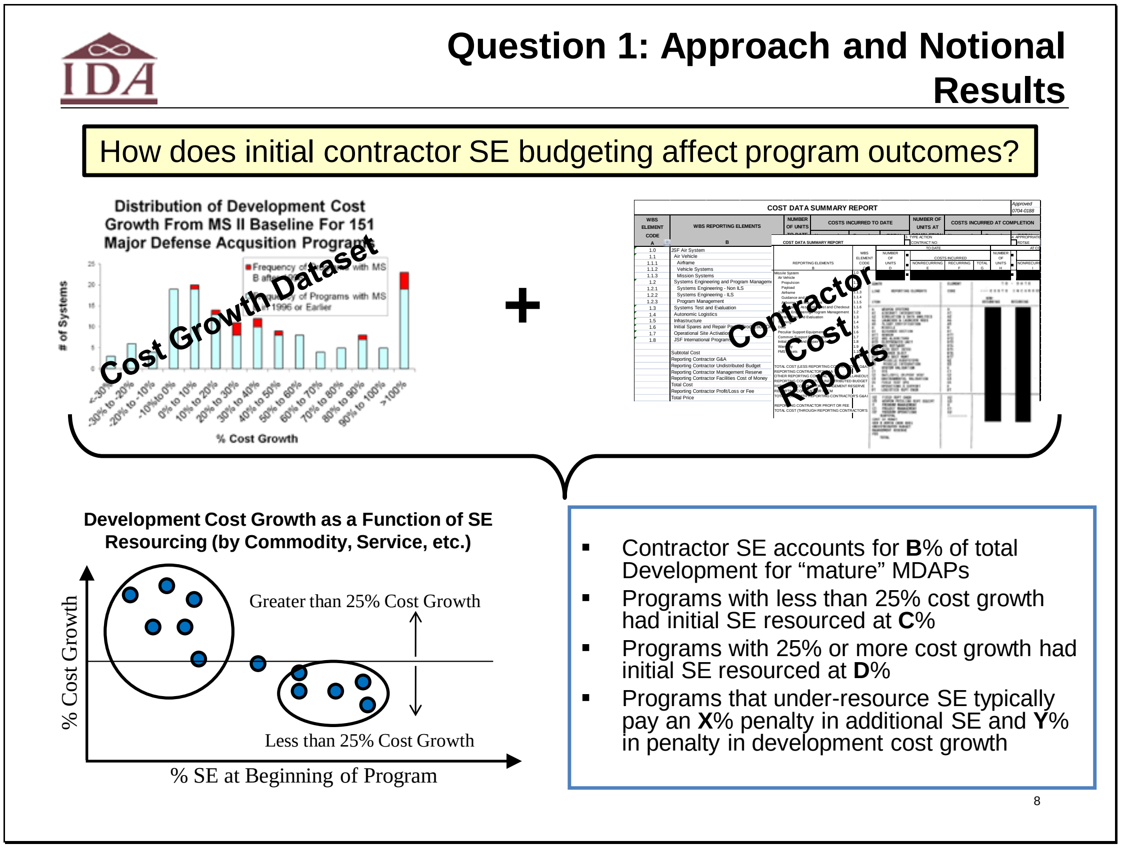
The sponsor of this task is primarily interested in three objectives: understanding whether SE is under-resourced by MDAPs, identifying metrics and programmatic factors that drive SE costs, and developing an SE “should cost” model. It may be difficult, if not impossible, to address the sponsor’s questions directly. Instead, IDA proposes to empirically address the three analytical questions in Slide 7 above. These questions act as proxies for the sponsor’s questions; however, the responses to the analytical questions can be empirically derived. Furthermore, addressing the three analytical questions should allow IDA to begin addressing ODASD(SE)’s long-term objective. The next three slides will present IDA’s project plan for addressing the three analytical questions.



This slide depicts the notional integration of MDAP cost growth information obtained from Selected Acquisition Reports with SE information from Contractor Cost Data Reports (CCDR). The goal of this approach will be to evaluate the growth (e.g., RDT&E, procurement) each MDAP had as a function of *initial* SE as planned at the beginning of the program. Cost growth will also be compared to the total *final* amount of SE funding (at the end of the program or most recently reported expenditure). From this study design, we will calculate an average RDT&E funding budgeted for SE by type of MDAP (e.g., size, commodity type, and Service). More importantly, we will evaluate how initial conditions of SE funding affected total cost growth for MDAPs of varying size, commodity type, and Service. This analysis should enable us to empirically identify the correlation between under-resourcing initial SE and cost growth (e.g., development, procurement, SE). It may also highlight "knees" in the curve that could indicate how much SE funding is required on average to minimize cost growth in MDAPs.

Question 2: Approach and Notional Results

- Objective:
  - Identify to what extent SE metrics (or lack thereof) affect MDAP outcomes
- Approach:
  - Collect and identify which SE metrics are used in MDAPs
  - Merge SE related metrics into dataset
  - Correlate the use of SE metrics (or lack thereof) with program outcomes
- Output:
  - Increased understanding of the extent to which SE metrics are reported and used to manage programs
  - Estimate effect of metrics (e.g., Not using SE metrics results in X% cost growth on average)
  - Develop heuristics (e.g., SE metrics YY and ZZ are the most correlated with low cost growth programs)

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In this second study we will identify the SE-related metrics (and practices) (e.g., requirements trends and technical measurement trends) actually used by programs to manage risk and correlate the use of these metrics with program success by building on the information obtained in addressing Question 1. This second study goes beyond current research on SE-related leading indicators in that it will rely on evidence from all DoD programs that comply with reporting policies instead of just programs that want to report.

Question 3: Approach and Notional Results

- Objective:
  - Understand how program-specific characteristics will affect SE funding requirements and program performance
- Approach:
  - Identify, collect, and integrate top-level programmatic factors (e.g., percentage software, number of new technologies) into dataset
  - Determine how SE effort and program outcomes depend on key programmatic factors
- Output:
  - Identification of which factors are correlated with SE costs and program performance
  - Understand the magnitude of specific programmatic properties on SE resourcing requirements and program performance

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During the third phase, we will determine what factors appear to have the greatest impact on the amount of SE resources required to successfully execute a program. To this end, we will select programmatic factors for consideration (guided by results of literature search) and look for cross-correlations between the selected factor, systems engineering effort, and program success. We will attempt to derive rules that allow for the estimation of SE resources required, based on program-specific characteristics. This third study goes beyond current research in that it will:

- Focus on DoD MDAPs, which is a limitation of the NDIA/SEI study and COSYSMO.
- Expand the scope of the RAND study by considering all DoD MDAPs and not just Air Force aircraft and guided weapon programs.
- Be based on government-mandated contractor cost data, which addresses a serious limitation of the NDIA/SEI study and COSYSMO.

Project Proposal: Required Effort and Considerations

- Execute under a single task order with three sequential phases
- Phase 1: SE budgeting vs. MDAP outcomes
  - OSD contractor cost data web archive contains relevant information, but limited to <40 programs
  - Data collection >4 staff months
  - Provide results of analysis
- Phases 2 and 3: SE metrics and program factors vs. MDAP outcomes
  - No central web archive of SE, technical, and programmatic information
  - Will have to collect and evaluate information from SE and program offices
  - Provide results of analysis as each phase is completed
- Can look at alternative data sources but it will require additional resources
- Research Team: ~3-4 research staff

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IDA proposes that the project be conducted under a single task order with individual statements of work to cover each analytical question. This approach should allow IDA to minimize the time required to collect the required information. Some issues to consider include the fact that the quality of the cost data is uncertain and the data collection effort will probably dominate the first four months of the task. The research team will be made up of three or four research staff members, who will undertake management and analysis roles. Several additional researchers will be used to front load the information gathering phase, thereby reducing the calendar time it takes to begin the analysis.

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Outline

- ✓ Literature Survey Results
- ✓ Systems Engineering Sizing
  - ✓ Project Objectives, Approach, and Notional Results
  - ✓ Project Proposal
- ***Physics-based Analyses of Cost and Capability Trade Space (PACCTS)***
  - ***Project Objectives, Approach, and Notional Results***
  - ***Project Proposal***
- Concluding Remarks

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In the section on PACCTS, we will define PACCTS, provide an overview on implementing and conducting it, and give a real world example of its benefits. Additionally, we will discuss how PACCTS can be used within the DoD acquisition process and provide a framework for conducting weapon system-specific analysis.

Project Objective

- In a transparent and communicable manner, display the cost and capability space of a weapon system using pre-Milestone A-like information
- Identify trade space, not just design points
  - Give decision makers the full range of options
- Identify cost drivers and how they are related to system level technologies
  - Get at why and what makes it expensive

Want to confidently state: "Capability X will cost Y **because of Z**"

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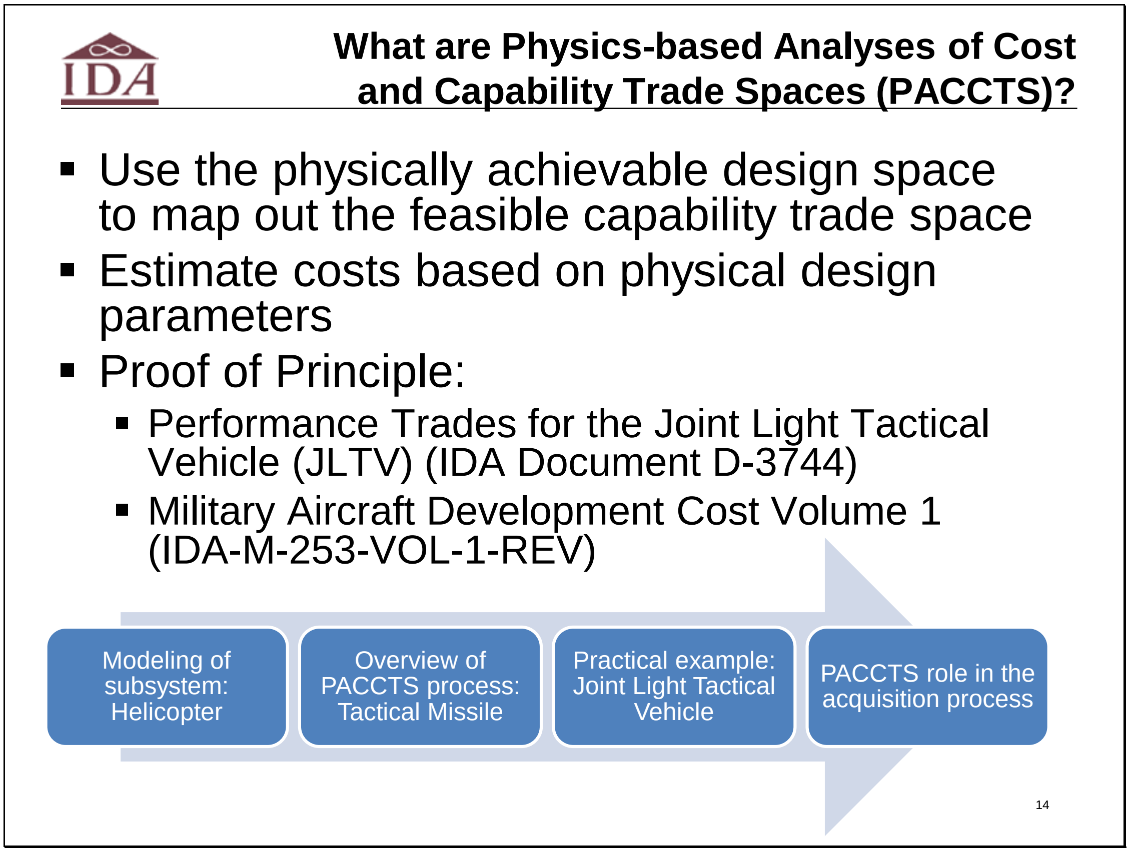
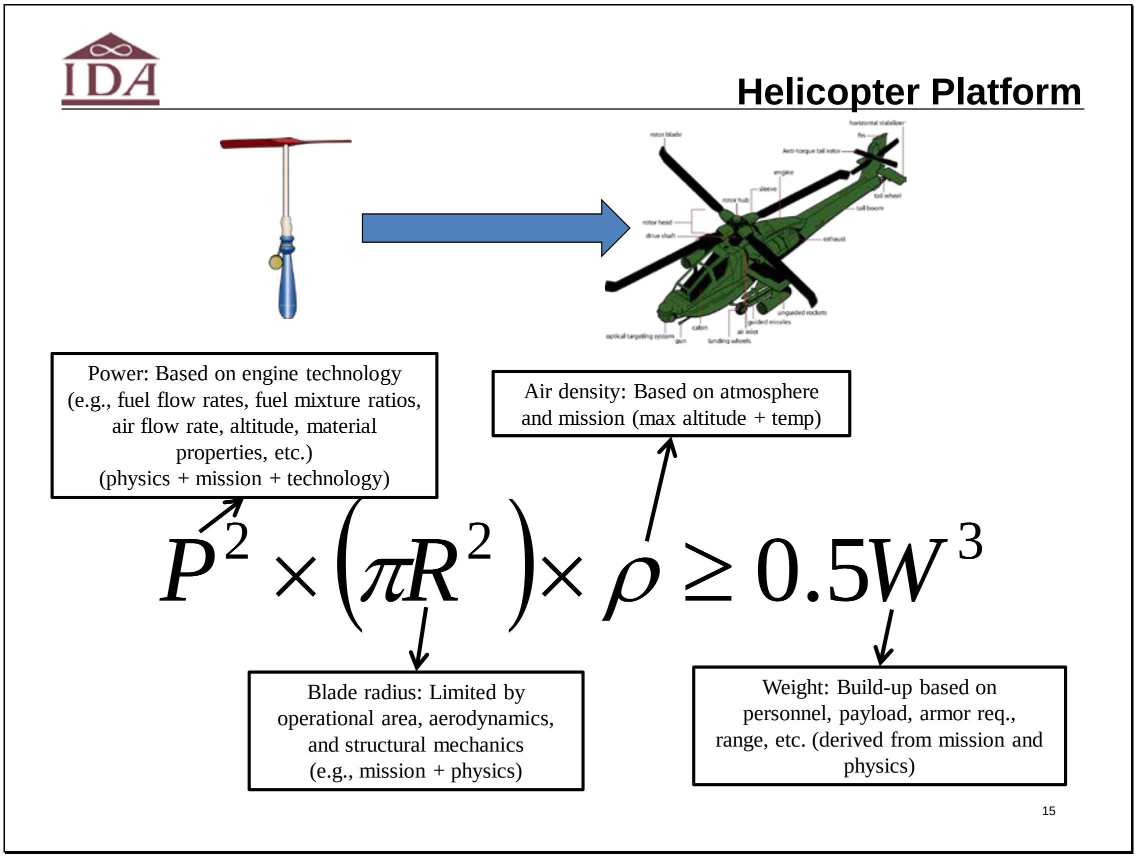
The top-level purpose of PACCTS is to be able to clearly and concisely communicate to a decision maker the range of capabilities that can be supported by a system, the associated costs of the different capability levels, and the driving reason for the associated costs. The ability to effectively communicate is a significant part of this project and was not treated as a secondary objective. Combining multidimensional capability and technical data with cost can be overwhelming. With this in mind IDA focused a significant part of its effort to outlining a process that lays out how design features, system capabilities, and cost can be combined into a visual chart that captures the relevant information. In practice we expect that the final visual product will vary depending on the weapon system and the factors that influence the decision metric (e.g., time, cost, risk, or quantity).



In previous parts of this report, PACCTS has been discussed broadly but it has not yet been clearly defined. The essence of PACCTS is to use the physically achievable design space to map out the feasible capability trade space. Additionally, PACCTS looks to estimate the costs based on physical design parameters.

Essentially PACCTS is designed to combine three key features into a single process, thereby directly linking costs to capabilities. One of the key features of PACCTS is that it uses physics and engineering principles as drivers of capabilities and cost, thereby linking the desired macro level programmatic properties with the micro level design features that will drive designer decisions. Additionally, the analysis is conducted over the feasible design space, thereby presenting the full range of options as opposed to isolated design points. Finally, it presents the benefits and consequences of the different options in a clear, transparent manner without making value judgments.

This section of the report is divided into four parts. In the first part, the report will discuss how to analytically implement PACCTS (e.g., by discussing an equation for a system). Next, we provide an overview of how PACCTS can be conducted and implemented end to end. Thirdly, we discuss the Joint Light Tactical Vehicle (JLTV) and how it could have benefited from physics-based analysis. Specifically, we discuss the current state of the JLTV program, the Analysis of Alternatives (AoA)-like process that led up to the current conundrum, and the IDA physics-based analysis that highlights several key issues that the program is currently attempting to address. Finally, we discuss several possible places for PACCTS to be used by ODASD(SE) to inform and improve the acquisition process.



This example discusses how PACCTS can be implemented at the system level. Specifically, this example is for a helicopter platform in hover. The end goal of PACCTS is to be able to link cost and capabilities to key physical design parameters of a weapon system like the Apache, as shown in the upper right hand corner of Slide 15. While being able to model a fully functioning weapon system like the Apache is the goal, it is not where the analysis begins. The analysis begins with a simple equation, to which we iteratively add complexity and detail until we have a model that represents the weapon system. We begin by modeling a simple and idealized version of the helicopter akin to the "whirligig" toy (upper left hand corner). The equation below the figures is an idealized helicopter equation and provides a relationship between the power, blade radius, air density, and weight of the vehicle. This represents the starting point of the analysis, from which we will discuss how it can be refined to incorporate additional information. We use this equation as an explanatory tool; in practice, we will have to solve multiple simultaneous equations.

The first stage in the process is to identify the relevant variables, the dependencies between them, and how capabilities can be incorporated into the equations. Using the ideal helicopter equation as a guide, we will discuss how the power (P), blade radius (R), air density (ρ), and air vehicle weight (W) depend on various physical processes, the mission, and different technological limitations. Additionally, we will discuss how they are linked to one another through several underlying physical attributes, which are not immediately apparent.

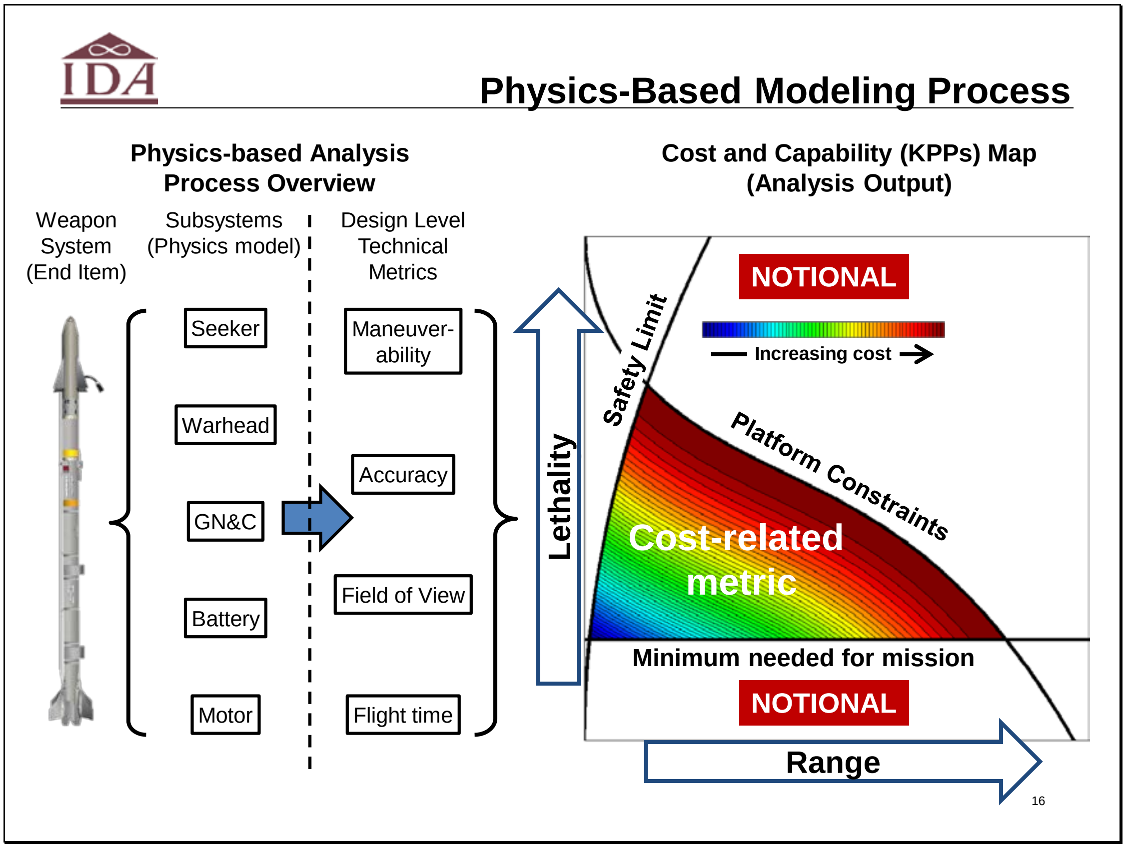
The power, P, represents the useful energy per unit time that is transferred into the air. The amount of power, P, that can be delivered will depend on a host of factors, including mechanical transmission efficiencies, fuel flow rates, allowable exit temperatures, air flow inlet area, and material properties. These variables encompass a host of factors including, the underlying physics, the role or mission of the vehicle, and fundamental material properties.

The blade radius, R, is constrained by the operational environment, the aerodynamics, and structural mechanics. R may have minimum and maximum constraints based on where the vehicle must operate (e.g., ship operations) and it will be limited by the local speed of sound and the torsional rigidity of the materials used in the blades. Once again, we have discussed several factors that will affect the blade radius that are linked to basic issues concerning the mission, physics, and fundamental material properties.

The air density, ρ, is an atmospheric property that depends on the maximum altitude and temperature (i.e., determined by mission and location).

Finally, the weight, W, can be built up based on the number of personnel, payload and armor requirements, and desired range. The range will impact weight because it depends on the fuel tank size, fuel flow rate, combustion temperatures, air density, and flight time. Once again, we see a link between capabilities (e.g., range) and physics (e.g., fuel flow rates and combustion temperature).

In the PACCTS process we would derive a physics-based model for each subsystem and then link them together in order to derive the system level performance. This slide demonstrates how we can begin the process by starting with an idealized equation and then expand it to identify the relevant dependencies. The next section will place this analysis in context and walk through a notional example.



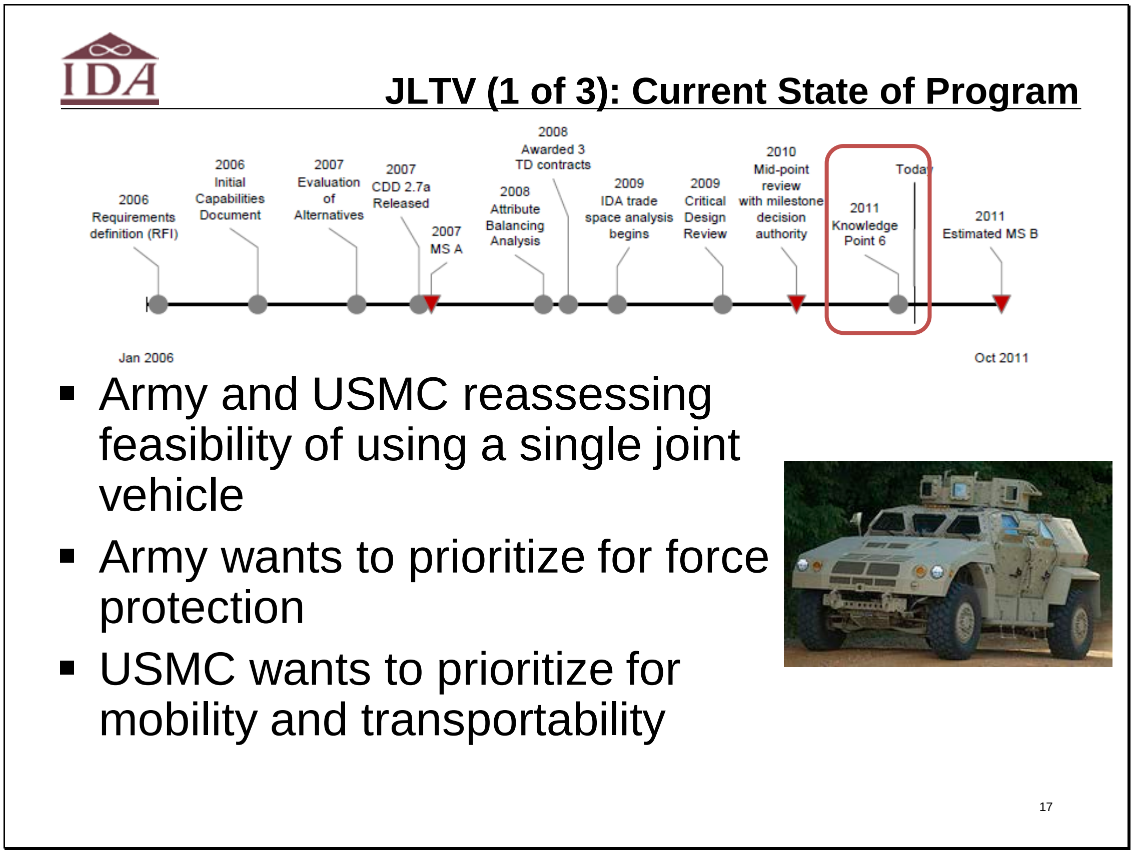
Slide 16 provides an overview of the PACCTS process for an air-to-air tactical missile. Before we discuss the analysis portion of the process, it is helpful to discuss the final output or deliverable. "The Cost and Capability (KPPs) Map," on the right hand side of the slide, is a notional figure that showcases the key features that PACCTS is designed to elucidate. Three key aspects of the figure are: it differentiates between feasible design space and infeasible design space, the axes are linked to capabilities (e.g., KPPs), and it applies a cost to the feasible space.

In this "Map," we have three constraints: platform constraints, a safety limit, and the minimum lethality required for the mission. The internal volume and weight limit of the F-22 weapons bay would be a type of platform constraint. The safety limit would represent the tradeoff between explosive power of the warhead and the minimum usable distance that ensures the aircraft is not endangered. The minimum lethality needed for the mission would represent the lower bound on lethality required in order to fulfill the mission. This constraint does not represent the desired level of capability but simply the absolute minimum required before the system would be ineffective (i.e., below this limit it would not take down the target).

The second aspect mentioned above is that the axes are tied to system level capabilities, such as range and lethality (e.g., probability of kill per target area). We note that capabilities are system-level attributes that depend on the interaction of multiple subsystems. Finally, a cost metric (i.e., life cycle costs or program average unit cost) is applied to the feasible space. In this notional example we color code the costs from blue (low) to red (high).

The cost contours (same cost-changing capabilities) are likely to follow immutable constraint boundaries (e.g., weight or volume limits). Furthermore, the costs sharply increase as we approach an immutable constraint, since reduced margin increases the difficulty of the design problem. Also, the figure does not prescribe the "best solution;" instead it describes how affordability will change with the desired system-level performance, thereby letting the decision makers choose without biasing their selection.

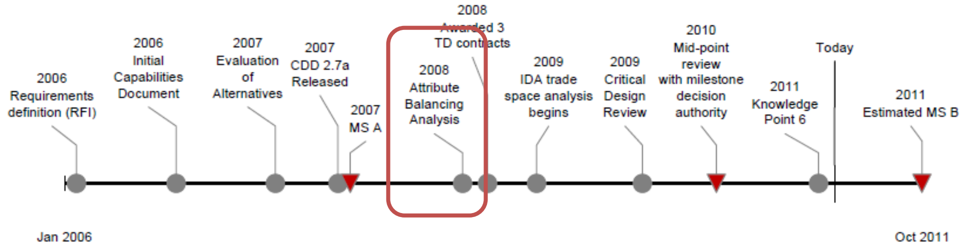
So far we have shown how we would analyze a specific subsystem (the helicopter platform) and we have shown a chart ("Cost and Capability Map") that is a representative output of the PACCTS process. Now we will discuss at a high level how we get from the weapon system concept to the "Cost and Capability Map." The first step is to break down the weapon system into its constituent subsystems. In this example of a tactical air-to-air missile, we list several subsystems: the seeker, warhead, guidance navigation and control, battery, and rocket motor. Once we have the governing equations for each subsystem we then map them to designable technical performance metrics. These are designable subsystem-level metrics that will govern performance. For example, accuracy could be measured as the expected miss distance of the guidance system. Field of view determines how much the seeker can see. Finally, the designable technical performance metrics would be combined to obtain the system level performance, such as lethality.



The JLTV is a real world example that demonstrates the potential value of physics-based analysis. The JLTV Category A vehicle is to be a single armored light wheeled vehicle that satisfies both the Army and U.S. Marine Corps (USMC). Currently, the values assigned to the two Services' requirements—namely, the Army's need for force protection and the USMC's need for a mobile and transportable vehicle—conflict. While RDT&E is supposed to highlight and address difficult issues before procurement, in this case the conflict between force protection and mobility and transportability was entirely predictable and highlighted in an IDA document[4] using pre-Milestone A-like information.

4 David R. Gillingham et al., "Performance Trades for Joint Light Tactical Vehicle" (Unclassified//FOUO), IDA Document D-3744 (Alexandria, VA: Institute for Defense Analyses, June 2009).

JLTV (2 of 3): Results of Army Attribute Balancing Analysis



- Army report evaluated six point designs (Category A vehicle)
- Constrained force protection, payload, and mechanical requirements
- All other KPPs were traded away (e.g., mobility and transportability)
- No consideration for affordability
- Outcome:
  - Heavily-armored, low-transportable vehicle
  - Qualitatively recognized force protection and weight linked

Source: Joint Light Tactical Vehicle Attribute Balancing Analysis Final Report

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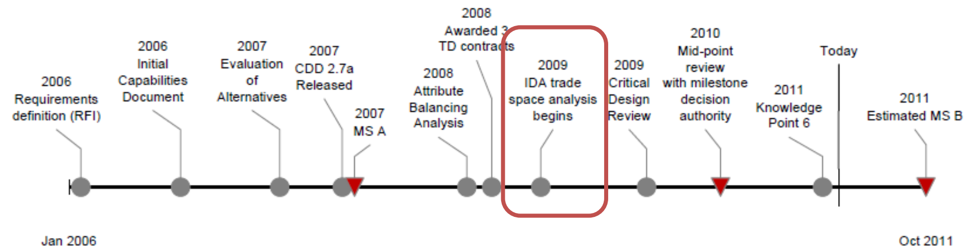
The JLTV program began its journey similar to most MDAPs. It underwent an AoA-like process. Specifically, the JLTV program conducted an Evaluation of Alternatives (EoA) followed by an Attribute Balancing Analysis (ABA). The EoA looked at a broad set of vehicles such as commercial solutions, modifications to existing vehicles, and new starts. It determined that a new start was the preferred option. The ABA determined what attributes (e.g., how much force protection, payload, mobility, etc.) the vehicle should have. Instead of fully considering the entire trade space, the ABA constrained the force protection, payload, and mechanical requirements, which limited its trades to mobility and transportability. Furthermore, the ABA failed to consider how the affordability would be affected. Due to the predefined constraints on force protection, payload, and mechanical requirements, the results were biased toward a heavily armored and minimally transportable vehicle. Unfortunately, we do not know the reason for the bias (e.g., institutional, management guidance, faulty analysis). While the ABA failed to fully explore the design space, it did qualitatively recognize that force protection and weight are linked.

JLTV (3 of 3): Results of IDA JLTV Analysis



- Analysis used pre-milestone A-like information
- IDA evaluated trade space for JLTV-like vehicle
- Quantified relationship between force protection and KPPs
- Quantified consequences of requirement choices (e.g., commonality and add-on armor kit)
- Laid out the possibilities and consequences without prescribing the answer

Use of trade space studies early in the acquisition process would have highlighted key challenges and reduced development time

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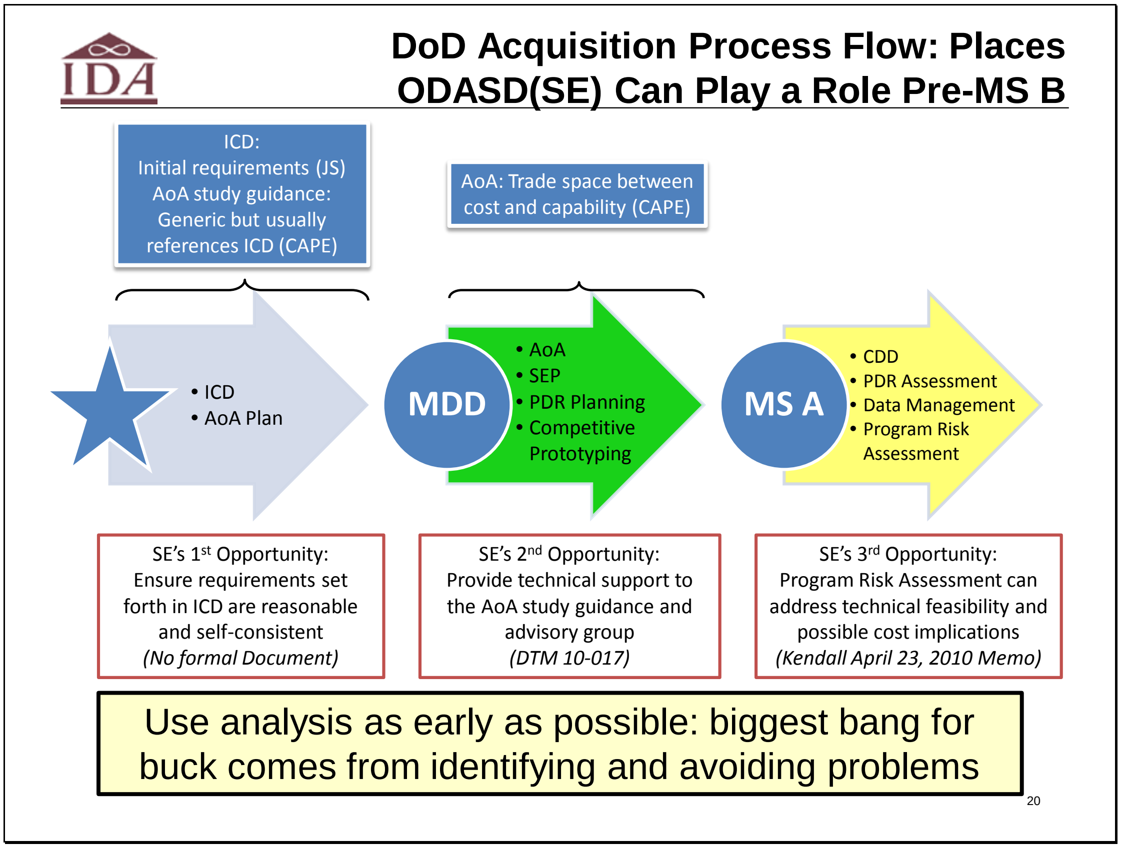
In 2009, IDA was asked to analyze the JLTV to understand how the different KPPs interacted. For this study, documented in IDA Document D-3744, IDA used pre-Milestone A-like information and conducted a physics-based analysis of the JLTV. In the course of the study, IDA quantified the tradeoff between force protection and mobility and transportability, as well as other KPPs. Specifically, IDA quantified the tradeoff between increased force protection and decreased mobility and transportability. IDA also identified the consequences (in terms of additional weight) for using a common chassis and add-on armor kits. Furthermore, the results were presented in a manner that highlighted the consequences of the different options without prescribing a particular solution as optimal. This study highlights two key issues: first, that physics-based analysis is feasible with pre-Milestone A-like information, and second, conducting physics-based analysis early on could have highlighted critical challenges, thereby giving managers sufficient time to address the issues and avoid costly delays late in the program.



IDA was able to identify at least three places that ODASD(SE) can use physics-based analysis to inform the acquisition process. The earliest opportunity is to work with the Joint Staff (JS) to ensure that the desired capabilities outlined in the initial capability document (ICD) correspond to an affordable and designable weapon system. Unfortunately, IDA was not able to locate any formal document that requires the JS to consult with ODASD(SE); therefore, this interaction, while beneficial, would be voluntary. The next opportunity IDA was able to identify is during the material development decision (MDD). During this phase, ODASD(SE) can serve in an advisory capacity to Cost Assessment and Program Evaluation (CAPE). The interaction between CAPE and ODASD(SE) is outlined in DTM 10-017. Finally, post Milestone A and pre Milestone B, ODASD(SE) can engage in the acquisition process using physics-based analysis to evaluate program risk and technical feasibility and the possible cost implications. The specific roles for ODASD(SE) are documented in a April 23, 2010 memo by the Principal Deputy Under Secretary of Defense for Acquisition, Technology and Logistics. An implication of the JLTV study is that using physics-based analysis early in the acquisition process will provide the most benefit by allowing DoD to identify and avoid issues before they become problems.

Physics-based Analysis of Cost and Capability Trade Space Proposal

- Previously proposed Ground Combat Vehicle (GCV) task (if funded) should demonstrate utility of physics-based analysis
- Draft a general task order for conducting physics-based analysis; use amendments to select and fund weapon system-specific analysis
- Start of analysis should begin ~1 year prior to a weapon system’s MS A
- Exact funding and schedule will depend on weapon system

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Currently, we have outlined how PACCTS could be implemented, where it could be used within the DoD acquisition process, and its benefits. The resources required to undertake PACCTS will heavily depend on the weapon system. For example, IDA’s GCV proposal to ODASD(SE) built on IDA’s JLTV study and, based on the limited scope of work, we estimated it could be done in approximately four months. We propose that the path forward incorporate a task order (IDA has one drafted) that describes at a high level the type of analysis that will be conducted. This allows for the use of amendments to fund weapon system-specific analysis, thus reducing administrative delays. Ideally, the analysis should begin well before Milestone A so that the results can inform the DAB.

Outline

- ✓ Literature Survey Results
- ✓ Systems Engineering Sizing
  - ✓ Project Objective, Approach, and Notional Results
  - ✓ Project Proposal
- ✓ Physics-based Analyses of Cost and Capability Trade Space (PACCTS)
  - ✓ Project Objective, Approach, and Notional Results
  - ✓ Project Proposal
- ***Concluding Remarks***

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Concluding Remarks

- Literature does not adequately quantify the value of SE or how to size SE for DoD MDAPs
- SE sizing and physics-based analysis projects are feasible, as other projects have conducted similar work on a limited scale
- SE sizing project goals:
  - Develop program-specific heuristics for evaluating contractor SE funding and metrics
  - Identify a set of top-level cross checks for SE reporting and budgeting
- Physics-based analysis can identify key program challenges and consequences early in acquisition
  - Allow acquisition process to preemptively address issues before they become problems

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Backup for Literature Survey

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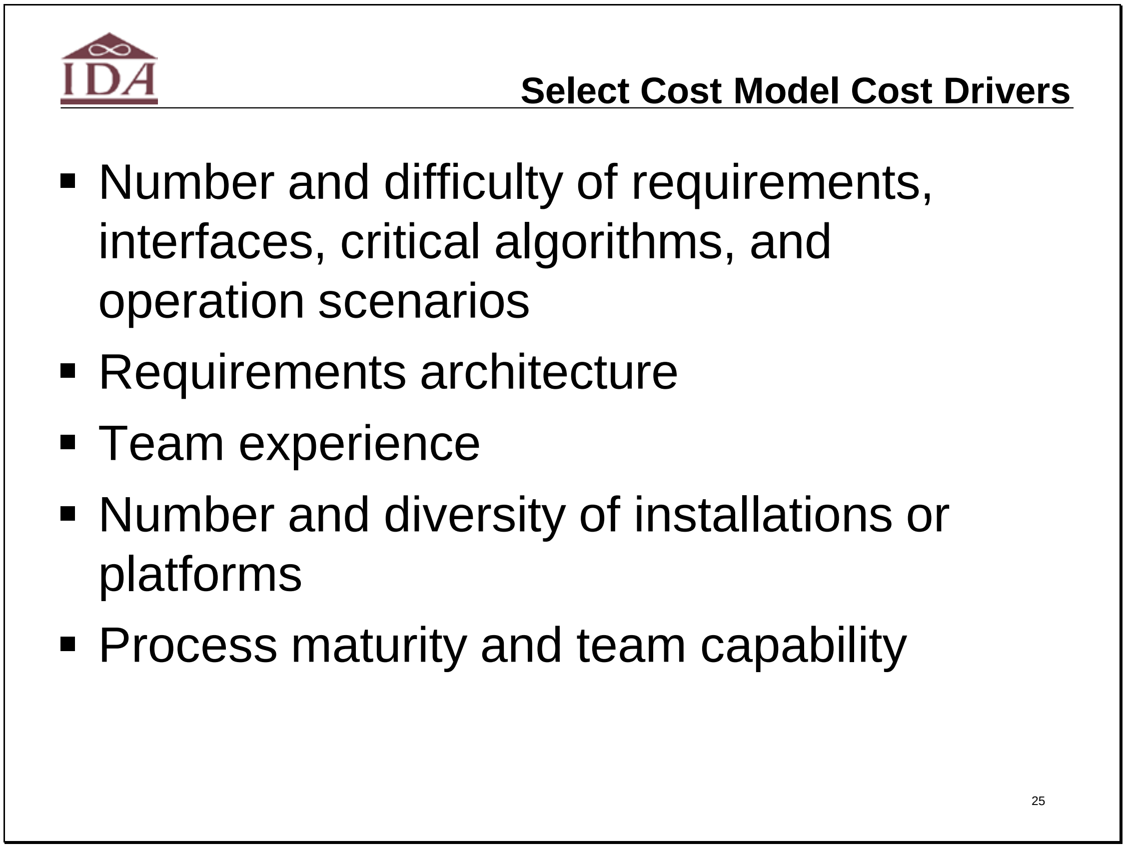

A partial list of SE-related program cost drivers was drawn from the papers by Dr. Valerdi and the NDIA/SEI Study.

INCOSE Categories of SE Leading Indicators

- Requirements Trends
- System Definition Change Backlog Trends
- Interface Trends
- Requirements Validation Trends
- Requirements Verification Trends
- Work Product Approval Trends
- Review Action Closure Trends
- Technology Maturity Trends
- Risk Exposure Trends
- Risk Treatment Trends
- Systems Engineering Staffing and Skills Trends
- Process Compliance Trends
- Technical Measurement Trends
- Facility and Equipment Availability
- Defect and Error Trends
- System Affordability Trends
- Architecture Trends
- Schedule and Cost Pressure

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This list of Categories of SE Leading Indicators was taken from the INCOSE 2010 “SE Leading Indicators Guide, Ver. 2.0.” Each Category includes a set of metrics that are recommended for use as leading indicators. An example is provided in the following slide.

Some INCOSE SE Metrics of Leading Indicators

- **Requirements Trends:** % Requirements growth and modifications
- **Interface Trends:** % Interface growth and changes
- **Requirements Validation Trends:** % Requirements validated
- **Requirements Verification Trends:** % Requirements verified
- **Technology Maturity Trends:** Technology Readiness Level for each Critical Technology over time, Cumulative Actual Cost for Realization of Technology Readiness Levels (for a critical technology), Actual Time to Realization for Realization of Technology Readiness Levels (for a critical technology)
- **Risk Exposure Trends:** Projected risk exposure (i.e., risk mitigation plan) vs. Actual Risk Exposure for each risk of interest
- **Risk Treatment Trends:** % of Risks that met risk reduction plans
- **Systems Engineering Staffing and Skills Trends:** Planned SE Effort/Planned Total Effort and Actual SE Effort/Actual Total Effort
- **Technical Measurement Trends:** Measured TPM value vs. Planned TPM value and deviation in performance
- **System Affordability Trends:** Baseline Cost/Schedule (with confidence) and Planned Cost/Schedule (with confidence)
- **Schedule and Cost Pressure:** Contract Cost/Schedule, Planned Cost/Schedule, and Actual Cost/Schedule

Track metrics over time to estimate performance

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This chart indicates some of the SE-related metrics that may be used as leading indicators of program performance that fall into each of the Leading Indicator categories.

Some Key NDIA/SEI SE Processes

- Requirements Development and Management
- Product Architecture
- Trade Studies
- Technical Solution
- Risk Management
- Verification and Validation

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This slide indicates the six SE-related processes that the NDIA/SE study found to be most highly correlated with program success.

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Abbreviations

ABA	Attribute Balancing Analysis
AoA	Analysis of Alternatives
CAPE	Cost Assessment and Program Evaluation
CARD	Cost Analysis and Research Division
CCDR	Contractor Cost Data Report
CDD	Capability Development Document
CMMI	Capability Maturity Model Integration
COSYSMO	Constructive Systems Engineering Cost Model
DAB	Defense Acquisition Board
DAU	Defense Acquisition University
DoD	Department of Defense
DPM	DAB Planning Meeting
DR&E	Defense Research and Engineering
DRM	DAB Readiness Meeting
DSMC	Defense Systems Management College
DTM	Directive-type Memorandum
EoA	Evaluation of Alternatives
FTE	Full Time Equivalent
GCV	Ground Combat Vehicle
ICD	Initial Capabilities Document
IDA	Institute for Defense Analyses
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering
ISO	International Organization for Standardization
JLTV	Joint Light Tactical Vehicle
JS	Joint Staff
KPP	Key Performance Parameter
MDAP	Major Defense Acquisition Program
MDD	Material Development Decision
MS	Milestone

NASA	National Aeronautics and Space Administration
NDIA	National Defense Industrial Association
ODASD(SE)	Office of the Deputy Assistant Secretary of Defense for Systems Engineering
OSD	Office of the Secretary of Defense
PACCTS	Physics-based Analyses of Cost and Capability Trade Space
PDR	Preliminary Design Review
PSM	Practical Software and Systems Measurement
RDT&E	Research, Development, Test and Evaluation
SE	Systems Engineering
SEI	Software Engineering Institute
SEP	Systems Engineering Plan
SERC	Science and Engineering Research Council
STD	Science and Technology Division
USMC	United States Marine Corps

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14. ABSTRACT
This paper, in the form of an annotated briefing, covers several topics related to systems engineering. It summarizes the key points found in literature on how to size systems engineering efforts and discusses the issues with those findings. We then present a proposal for empirically evaluating if systems engineering is under-resourced and how systems engineering metrics and program-specific characteristics will affect the proper level of systems engineering funding. The paper also focuses on improving the early acquisition process (e.g., pre-Milestone A) through the use of physics-based analysis in conducting cost and capability trades. We discuss at a micro and macro level the process for conducting physics-based analysis, the expected outcomes, and how they can be utilized within the current acquisition process to identify and avoid critical issues. Specifically, we focus on how to use physics and engineering principles and pre-Milestone A programmatic information to evaluate how the system level capability (e.g., key performance parameter) trade space will affect costs.

15. SUBJECT TERMS
Systems Engineering, Physics-Based, Engineering, Cost, Capability, Trade Space, Trade Study, Analysis, Resourcing

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