



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



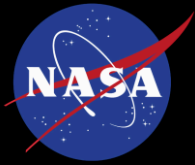
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Steve Sterk (AFRC), Anthony Olguin (AFRC), Marc Greenberg (NASA HQ)

NASA Armstrong Flight Research Center

Presented at the 14 December 2016 ICEAA SoCal Workshop

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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.



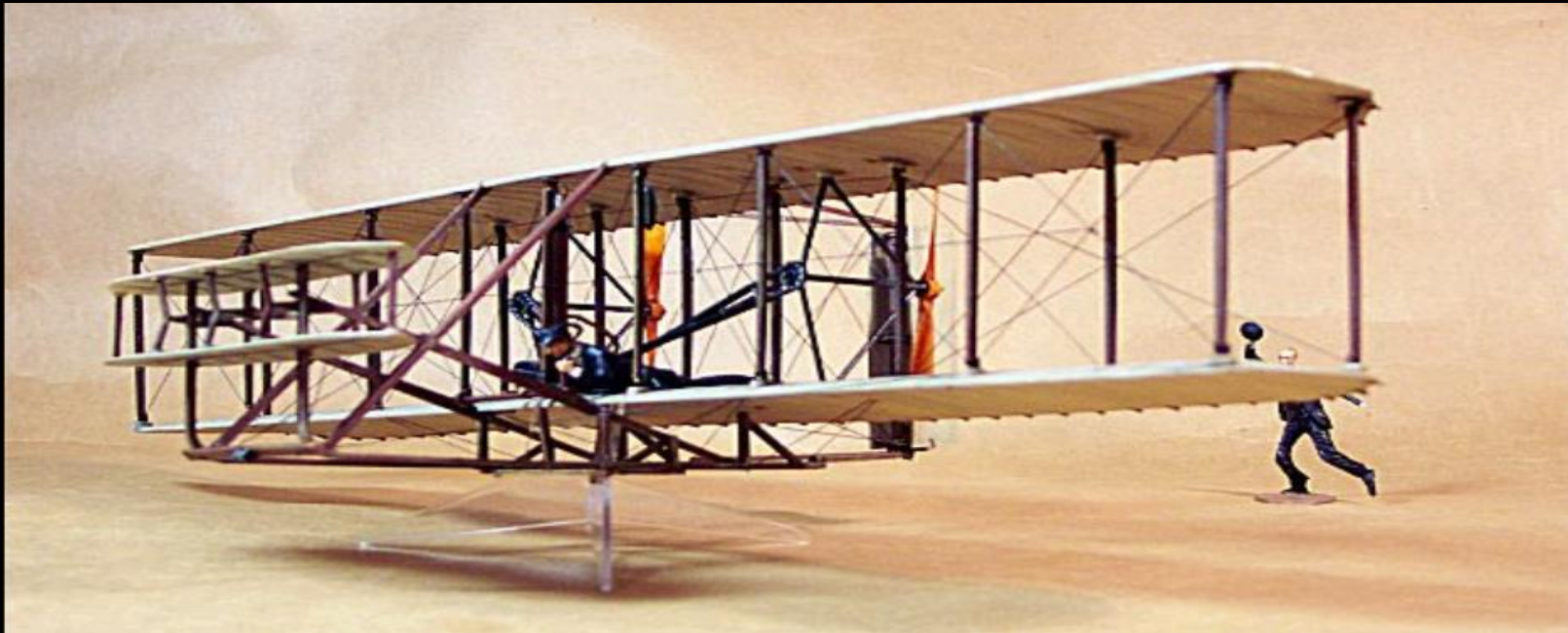
Definition of an X-plane



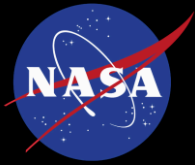
- X-planes (from the 1946 Bell X-1 through the current X-57) are a series of experimental United States (U.S.) airplanes and helicopters (and some rockets) used to test and evaluate new technologies and aerodynamic concepts.
- **X-planes are not prototypes, and are not intended or expected to go into 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.



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

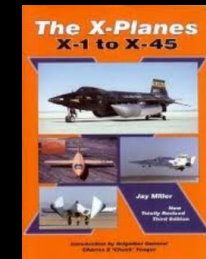
- 1940s, -50s, -60s and -70s: basically jointly funded: National Advisory Committee for Aeronautics (NACA); NASA; and various DoD programs.
- Salary dollars were paid under a different “appropriation.”
- NASA Dryden (now Armstrong) was under various NASA Centers until January 1994.
- Full-Cost Accounting 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).

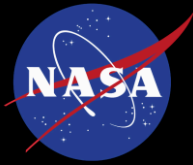


Source of the Data



- 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.

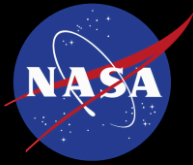




Hierarchical Cataloging of the Data



- Some of the X-planes had three or more 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.

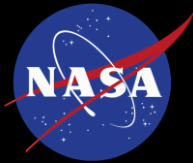




Cost of using Advanced Composite Materials for Prototyping X-Planes



- 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












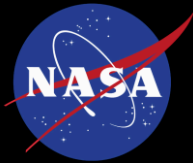
Version #1 CERs

- 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 |

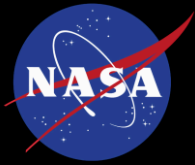


Final X-Plane Database



- Number of X-planes used in the Final Model





Verification Process

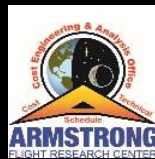


- **When we had “no data” – we went to the Museum !**

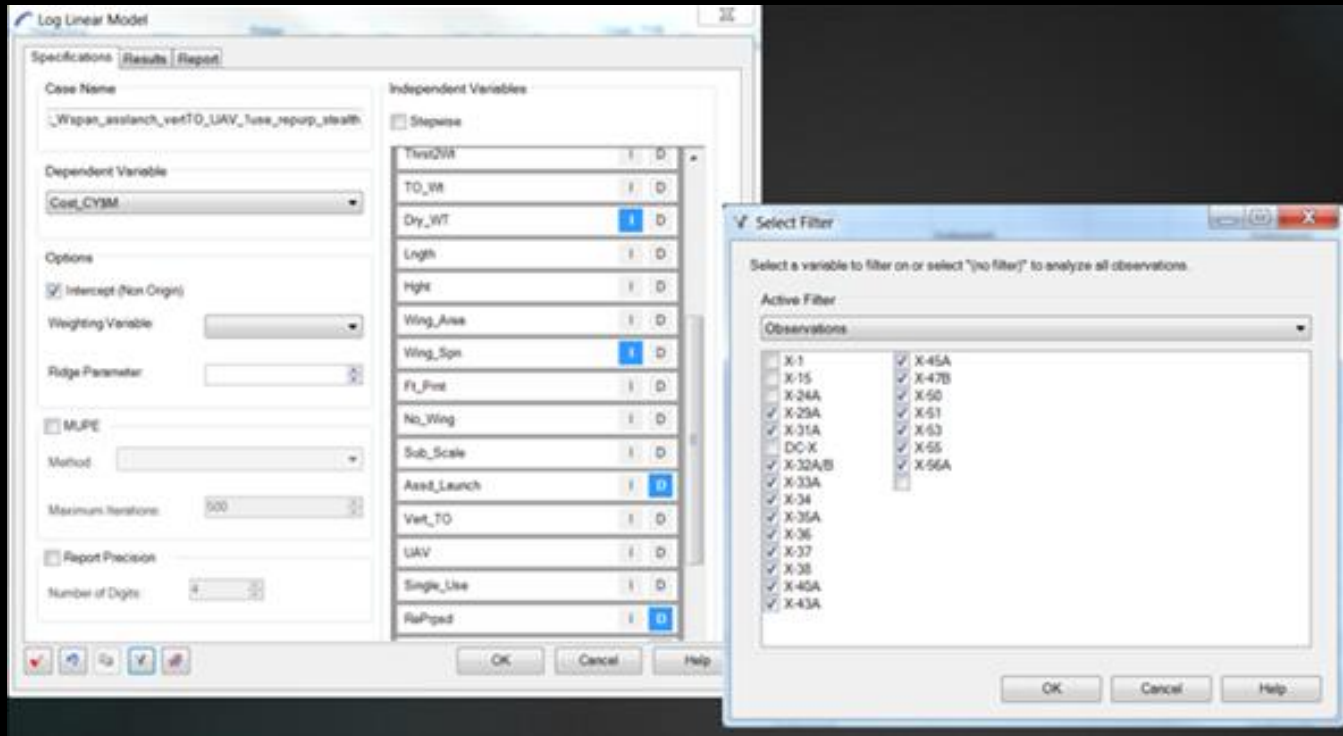


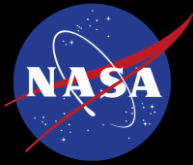


Narrowing the Field of Predictors

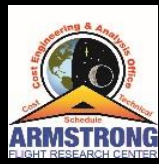


- An example of the selection input of the desired variables in CO\$TAT:

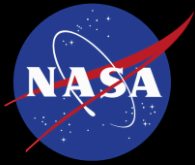




Narrowing the Field of Predictors



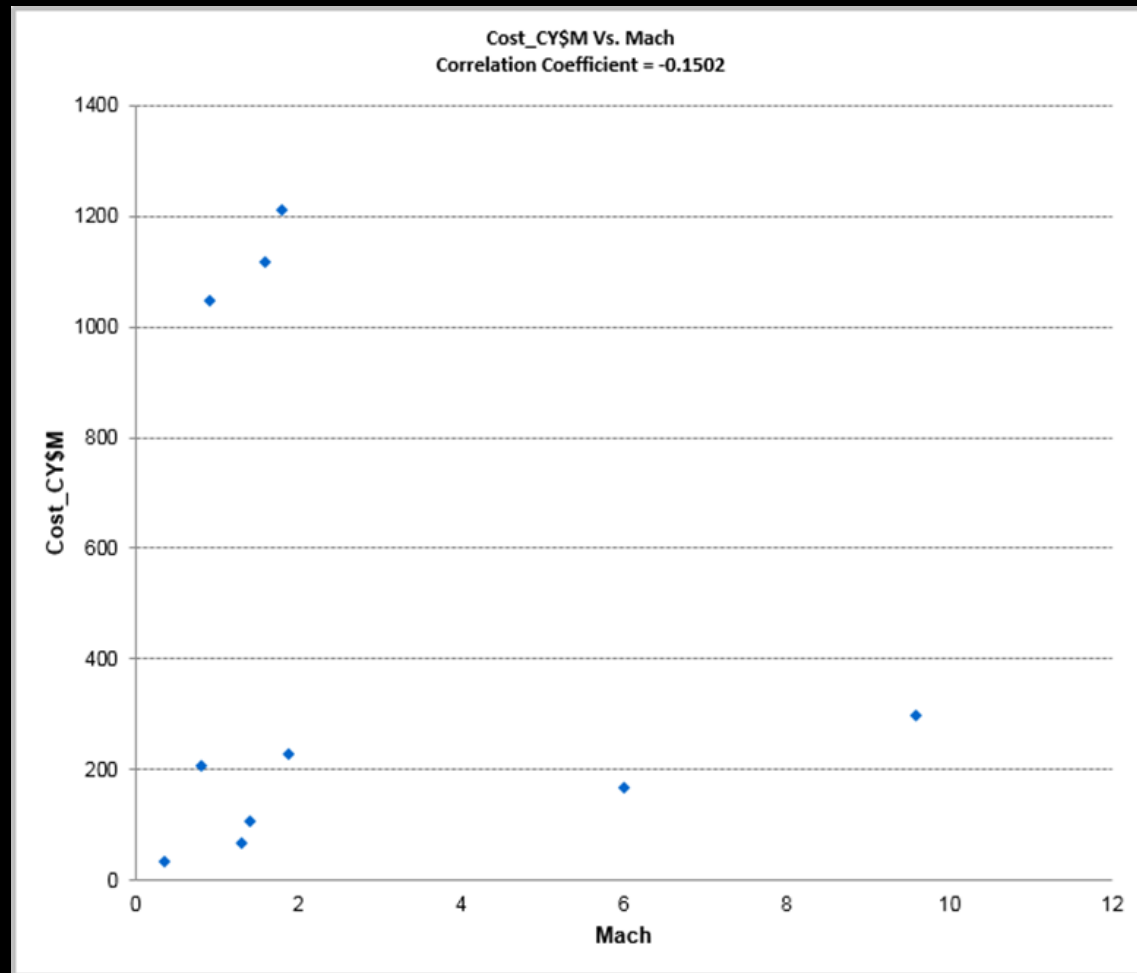
- **NASA Armstrong took a step backward to ensure accuracy and traceability, which led to narrowing the field of predictors:**
 - Groupings,
 - Outliers, and
 - Spread of data points.
- We performed 2-D plots on every combination or variable.
- We looked at the predictor measures (in unit space).
- We 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"**

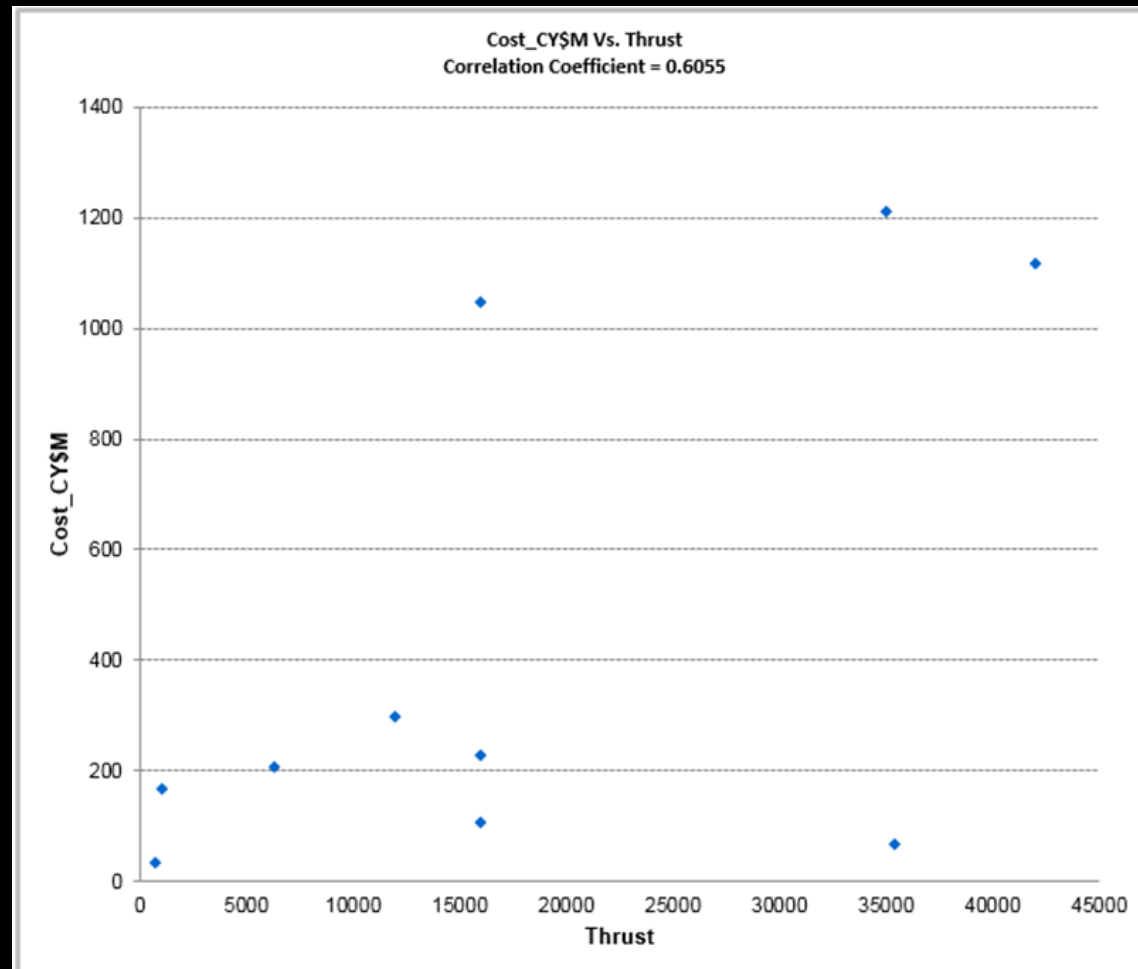


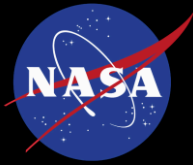


2-D Plot Analysis



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

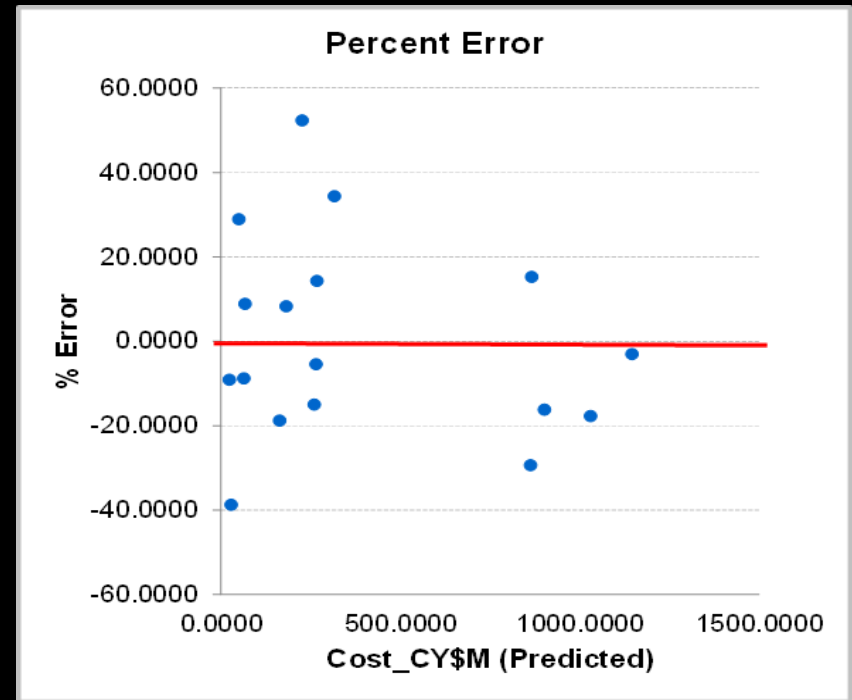
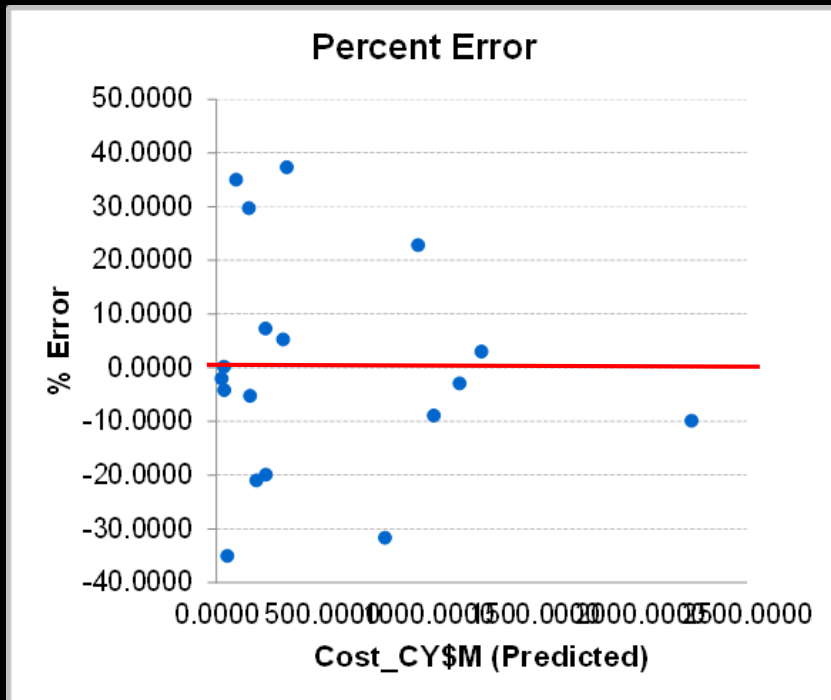




Percent Error Analysis



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: $\text{Cost} = f(\text{Dry_weight} * \text{Wing_Span} * \text{Assist_Launch} * \text{Vertical_TO} * \text{Scramjet} * \text{Repurposed} * \text{Stealth}, \dots)$
 - Equation #2: $\text{Cost} = f(\text{Dry_weight} * \text{Wing_Span} * \text{Sub_Scale} * \text{Repurposed}, \dots)$



The Top 2 CERs Chosen Ver. #2



- **Equation #1: CER to estimate Cost CY\$M**

- $\text{Cost} = f(\text{Dry_weight}, * \text{Wing_Span}, * \text{Assist_Launch}, * \text{Vertical_TO}, * \text{Scramjet}, * \text{Repurposed}, * \text{Stealth}, \dots)$

- **Legend**

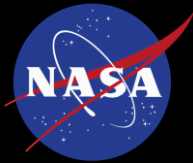
- Dependent variable:
 - Cost_CY\$M
- Independent variables (primary drivers):
 - Dry_weight
 - Wing_span
 - More independent variables
- Independent dummy variables:
 - Assist_Launch
 - Vertical_TO
 - Scramjet
 - Repurposed
 - Stealth
 - More independent dummy variables



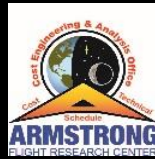
The Top 2 CERs Chosen Ver. #2



- **Equation #2: CER to estimate Cost CY\$M**
- $\text{Cost CY\$M} = f(\text{Dry_weight}, * \text{Wing_Span}, * \text{Sub_Scale}, * \text{Repurposed}, \text{and more } \dots \dots \dots)$
 - **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



Testing the New Coefficients



Standard Error Calculation (for Determining Prediction Interval)

Enter Data in GREEN Cells only!!!

Costs in 2016\$M, excludes Phase E costs

Extrapolation Setting = 10%

| | | Range from Historical Data: | Approx Max | User Instructions & Guidance | |
|-------------------------------------|---------------------------|-------------------------------------|------------|------------------------------|---|
| <u>CER Inputs:</u> | Mission Cost (optional) = | \$35 | to \$2,461 | Approx Max \$2,707 | <p>Leave blank only if given all tech data!</p> <p>Pick one tech input to check value of the other tech input (in "CER Outputs")</p> <p>Note: Dry Weight must be entered in pounds. Wing Span must be entered in feet.</p> |
| | Design Input (optional) = | Dry Weight | | | |
| | Dry Weight (optional) = | 16,200.0 | | | |
| | Assist Launch | No | | | |
| | Vert Takeoff | No | | | |
| | Scramjet | No | | | |
| | Repurposed | No | | | |
| | Stealth | No | | | |
| <u>CER Outputs:</u> | Calculated Wing Span* = | 2 | to 77 | 85 | <div style="border: 1px solid black; height: 20px; width: 100%;"></div> <div style="border: 1px solid black; height: 20px; width: 100%;"></div> |
| <u>& Calibration:</u> | Modify Wing Span? | <input checked="" type="checkbox"/> | | | |
| | User-Defined Wing Span = | 30.0 | | | |
| | Wing Span = | 2 | to 77 | 85 | |
| | Adjusted Mission Cost = | \$231 | | | |
| | | <--- You Must Enter Value | | | |
| <u>Std Error & Coeff of Var</u> | ln(Mission Cost) = | 5.4442 | | | |
| | Standard Error = | 0.2724 | | | |
| | Coeff of Variation = | 5.00% | | | |

Note: This Value, which is in Fit Space, was taken from CO\$TAT output.

Note: Value is relative in Fit Space.

CO\$TAT CV in unit space = 26.4% (SE/Avg); = 12.67% (MAD/Avg)

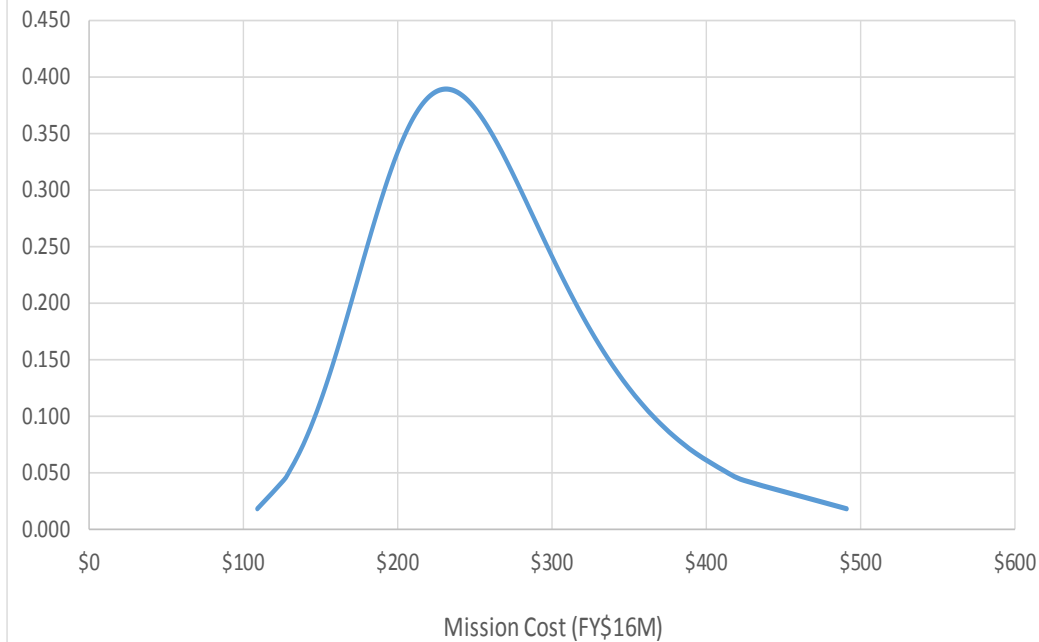


Probability Distribution Example

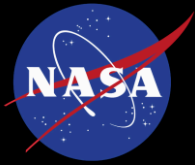


| | | | |
|---------------------------|-------|----|-------|
| 68% Prediction Interval = | \$174 | to | \$308 |
| 90% Prediction Interval = | \$141 | to | \$379 |
| 95% Confidence Interval = | \$126 | to | \$425 |

Distribution of Estimate (Unit Space)



| | |
|------------|--------------|
| 2.5% | \$126 |
| 5% | \$141 |
| 10% | \$159 |
| 16% | \$174 |
| 20% | \$182 |
| 30% | \$200 |
| 40% | \$216 |
| 50% | \$231 |
| 60% | \$248 |
| 70% | \$268 |
| 80% | \$294 |
| 84% | \$308 |
| 90% | \$336 |
| 95% | \$379 |
| 97.5% | \$425 |

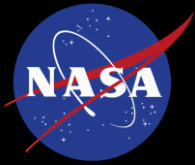


Future State



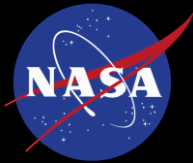
- The Towed Glider Air-Launch System (TGALS) has been priced using the earlier algorithms of Armstrong's Parametric Cost Model.





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.

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

Budget plan could propel next-generation aircraft

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 develop-

ment 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

RELATED STORY

► Obama unveils record \$4.1 trillion budget, B1.

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

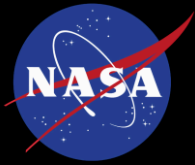
See NASA on A4

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



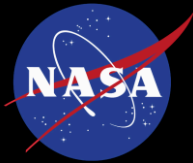
Future NASA X-planes





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



- steve.a.sterk@nasa.gov
- Telephone (661)-276-2377



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

