Presented at the 2016 International Training Symposium: www.iceaaonline.com/bristol2016

NASA's X-plane Database and Parametric Cost Model V2.0

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Introduction

- In today's cost-constrained environment NASA needs an X-plane database and parametric cost model that can quickly provide rough order-of-magnitude cost predictions for experimental aircraft.

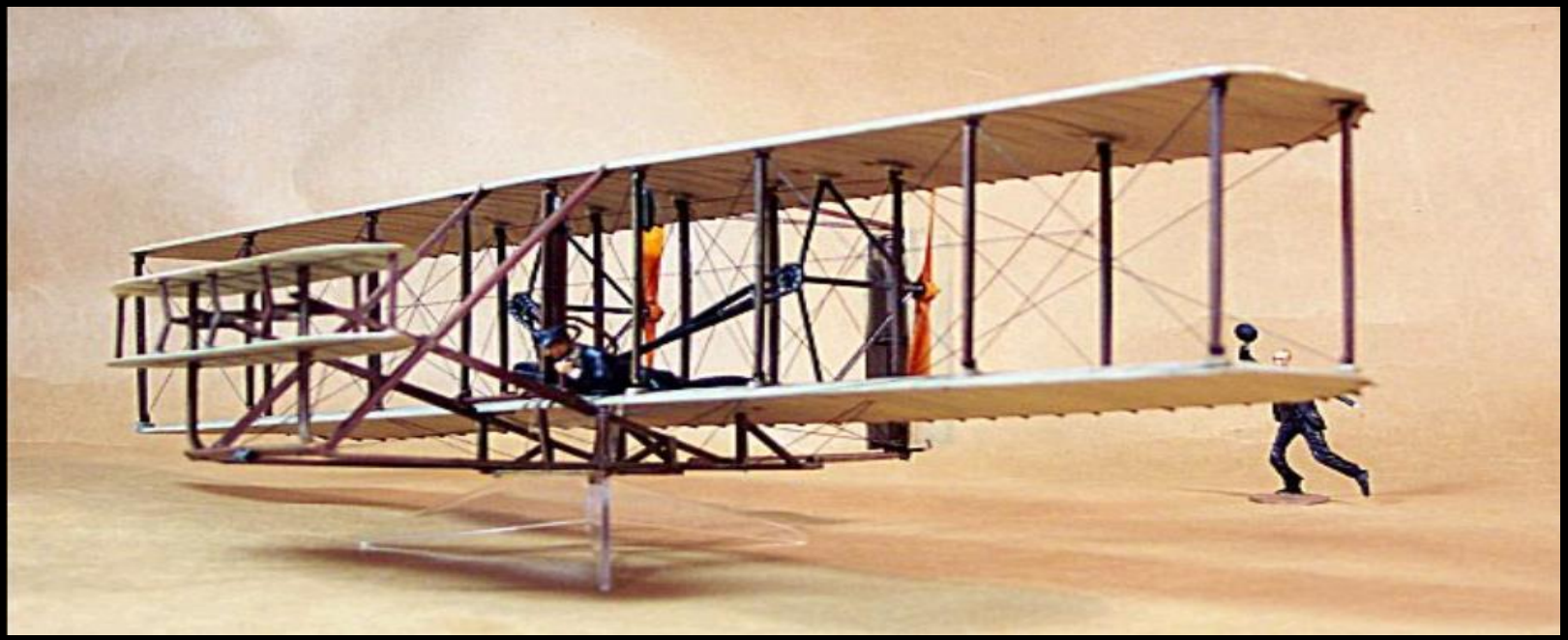
- The model should be based on critical aircraft design parameters such as weight, size, and speed, as well as some sort of complexity factor.

- It's commonly known among cost-engineering professionals in both government and industry that weight-based Cost Estimating Relationships (CERs) have the highest correlation.

Definition of an X-plane

- X-planes (from the 1946 Bell X-1 through the current X-57) are a series of experimental United States (U.S.) airplanes and helicopters (and some rockets) used to test and evaluate new technologies and aerodynamic concepts.
- **X-planes are not prototypes, and are not intended or expected to go into full-scale production.**
- **X-planes are flight research tools.**
- X-planes are produced in groups of typically 2 or 3, to ensure the completion of program objectives.
- The "X," or "experimental," designation is assigned to a U.S. research vehicle by the U.S. Department of Defense (DoD) and is used to indicate the higher risk associated with the dedicated research mission objectives.
- The "X" designation is a U.S. military aircraft designation, like "B" for "bomber;" "F" for "fighter;" "MQ" for "drone;" and "T" for "trainer."
- Not all U.S. experimental aircraft have been designated X-planes; some received U.S. Navy designations before 1962, while others have been known only by the manufacturer's designation, non-'X'-series designations, or classified code names.

Every Aircraft has been Weighed



Every aircraft manufacturer, beginning with the Wright brothers, has weighed their aircraft. Weighing the aircraft is a lift-over-drag (L/D) engineering aeronautic design function. The Wright Flyer I weighed 604.1 lb (274 kg). A military version of that aircraft (Wright Flyer III), also weighing 604.1 lb, was capable of carrying one passenger. The Flyer III was procured by the Army Signal Branch for $30,000, establishing the first CER at $49.66 per pound.

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The Story behind the Bell X-1E

The X-1E, part of the Bell Aircraft X-1 series of aircraft, broke the sound barrier on October 14, 1947. The X-1E is the most photographed aircraft at NASA Armstrong, yet no one seemed to know how much it cost to design, build, or fly it.

I made a quick cost estimate using the Wright Flyer weight CER and adjusted for inflation. The result was an estimate of $1.8 million in FY52 dollars, which is reasonably close to the actual cost.

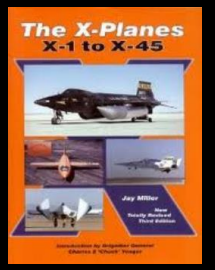
Source of the Data

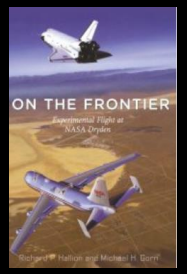
Timeline

- 1940s, -50s, -60s and -70s: basically jointly funded: National Advisory Committee for Aeronautics (NACA); NASA; and various DoD programs.
- Salary dollars were paid under a different “appropriation.”
- NASA Dryden (now Armstrong) was under various NASA Centers until January 1994.
- Full-Cost Accounting went into affect in 2002.
- Some Project Managers (PMs) have cost data stored:
  - Organized in three-ring binders;
  - Organized by burning technical, scope, schedule, and cost data onto CDs.
- NASA has a Cost Analysis Data (CAD) Requirement (CADRe) for projects subject to NPR 7120.5E.
- Generally, CAD and NASA Aeronautic Centers cover CADRe for NPR 7120.8 Research and Technology Programs and Projects (X-planes).

Source of the Data

- NASA Technical Libraries
  - Armstrong's Technical Reference Library
  - Marshall Space Flight Center – Library "Redstar"
- Various Publications: books specifically written about X-planes
  - "The X-Planes" group, by Jay Miller
  - "On the Frontier," by Richard P. Hallion and Michael H. Gorn





- Subject Matter Experts
  - Dr. Joseph Hamaker
  - Third-party "cost research" companies
- Government Accountability Office (GAO)
  - Various cost reports on X-planes
- Industrial Partners or Aeronautical Manufacturers
  - Proprietary and "thin-slicing" the data
- Wikipedia and other online sources
  - Beware of the information! Document the source, date, and URL.

Hierarchical Cataloging of the Data

- Some of the X-planes had three or mores sources of cost data.
  - For example, NASA Technical Data, GAO, Hamaker; all for the same airplane
  - How does the Cost Engineer know whose data are correct?
- The entire set of X-plane parameters are now cataloged in a Microsoft Excel® database with a Microsoft Word document linked in a separate folder serving as the source document.
- Source documents are in Microsoft Word format.
  - **Name** of the person collecting the data;
  - **Date** the source was collected; and
  - **The URL** if the source was collected on-line:
    - Copy of the entire online source document includes references.
    - Note: A data element appeared to be changed within a one-year time span.
- Hierarchy currently being used for Source Data.

1.) Government source (technical libraries) go first-in-line. "**Validated Source Data**"

2.) People involved in collecting cost data for NASA or for the Government.

3.) Thin-slicing, Wikipedia, and other online forums.

Advanced Composite Materials

- Advanced Composite Materials (ACM) have come a long way since the creation of carbon fiber and epoxy.
- Hand layup versus autoclave composite “sandwich” manufacturing:
  - Hand layup is the process wherein which resins are impregnated by hand in the form of woven, knitted, stitched, or bonded fabrics. Hand layup usually involves using rollers or brushes. The article is cooked in a warm “unpressured oven” and cured under standard atmospheric conditions.
  - Autoclaves eliminate voids in the article by applying vacuum, pressure, and heat to the article while it is held within a closed mold .
- Using ACM, aircraft manufacturers can replace 30,000 or more rivets or other components that were used in previous aircraft manufacturing processes.

Cost of using Advanced Composite Materials for Prototyping X-Planes

- Large and small aircraft manufacturers are using ACM.
  - Reports indicate a 30% cost savings for aircraft companies using composites instead of aluminum and rivets.
  - Known past problems with adhering processes seem to be fixed.
- Eliminates the need for Unidentified Future Expenses (UFE).
- Note: Over 30 white papers have been written on ACM for manufacturing use within the aircraft industry.
  - Depending on the year written, starting in the early 1960s, may show different results.

Parametric Cost Modeling

- Assumptions
  - Cost can be predicted by a few design parameters
  - Cost is from initial concept to first flight
- Parameters
  - Technical and performance parameters for 22 experimental aircraft:
    - Dry weight, takeoff weight
    - Length, wingspan, wing area
    - Mach number, thrust, speed regime
    - Maximum altitude, range
    - Material (skin), number of engines, crew size
    - Assisted launch, repurposed, and stealth
- Goal
  - Identify the best parameters (predictors of cost)
  - Develop the best CER

Original Database

Version #1 CERs

- Independent variables: 13
- Dummy variables: 0
- Usable observations: 22

Issues:

Duplicate # of X-planes

Thin-slicing

X-Plane Name	Photo	Maiden Flt	Dry_Wt	Length	Height (ft)	Crew	Mach (ma)	#of Eng	Material
Flyer I		12/17/03	605	21	9.00	1	0.02	1	Cloth & Wood
X-1 (Sterk)		01/25/46	6,750	31	10.83	1	1.26	1	Aluminum
X-1 (Hamaker)		04/11/47	7,000	31	10.00	1	1.50	1	Aluminum
X-1 #3		07/24/51	6,850	31	10.83	1	1.90	1	Aluminum
X-1E		12/12/55	6,850	31	10.83	1	1.90	1	Aluminum
⬇	⬇	⬇	⬇	⬇	⬇	⬇	⬇	⬇	⬇
X-15		06/08/59	11,374	51	22.33	1	6.00	1	Steel, Titanium, Nickel alloys
X-55		06/02/09	28,814	69	23.75	2	0.61	2	Composite & Aluminum
X-56A		07/26/13	377	7		0	0.23	2	Composite
X-56B		04/08/15	377	7		0	0.23	2	Composite

Improving the Database

Version #2 CERs

- Independent variables: 15
- Dummy variables: 21
- Usable observations: 22

Resolution:

No duplicates

All figures "verified"

Designation	Date of First Flight	No. Built	No. of Eng.	Crew Size	Mach No.	Dry Weight	Length	Height	Aluminium	Composite	Titanium
X-1	1/25/46	3	1	1	2.44	6,866	31	11	1	0	0
X-15	6/8/59	3	1	1	6.04	11,374	50	12	0	0	0
X-24A	4/17/69	1	1	1	1.55	6,300	25	10	1	0	0
X-29A	12/14/84	2	1	1	1.87	13,326	48	14	1	1	0
X-31A	10/11/90	2	1	1	1.40	11,410	43	15	1	1	1
⬇	⬇	⬇	⬇	⬇	⬇	⬇	⬇	⬇	⬇	⬇	⬇
X-43A	3/2/01	3	1	0	9.60	2,774	12	2	0	1	0
X-45A	5/22/02	2	1	0	0.80	8,000	27	7	0	1	0
X-47B	2/4/11	2	1	0	0.90	14,000	38	10	0	1	0
X-50	11/24/03	2	1	0	0.57	1,265	18	7	0	1	0
X-51	5/26/10	4	1	0	6.00	3,677	25	2	1	1	1
X-53	12/8/06	1	2	1	1.30	23,000	56	15	0	1	0
X-55	6/2/09	1	2	2	0.61	28,814	69	24	0	1	0
X-56A	7/26/13	2	2	0	0.25	425	8	4	0	1	0

Final X-Plane Database

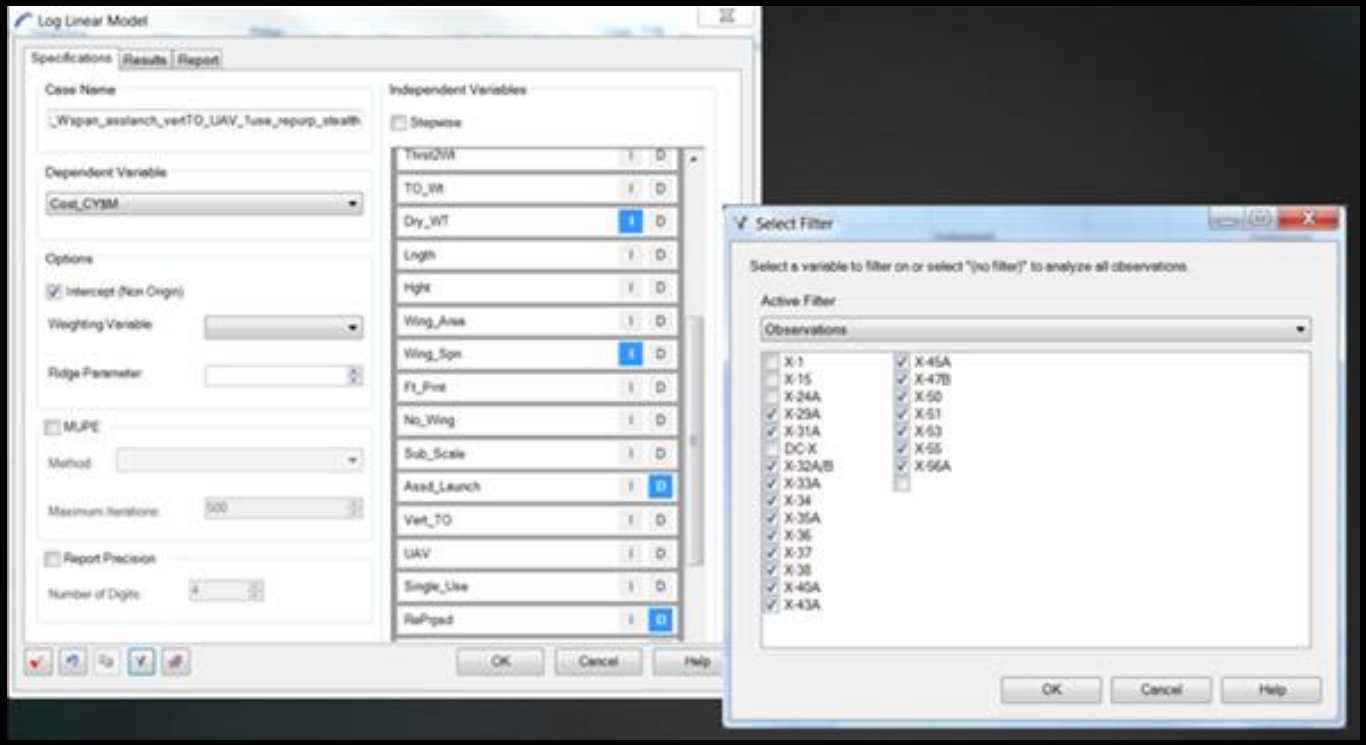
- **Number of X-planes used in the Final Model**

Verification Process

- **When we had "no data" – we went to the Museum !**

Narrowing the Field of Predictors

- **An example of the selection input of the desired variables in CO$TAT:**



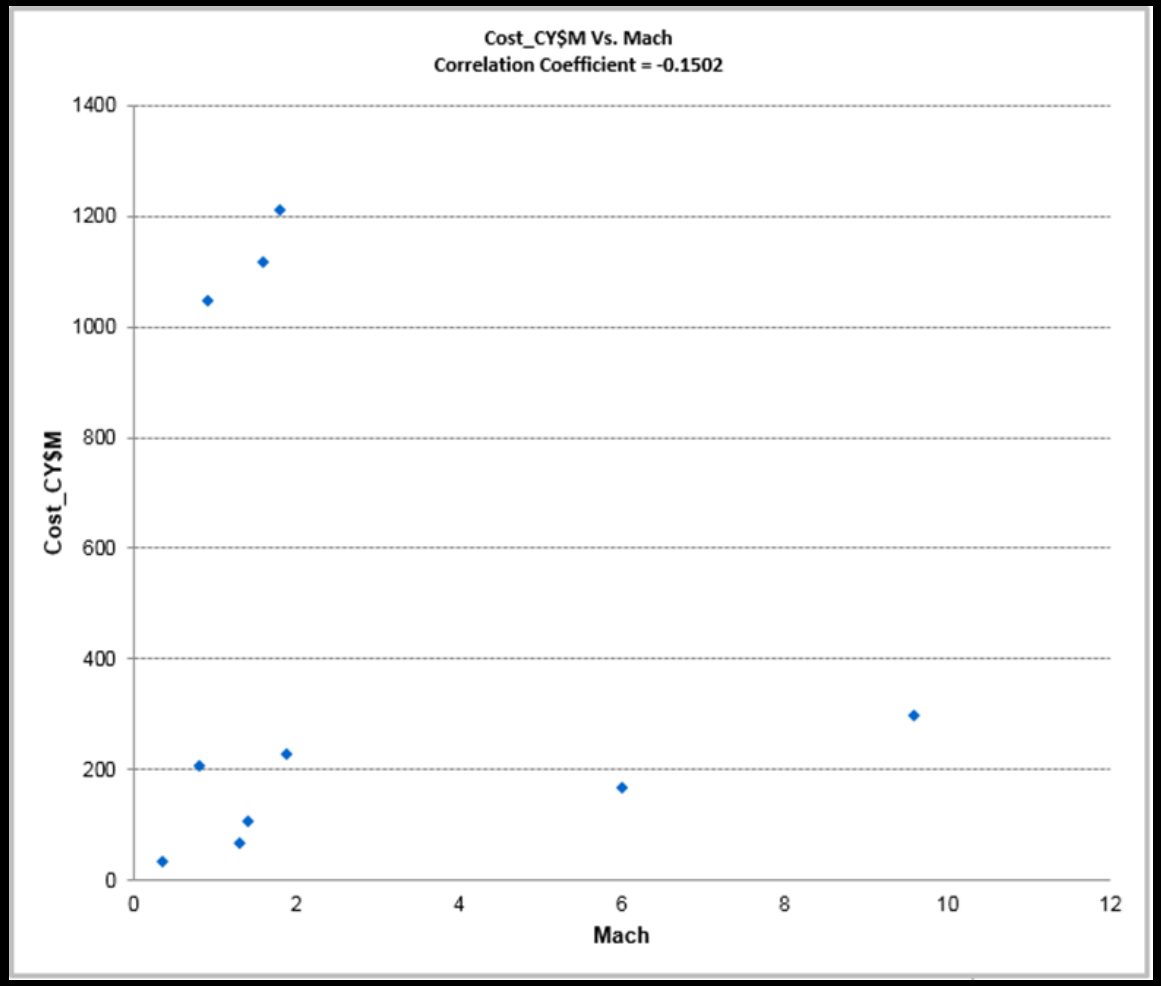
Narrowing the Field of Predictors

- **NASA Armstrong took a step backward to ensure accuracy and traceability, which led to narrowing the field of predictors:**
  - Groupings,
  - Outliers, and
  - Spread of data points.

- We performed 2-D plots on every combination or variable.
- We looked at the predictor measures (in unit space).
- We looked at the residuals in (log space).
- We looked at the predictor measure in (MUPE).

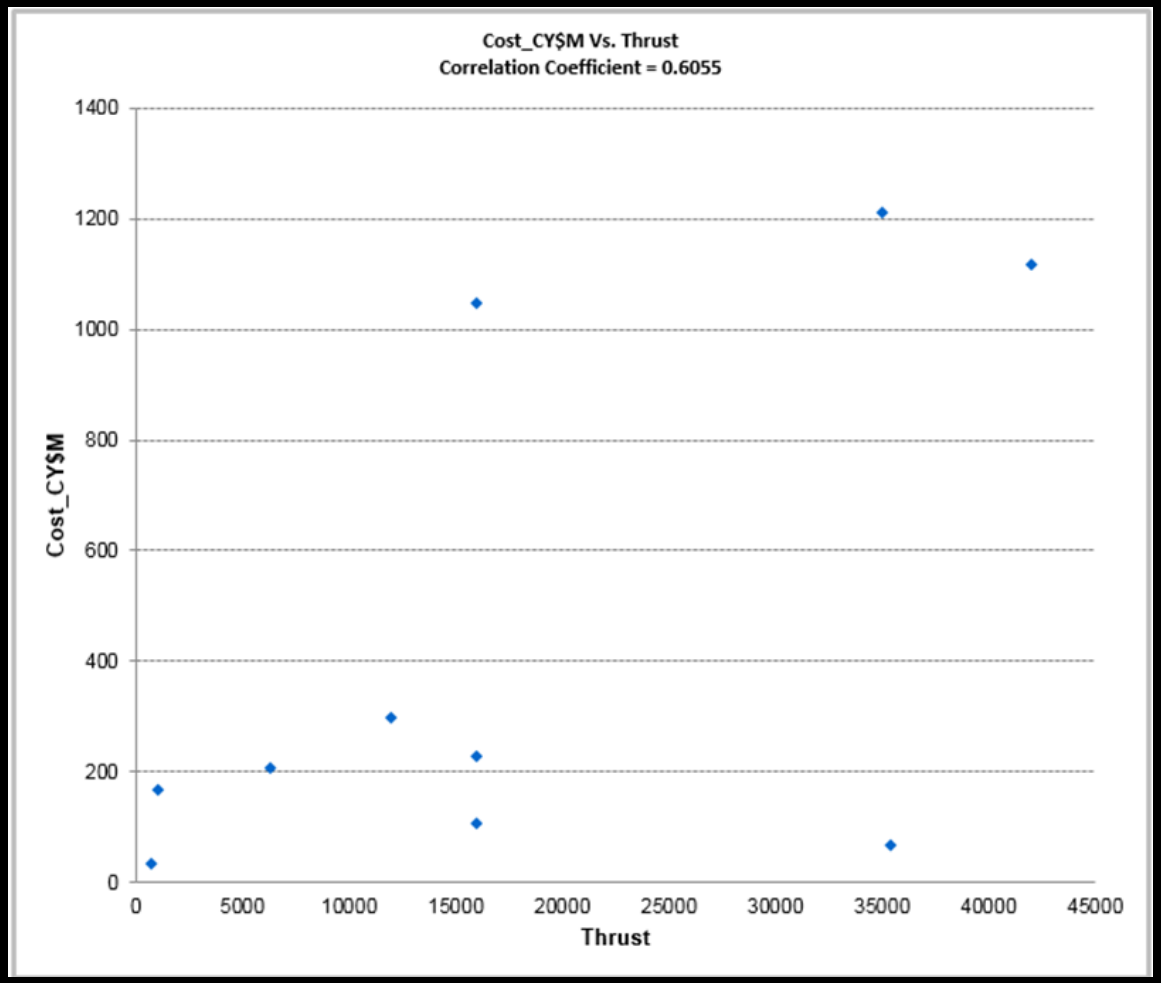
2-D Plot Analysis

- **Sample of a 2-D Plot Analysis: "Cost vs Mach"**



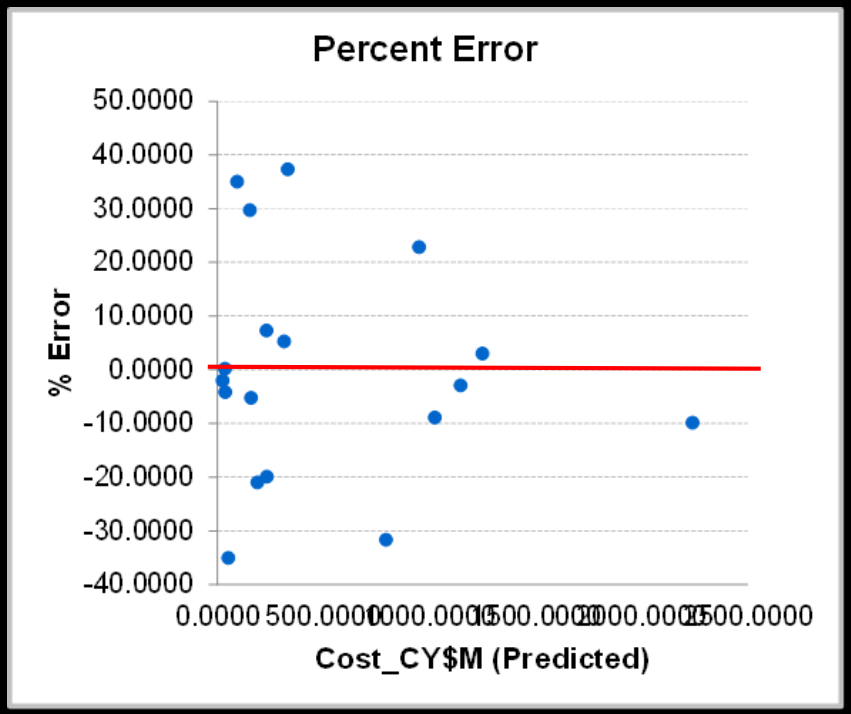
2-D Plot Analysis

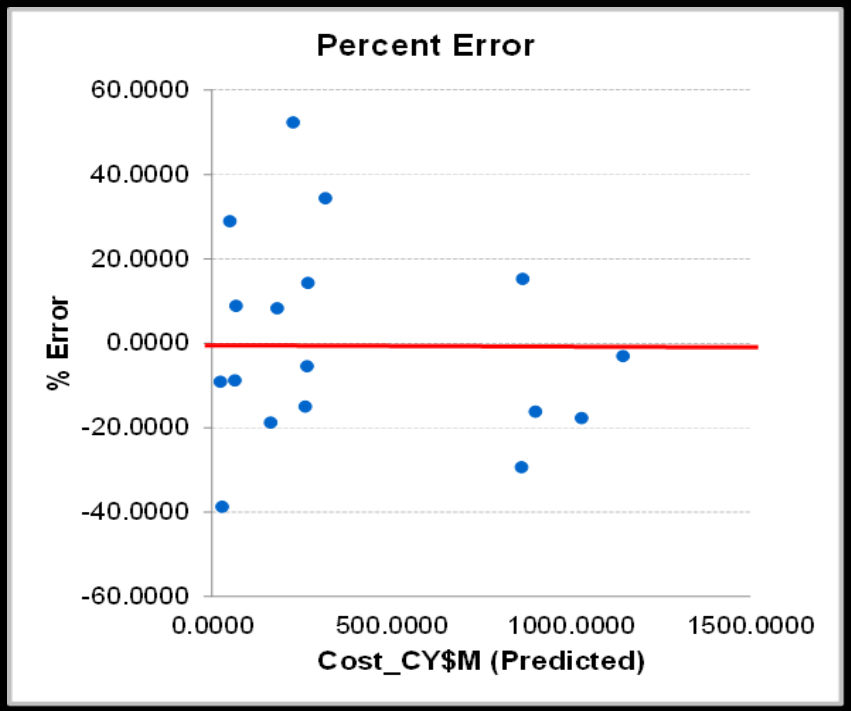
- **Sample of a 2-D Plot Analysis: "Cost vs Thrust"**



Percent Error Analysis

A useful step in assessing each CER is to view its residuals on a scatter plot. One reason for doing this is to identify any evidence of autocorrelation. Below, note what appear to be fairly random residual patterns, with no obvious indication of autocorrelation





Determining the "Best Fit"

- Aircraft too complex for simple linear regression
  - Use more than one predictor in the model
  - Limited by number of data points in database
    - Over-fit data if too many predictors
    - Higher R^2 but lower predictive accuracy
- Variable selection
  - Start with the best predictors, identified with simple linear regression
  - Add independent variables one at a time to identify the best fit.
- Added "Dummy 21 Variables"
- Best two equations:
  - Equation 1: Cost = f (Dry_weight * Wing_Span * Assist_Launch * Vertical_TO * Scramjet * Repurposed * Stealth, ...)
  - Equation #2: Cost = f (Dry_weight * Wing_Span * Sub_Scale * Repurposed, ...)

The Top 2 CERs Chosen Ver. #2

- **Equation #1: CER to estimate Cost CY$M**
- Cost = f (Dry_weight, * Wing_Span, * Assist_Launch, * Vertical_TO, * Scramjet, * Repurposed, * Stealth, . . .)
  - **Legend**
    - Dependent variable:
      - Cost_CY$M
    - Independent variables (primary drivers):
      - Dry_weight
      - Wing_span
      - More independent variables . . . .
    - Independent dummy variables:
      - Assist_Launch
      - Vertical_TO
      - Scramjet
      - Repurposed
      - Stealth
      - More independent dummy variables . . . .

The Top 2 CERs Chosen Ver. #2

- **Equation #2: CER to estimate Cost CY$M**
- Cost CY$M = f (Dry_weight, * Wing_Span, * Sub_Scale, * Repurposed, and more . . . . .)
  - **Legend**
    - Dependent variable:
      - Cost_CY$M
    - Independent variables (primary drivers):
      - Dry_weight
      - Wing_span
      - More independent variables . . . .
    - Independent dummy variables:
      - Sub_Scale
      - Repurposed
      - More independent dummy variables . . . .

Future State

- The Towed Glider Air-Launch System (TGALS) has been priced using the earlier algorithms of Armstrong's Parametric Cost Model.

Two-minute TGALS Video

NASA X-planes to Return

NASA X-planes to return

NASA

BEYOND TRADITIONAL — NASA's proposed 2017 budget contains money for three types of experimental aircraft to be tested in the Antelope Valley. At top is a low sonic boom flight demonstrator, at right is a hybrid wing body and at lower left is a hybrid electric aircraft.

Budget plan could propel next-generation aircraft

By ALLISON GATLIN
Valley Press Staff Writer

EDWARDS AFB — Piloted X-planes could return to the skies over NASA Armstrong Flight Research Center under a new initiative to develop the next generation of aircraft, moving beyond traditional designs toward more efficient, quieter, low-emission planes.

President Barack Obama's final proposed budget, unveiled Tuesday, includes an increase of $3.7 billion over the next 10 years for NASA's aeronautics research to advance technologies for aircraft of the future.

"We expect over the next 10 years to see vehicles that represent all of these flying here at NASA and eventually making it into the market," Armstrong Center Director David McBride said. "It's good news for aerospace in general.

"We really are at an inflection point in technology."

Armstrong, the space agency's primary flight research center at Edwards Air Force Base, will play a key role in the development of the new X-planes, building on the legacy of such experimental craft as the legendary X-15 rocket plane and the X-43 hypersonic aircraft.

"It's a big re-entry into what our heritage at the center is, flying x-classified, experimental aircraft," McBride said. "Aeronautics is where Armstrong's going to have a big impact in the future."

Overall, the NASA budget comes in at $19 billion, a reduction of about $260,000 over the current fiscal year.

Of that, aeronautics is budgeted at $790 million, an increase of $150 million over the previous year.

Even with the additional funding for the aviation initiative, aeronautics remains a small portion of the total NASA budget, McBride said.

Over the past decade, the

See NASA on A4

RELATED STORY

▶ Obama unveils record $4.1 trillion budget, B1.

Official announcement at the AIAA Conference in Washington, D.C., on June 28, 2016

Future NASA X-planes

Future NASA X-plane

Summary

- The NASA Armstrong Cost Engineering Team with technical assistance from NASA HQ (SID) has gone through the full process in developing new CERs from Version #1 to Version #2 CERs.
- We took a step backward and reexamined all of the data collected, such as dependent and independent variables; cost, dry weight, length, wingspan, manned versus unmanned, altitude, Mach number, thrust, and skin.
- We used a well-known statistical analysis tool called CO$TAT instead of using “R” multiple linear or the “Regression” tool found in Microsoft Excel®.
- We setup an “array of data” by adding 21 “dummy variables;” we analyzed the standard error (SE) and then determined the “best fit.”
- We have parametrically priced-out several future X-planes and compared our results to those of other resources.
- More work needs to be done in getting “accurate and traceable cost data” from historical X-plane records!

Questions

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- Telephone 1-011 (661)-276-2377

The cost estimate can be done today (within minutes) by hitting the blue button !