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# A Quantitative Analysis of the Benefits of Prototyping Fixed-Wing Aircraft

U.S. AIR FORCE

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  - Generally about 700-900 resident students
  - AF officers/ enlisted, DoD civilians, Int'l Officers, Army/Navy
- Masters of Science and Doctorates
  - Over 30 programs including Eng Physics, Ops Science, Electrical, Aeronautical, Astronautics, Computer Science, Environ/ Industrial Hygiene, Eng Management, Log Science, Systems Engineering
- 6 Research Centers / 50 Laboratories
  - Cyber, GeoSpatial Intel, Ops Analysis, Test& Eval, Advanced Nav, Space

# Overview



- Introduction
- Background
- Methodology
- Results & Recommendations

Disclaimer: The views expressed in this thesis are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the United States Government

Acknowledgement: Thanks to students Major Walter ”Rocky” Harvey and Major Matt Ryan, and our sponsor, ASC/XR, Donna Milam, whose passion and enthusiasm for process improvement is inspiring.

# How to Eat an Elephant



# Original Research Task



**How does large set of acquisition policy (and policy updates) impact life cycle cost?**

- Cost estimators - Generally, policy changes stemming from DoDI 5000.02 (2008), WSARA 2009 and recent Policy Memos do not factor into contract cost estimates – no basis of estimate
- Items that were thought to have some impact on cost:
  - Organic maintenance vs Contractor logistics
  - Implications of Will cost/Should cost policy
  - WSARA MS A certification process: MDA consider termination if 25% over original cost /schedule target prior to MS B
  - Desire to not be the cause of killing a program
  - **Acq strategy that includes prototyping**

# So, New Research Question



- **Does early prototyping (prior to PDR) result in lower cost growth?**
- **Are there any relationships between the cost of prototyping and cost growth or program schedule?**

***Hypothesis: prototyping has a positive impact***

# Timely Question



- **WSARA 2009 mandate that MDAPs use competitive prototyping as a means to ensure competition. In section 203 WSARA states**:

  *"The acquisition strategy for each major defense acquisition program provides for competitive prototypes before Milestone B approval … unless the Milestone Decision Authority for such program waives the requirement…"*

- **DoDI 5000.02 further details prototyping:**

  "*The [Technology Development Strategy] and associated funding shall provide for two or more competing teams producing prototypes of the system and/or key system elements prior to, or through, Milestone B. Prototype systems or appropriate component-level prototyping shall be employed to reduce technical risk, validate designs and cost estimates, evaluate manufacturing processes, and refine requirements."*

# Cost Growth Facts



- Cost Growth – Adjusted Current Estimate / Original Estimate
- No real change in cost growth over decades: 70s, 80s, 90s
- Few programs with extreme cost growth skew the CGF curve
- Longer programs tend to have higher cost growth
- Acq reforms generally have showed minimal correlation to cost growth, with exception of multi-year procurement
- Prototyping has showed mixed results; and no recent studies (1992)

# Prototype Definition



- Defense Acquisition University defines a prototype as "an original or model on which a later system/item is formed or based"
- *Early* prototyping occurs prior to full scale development (EMD or SDD)
- Purpose is to gain knowledge about:
  - Feasibility of technology
  - Validity of requirements
  - Validity concept's operational suitability
  - Identify resource requirements

YF-22,YF-23

- Not all prototypes will result in a fielded weapon system

# Prototype Research Review



- Prototyping the wrong thing leads to extended schedules, wasted resources and poor decisions
- Potentially provides a basis for accurate cost estimates
- Identifies technical risk and design flaws

- 1989 and 1991 IDA Study
  - Prototyping before full scale development generally successful
  - Prototyping resulted in 17% vs 62% Dev Cost Growth
  - And 29% vs 55% for Production Cost Growth
- 1992 RAND Study
  - Found “few significant differences between prototyping and non-prototyping programs with respect to cost growth, total actual program duration, or schedule slip”

# Examples – Case Studies



## Light Weight Fighter (later known as the F-16)

- "the fly-by-wire control and autostabilization system was refined and proven during prototyping"

## Advanced Medium STOL Transport (AMST) (C-17)

- "AMST program was a vital step in developing the technology that made the C-17 Globemaster III possible"
- "a wealth of practical experience and engineering data"
- "gave insight into the costs"

## HAVE BLUE program (led to F-117)

- "demonstrated manned aircraft could achieve radar signatures low enough to perform tactical missions without being detected"

# Methodology



- Collected cost data from Selected Acquisition Reports (SAR) for acquisition programs
  - Used base-year costs of final (or latest) SAR to remove majority of inflation related cost growth
  - Calculated Cost Growth as Ratio of current estimate (CE) to original development estimate (DE), factoring for quantity
  - Used Cost Improvement Curves (CIC) to normalize for quantity changes; otherwise quantity variance documented in SAR used
  - Single-sided hypothesis testing on the mean to test for significance (null hypothesis: means are equal)
  - Assumed log normal distribution as found by RAND
- Collected cost data for prototype programs from various SPO documents (WPAFB history office)

# Cost Improvement Curves



$$CGF = \frac{Adjusted\ CE}{DE} = \frac{CE-(C_c-C_r)}{DE}$$

$$C_c = F_c + U_c \cdot Q_c^{(S_c+1)}$$

$$C_d = F_d + U_d \cdot Q_d^{(S_d+1)}$$

$$C_r = F_c + U_c \cdot Q_d^{(S_c+1)}$$

$C$ = total cost

$U$ = recurring cost at unit 1

$Q$ = cumulative quantity

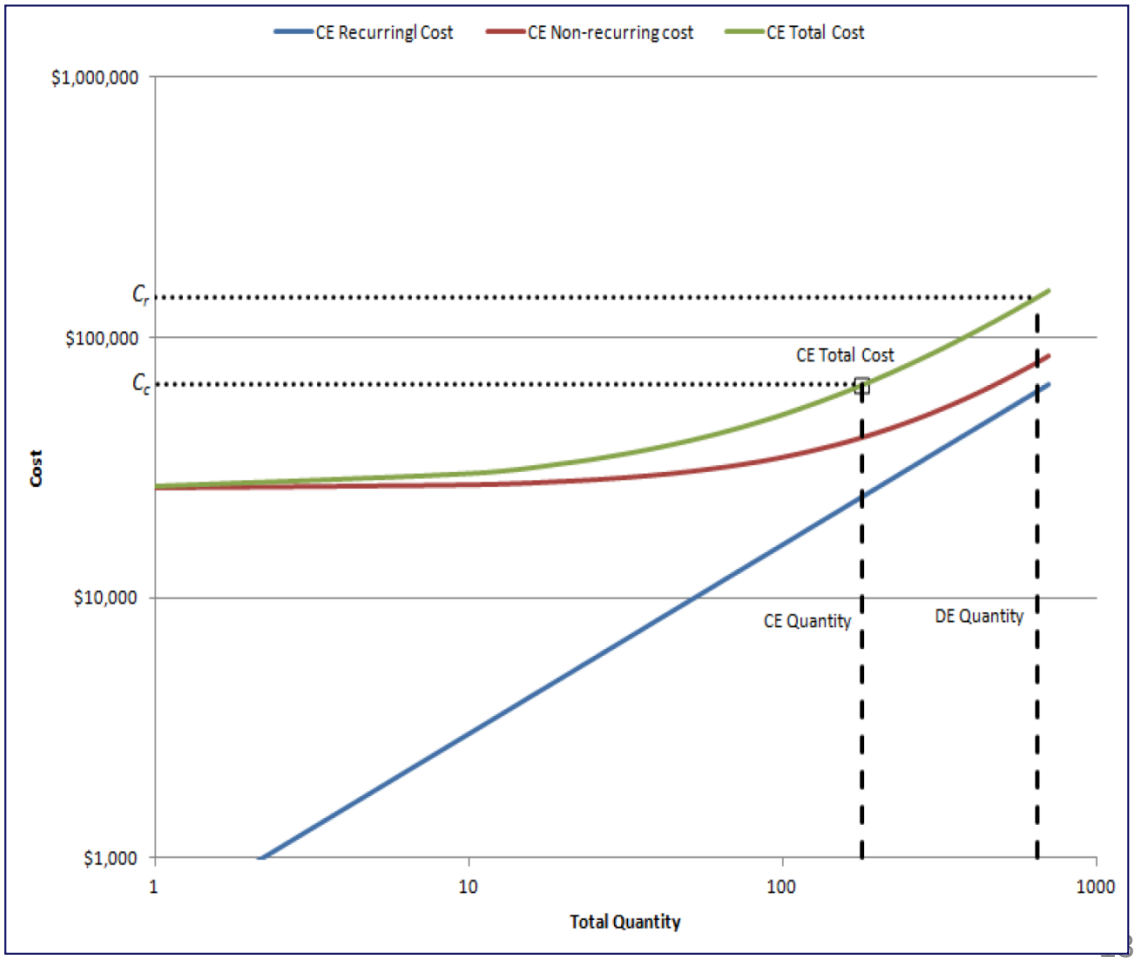
$S$ = cost-quantity curve slope

$F$ = non-recurring cost

$d$ = development estimate

$c$ = current estimate

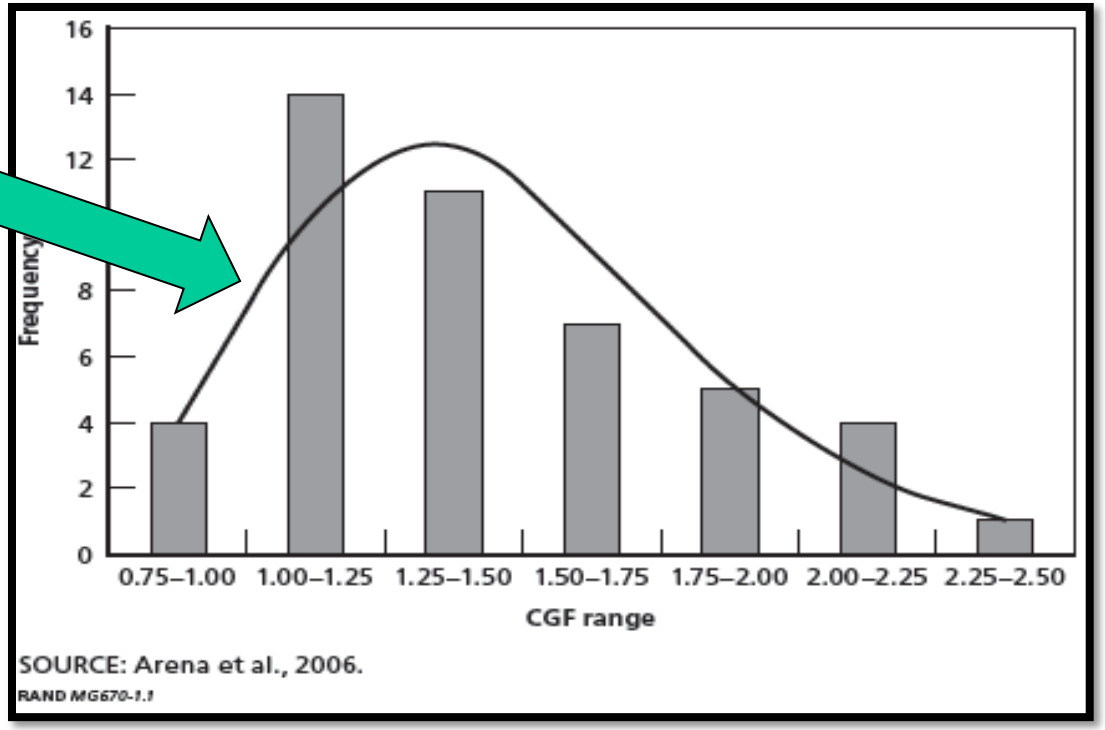
$r$ = adjusted estimate



# RAND 2006 Cost Growth Data



Hypothesis: Prototypes would show low CGF




| Category | # Observations | Mean | Median | Std Dev | Min | Max |
|---|---|---|---|---|---|---|
| Total | 46 | 1.46 | 1.44 | 0.38 | 0.77 | 2.30 |
| RDT&E | 46 | 1.58 | 1.34 | 0.79 | 0.77 | 5.47 |
| Procurement | 44 | 1.44 | 1.40 | 0.42 | 0.51 | 2.29 |

# 11 Prototyped Fixed-Wing Aircraft Programs



| Weapon System | Prototype | Aircraft Type | ACTD | Derivative | Base Year | Quantity Norm Method |
|---|---|---|---|---|---|---|
| A-10 | YA-10 | Fighter/Attack | No | No | 1970 | SAR variances |
| AV-8B | YAV-8B | Fighter/Attack | No | Yes | 1979 | CIC |
| C-17A | C-15 | Airlift | No | No | 1996 | CIC |
| F-16 | YF-16 | Fighter/Attack | No | No | 1997 | CIC |
| F-18A/B/C/D | YF-17 | Fighter/Attack | No | No | 1975 | CIC |
| F-22 | YF-22 | Fighter/Attack | No | No | 2005 | CIC |
| F-35 | X-35 | Fighter/Attack | No | No | 2012 | CIC |
| F-117 | HAVE BLUE | Fighter/Attack | Yes | No | 2010 | CIC |
| MQ-1 | Predator | UAV | Yes | No | 2008 | CIC |
| RQ-4 | Global Hawk | UAV | Yes | No | 2000 | CIC |
| V-22 | XV-15 | Airlift | No | No | 2005 | CIC |

# Prototyped Total Program CGF

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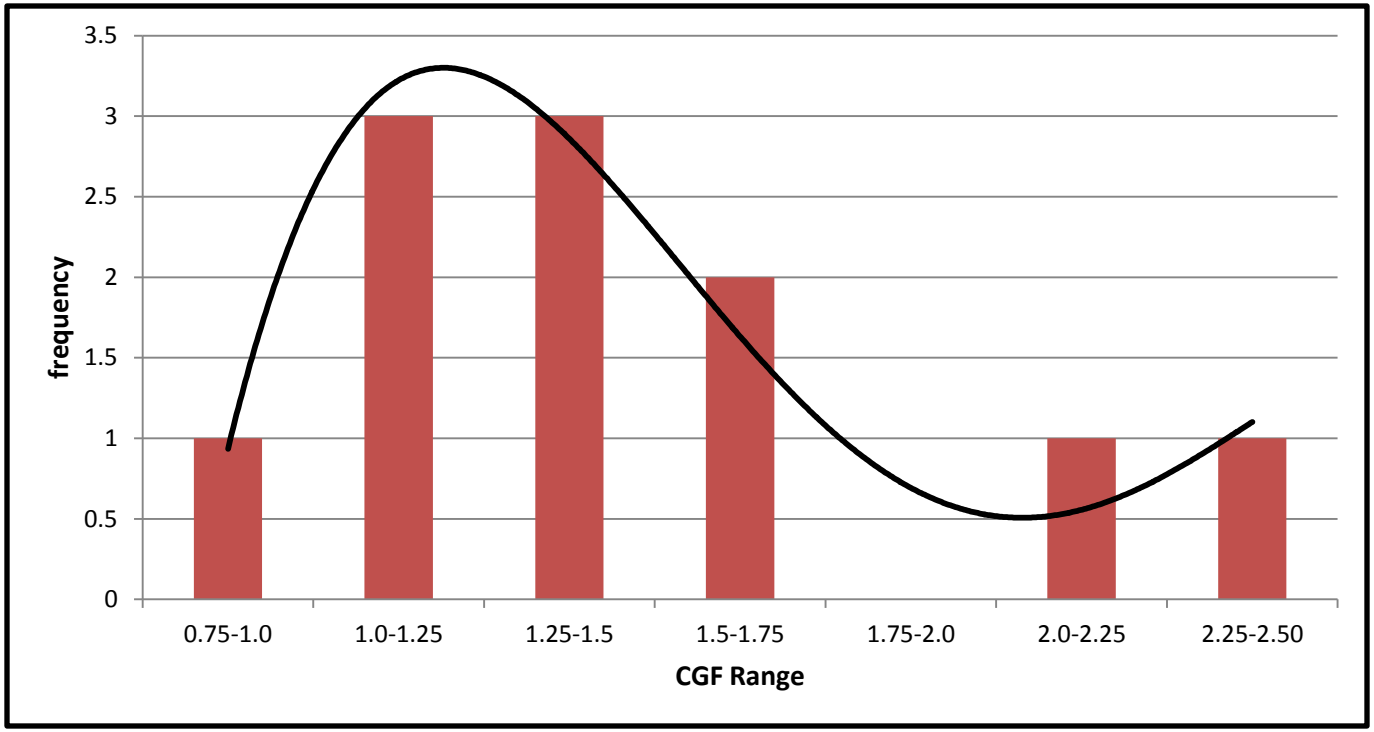


| Category | # of Programs | Mean | Median | Std Dev | Min | Max | P-value |
|---|---|---|---|---|---|---|---|
| Total | 11 | 1.52 | 1.42 | 0.43 | 0.97 | 2.40 | N/A |
| RDT&E | 11 | 2.15 | 1.54 | 1.15 | 1.32 | 5.04 | N/A |
| Procurement | 11 | 1.43 | 1.36 | 0.39 | 0.89 | 2.03 | 0.550 |

# Expanded Results



- Comparison with RAND data set showed no statistical difference between the means of the data sets
  - RAND study included non-aircraft programs
    - M1A2 Abrams, MILSAT Comm, C2 systems
  - Four aircraft programs are included in both data sets

- So, collected SAR data on 19 non-prototyped fixed-wing acquisition programs
  - Now compare to our prototyped fixed-wing aircraft CGF to our non-prototyped fixed-wing aircraft CGF
  - Examine subsets: no mod, no UAV, fighter/attack only

# 19 Non-Prototyped Programs Included in Study



| Weapon System | Aircraft Type | Derivative | Base Year | Quantity Norm Method |
|---|---|---|---|---|
| F-18E/F | Fighter/Attack | Yes | 2000 | CIC |
| F-15 | Fighter/Attack | No | 1970 | CIC |
| JPATS (T-6 II) | Trainer | Yes | 2002 | CIC |
| T-45 | Trainer | No | 1995 | CIC |
| P-8 | ISR | Yes | 2010 | CIC |
| MQ-4C | UAV | Yes | 2008 | CIC |
| B-1B | Bomber | Yes | 1981 | CIC |
| F-111A/C/D/E/F | Fighter/Attack | No | 1963 | CIC |
| EF-111A | Fighter/Attack | Yes | 1973 | SAR variance |
| E-6A | C2 | Yes | 1982 | CIC |
| F-14A | Fighter/Attack | No | 1969 | CIC |
| F-14D | Fighter/Attack | Yes | 1989 | CIC |
| KC-10A | Tanker | Yes | 1976 | CIC |
| JSTARS | C2 | Yes | 1998 | CIC |
| S-3A | C2 | No | 1968 | SAR variance |
| C-5A | Airlift | No | TY* | SAR variance |
| A-7D | Fighter/Attack | Yes | 1967 | SAR variance |
| A-7E | Fighter/Attack | Yes | 1967 | SAR variance |
| E-3A | C2 | Yes | 1970 | CIC |

# Total Program CGF

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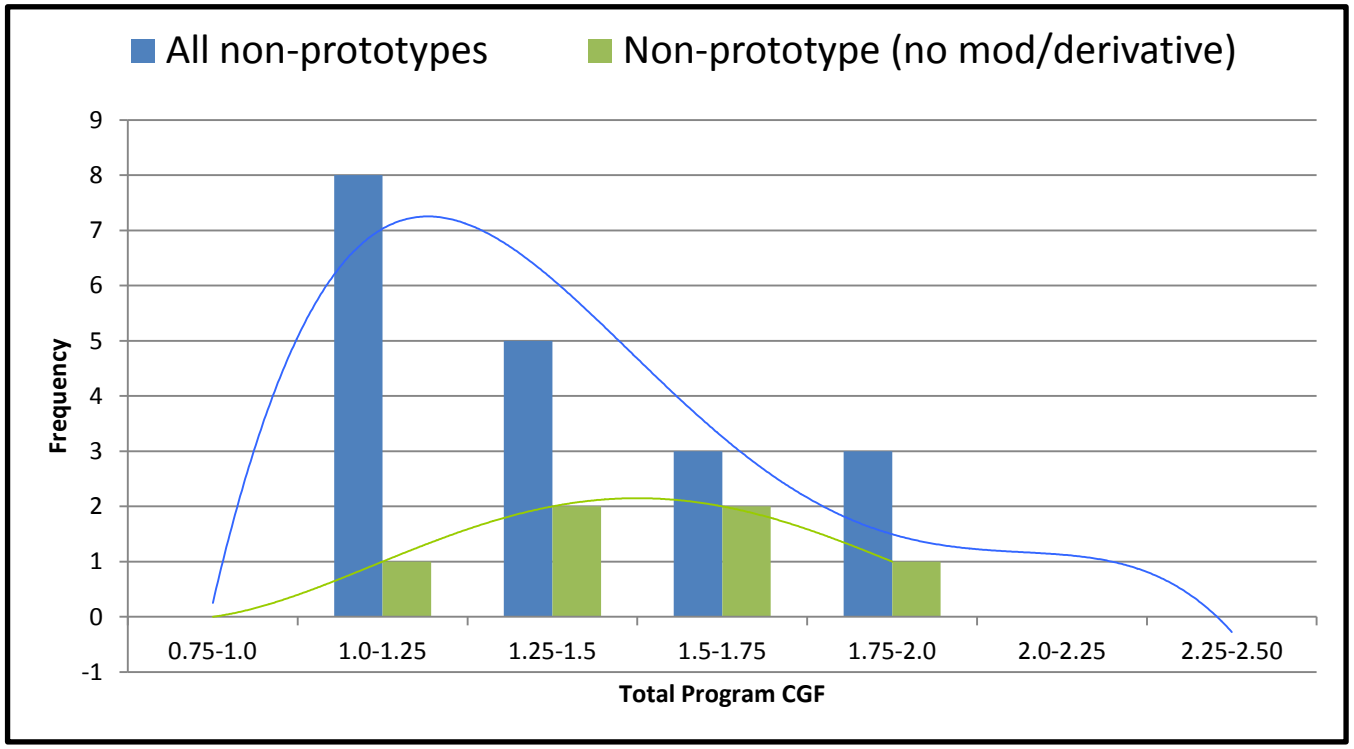


Need to consider the effect of data on no mod/derivative programs (typical lower CGF)

F-18 E/F
F-16 C/D, etc

| Category | Number of Programs | Mean | Median | Standard Deviation | Minimum | Maximum |
|---|---|---|---|---|---|---|
| Total | 19 | 1.36 | 1.31 | 0.34 | 1.00 | 1.99 |
| RDT&E | 19 | 1.36 | 1.22 | 0.39 | 0.91 | 2.16 |
| Procurement | 19 | 1.33 | 1.25 | 0.34 | 0.96 | 2.00 |

# Fighter/Attack CGF

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### Non-Prototyped CGF Summary (Fighter/Attack)

| Category | # of Programs | Mean | Median | Std Dev | Min | Max |
|---|---|---|---|---|---|---|
| Total | 8 | 1.46 | 1.35 | 0.34 | 1.03 | 1.98 |
| RDT&E | 8 | 1.47 | 1.51 | 0.44 | 0.98 | 2.16 |
| Procurement | 8 | 1.44 | 1.37 | 0.30 | 1.06 | 1.90 |

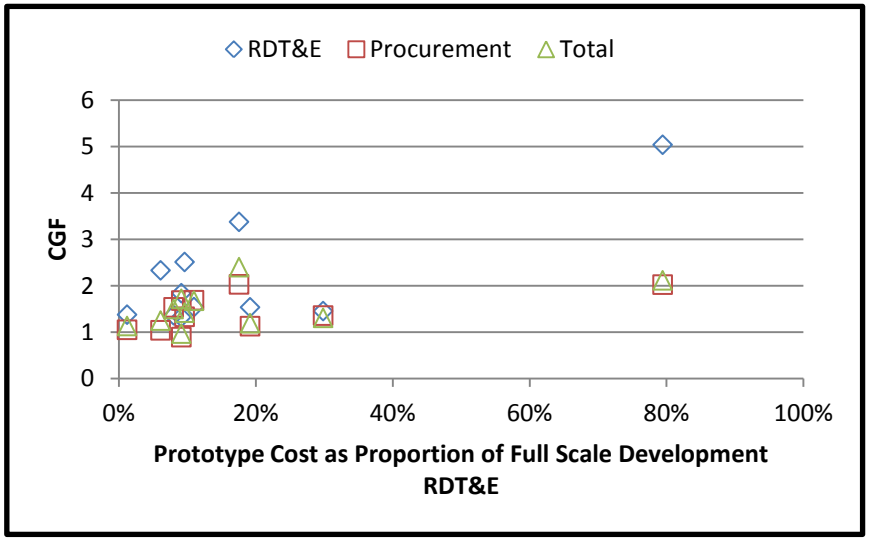
### Prototyped CGF Summary (Fighter/Attack)

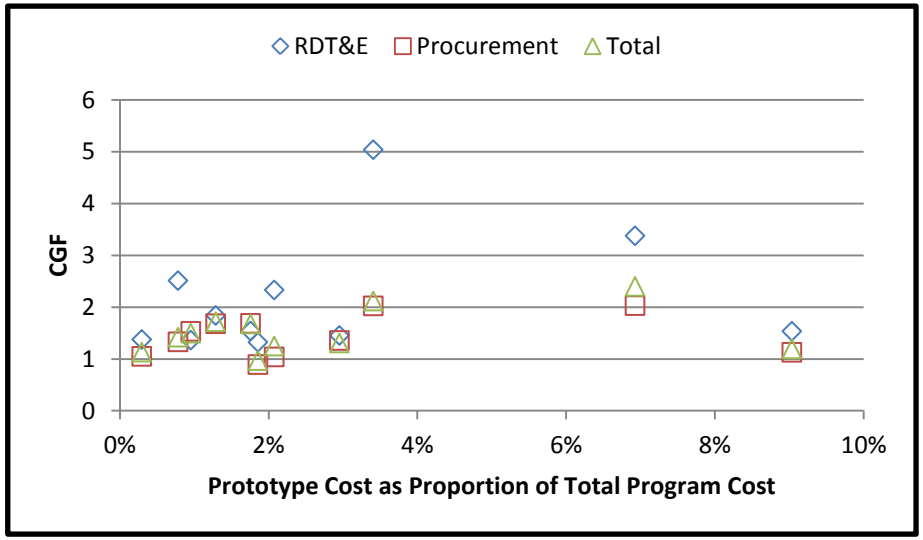
| Category | # of Programs | Mean | Median | Std Dev | Min | Max | P-value |
|---|---|---|---|---|---|---|---|
| Total | 7 | 1.33 | 1.31 | 0.23 | 0.97 | 1.68 | 0.169 |
| RDT&E | 7 | 1.72 | 1.54 | 0.49 | 1.32 | 2.51 | |
| Procurement | 7 | 1.28 | 1.33 | 0.28 | 0.89 | 1.69 | 0.068 |

# Grasping at Straws



- Very few statistically significant results found – only exception was procurement cost growth
- Analyzed cost growth relationship to Prototyping Cost:
  - No strong correlation (-0.31 Total)
  - Programs that spent a small proportion on prototyping seem to fair just as well as programs that spend more



# Summary



- Policy Analysis
  - DODI 5000.02 states prototyping should be used in tech development phase
  - WSARA 2009 states prototyping will be used unless a waiver is issued
  - Emphasis in both implies the goodness of prototyping is absolute

- Early prototyping for fixed-wing aircraft is not a panacea for cost growth - only showed promise in production for limited case
  - Prototyping statistically less for non-mod, fighter/attack programs
  - Modification programs show very low cost growth

    Example: F-18E/F procurement CGF = 1.06; total CGF = 1.03!

# Summary / Recommendations



- No relationship seen between acquisition program cost growth and prototype cost

- Suggest emphasize analyzing cost-benefit of early prototyping effort:
  - How would a prototype provide knowledge to make a better decision at M/S B?
  - What type of prototype is required (system or subsystem)?
  - What is the cost to get this knowledge?
  - Cost /Time for better cost estimates, mature TRL, reduced risk
  - Instead of waivers; programs perform appropriate analysis

- That's how you eat the elephant

# Future Research



- Study of prototyping for other USAF weapon systems
- Detailed (case) studies on prototyped programs
  - Differences/ Similarity amongst the early prototype programs
  - Root causes for lower or higher cost growth
  - Track progress of TRLs throughout prototype phase
  - Benefits of competition during pre-MS B prototyping
- Study on modification & derivative programs
  - Cost growth compared to other programs
- Analyze early cost estimates
  - Data hard to find – non SAR: Pre MS A, MS A to MS B