NASA's X-Plane Database and Parametric Cost Model

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Abstract:

In today's cost-constrained environment, NASA needs a "NASA X-Plane Cost Calculator" ™ that can quickly provide an accurate, high level, rough order of magnitude (ROM) for cost and schedule from initial concept to first flight. This paper takes a look at the steps taken in developing a mathematical algorithm from version #1 to version #2 for the X-Plane calculator as well as the challenges encountered in the collection of historical x-plane data and finally refining the X-Plane data base involves the demanding task of tracking down, documenting and cross-referencing numerous X-Plane parameters across countless sources and recommendations for future database management are discussed This is especially difficult since X-Planes were acquisitioned by other government agencies (OGA) and tested at NASA, with NASA being the responsible test organization (RTO). Then a step-by-step discussion of the development of Cost Estimating Relationships (CERs) and Schedule Estimating Relationships (SERs) is mentioned. The data is heterogeneous in nature and some specifications are unquantifiable, but will be of future use to create groupings for potential "dummy variables" or "qualitative discriminators". Examples of these groupings are; composite vs. aluminum bodies, autonomous vs. piloted aircraft and the different "generations" of plane such as the transition of flight controls from stick and rudder to "fly-by-wire". This white paper includes a statistical look at the relationship between potential cost/weight drivers and cost/dummy variables, the correlation between an array of independent variables, the selection of R^2 parameters used in the model, and sensitivity analysis of the model coefficients e.g. stand deviation. An emphasis (or very deep dive) was placed on the analysis and the complexity-based CERs function of certain engineering design parameters such as (Mach number, weight, max altitude etc.) which improved costs from the prior version for upcoming X-Plane endeavors. Finally, X-Planes are designated as such, due to their innovative design and their dissimilarity to their predecessors, the model was used to calculate cost estimates for some conceptual designs, currently being floated around NASA summer of 2016.

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INTRODUCTION AND BACKGROUND:

NASA wants to bring back the era of the X-Planes [1]. In today's cost-constrained environment, NASA needs an X-Plane database and parametric cost model that can quickly provide rough order of magnitude (ROMs) predictions of cost and schedule from initial concept to first flight of potential X-Plane aircraft. It is commonly known among the cost engineering professionals (from NASA to Industry) that weight based cost estimation relationships (CERs) has the highest correlation between the weight of the aircraft and cost.

Throughout history every aircraft has been weighed, starting with the Wright Brothers invention called the *Wright Flyer* (often retrospectively referred to as ***Flyer I***) weighed in at 604.1 lbs. or (274 kg) [2] in 1903. The cost of a military version of the Flyer III that could carry one passenger was procured by the Signal Army Branch in 1909 for $30,000 (included a $5,000 bonus). Orville Wright using Sir Isaac Newton's theory "*that a rearward-channeled propeller could propel a machine forward at a great rate of speed*", therefore Orville and Wilbur (American Inventors) concluded that there are four forces that act on an aircraft in flight: lift, drag, weight, and thrust. [3] The weight of an airplane is determined by the size and materials used in the airplane's construction and on the payload and fuel that the airplane carries. The weight is always directed towards the center of the earth. The thrust is determined by the size and type of propulsion system used on the airplane as well as the throttle setting selected by the pilot. Thrust is normally directed forward along the center-line of the aircraft. Lift and drag are aerodynamic forces that depend on the shape and size of the aircraft, air conditions, and the flight velocity. Lift is directed perpendicular to the flight path and drag is directed along the flight path. Based on Newton's third law of motion as air blasts backwards through the nozzle the plane moves forward. This was indeed the case when General Chuck Yeager broke the sound barrier on October 14th, 1947 in the X-1 Bell.

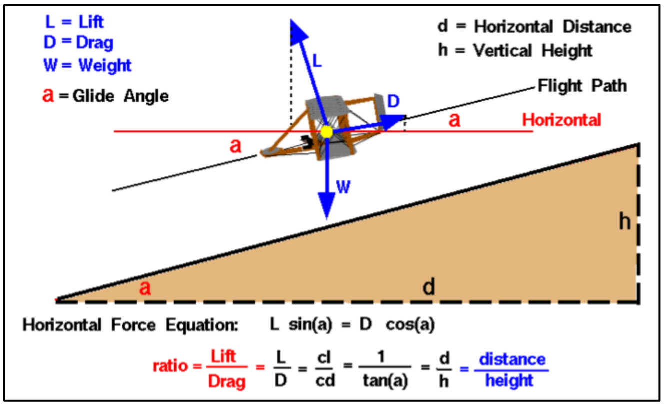

Figure 1

"Aerospace Valley" is a prevalent nickname for Antelope Valley because of all the early aircraft manufactures (including the Space Shuttles) located and built in Palmdale as well as flight research activity located on nearby Edwards Air Force Base that occurs in the restricted air space. Sonic booms occur daily, as various research planes and test pilots pass through the sound barrier.

From numerous workshops, symposiums, and conferences that I attended, I became amazed at the passion of the speakers who stood up and talked about the "*S-Curve, their Regression Analysis and Monte-Carlo simulation*" that went behind the numbers. As I walked to my office and passed by the X-1E Bell, I started asking questions how much did it cost? To my surprise no one knew; how much the X-1E Bell originally cost, but they all had a story to why there were no financial records.

Figure 2
The X-1E Bell sits on a pedestal in front of NASA Armstrong Flight Research Center (AFRC) original named Dryden Flight Research Center (DFRC) after the first deputy administrator.

The Challenges in getting Cost Data:

The National Advisory Committee for Aeronautics (NACA) came into being, much like its successor organization, the National Aeronautics and Space Administration (NASA), in response to the success of others. Even though the Wright brothers had been the first to make a powered airplane flight in 1903, by the beginning of World War I in 1914, the United States lagged behind Europe in airplane technology. In order to catch up, Congress founded NACA on March 3rd, 1915, as an independent government agency reporting directly to the President. Between its founding in 1915 and its incorporation into NASA in 1958 [4]. Government Appropriation Laws are different than as seen today. Basically the procurement contract or acquisition order described what the government wanted i.e. "*jet airplane, weighs about 6800 pounds, delta wings, flies fast*". One or two of the aircraft manufactures would compete for the contract and the aircraft was built and delivered to either Langley or Dryden for aircraft flight testing. Civil Service Labor was paid from another government appropriation and facilities cost was paid from yet another. The challenge is aircraft(s) were bought on an U.S. Army acquisition instrument. As a further nuisance in getting "pure cost data" Dryden Flight Research Center was under Ames Research Center until January 7th, 1994. Basically the only way to determine the cost of labor is to count how many people were standing in front of the building 4800 (about 100) and segregate out Management and their Secretaries about 10%, leaves about 90. According to historical logs there were about 3 supersonic aircraft in the hangar, so about 25 to 30 people was about the appropriate size for a research flight test project, including contractors. This equation still holds true today for a typical X-Plane Flight Test Program at NASA Armstrong.

Sources of Information:

It is from my natural intuition and curiosity that I started to think about a weight based formula or algorithm that I could derive the cost of the X-1E Bell. I headed to Research library and checked out several books: Jay Miller wrote a book called the "***The X-Planes*".** A beautiful collection of photos, specifications, engineering and most importantly the challenges that the early research staff, engineers and pilots had back in the day. Out of the 440 pages along with the references not one bit of "cost data" could be found. The main reason is the aircraft companies like; Bell Aircraft, Boeing, Convair, Lockheed, Marietta, Northrop, and Rockwell International, were building aircraft in support of World War II and then as time passed you seen other companies like; Aurora Flight Sciences, Scaled Composite, Sierra Nevada Corp. and others enter the market as "low cost fabricators". Another great book is called "***On the Frontier***" 554 pages, written by Richard Hallion and Michael Gorn, published 1984. With knowledge in hand, I started to "data mine" specific x-plane parameters like; first flight, dry weight, length, wing span, wing area, take-off weight, thrust, mach speed, altitude, and the number of test flights. The biggest issue is getting our hands around "pure" cost data.

Aircraft in the NASA Armstrong Database:

There are presently, one-hundred aircrafts in the X-Plane data base, starting with the Wright Brothers powered flight in 1903 commonly referred to as "Flyer 1". We then picked up the X-1 Bell commissioned in 1945 and continued through the series of X-Planes up to X-57. There are other aircraft of interest that has been added like; Scaled Composite's Proteus aircraft 1996. Proteus one of the first to utilize an all-composite airframe with graphite-epoxy sandwich construction. It was developed under NASA's Environmental Research Aircraft and Sensor Technology (ERAST) project. NASA's Dryden Flight Research Center assisted Scaled Composites in developing a sophisticated station-keeping autopilot system and a satellite communications (SATCOM)-based uplink-downlink data system for Proteus' performance and payload data [5]. As a footnote at the time of publication (September 9th 2016) we could only validate 22 of the 65 aircrafts in the data base with verifiable cost data.

Validation of Data – Version #1:

As we struggle to get good "validated" cost data (like the Platonic argument based on philosophical constructs of who came first? i.e. the chicken or the egg) we gone to numerous sources and revisited the source not one nor twice, but a multitude of times with new questions in hand. One example is; we found the original contract between Bell Aircraft Corporation's located in New York and the United States Army and Air Force, to build the first X-1 experimental aircraft/demonstrator, listed for approximately $6.0 M back in 1944. Using the NASA New Start "Inflation Calculator" one could get pretty close to $77.0 M in FY10$. Then the $77.0 M was validated by a second source and you believe the data is good! Several months go by and you pick up a book called "***The X-Planes***", written by Jay Miller, a well know X-Plane Researcher and Author. From there you understand the acquisition was to **<u>build three X-1 Bells</u>**. From there you can use the “Learning Curve Manufacturing Theory” developed by Galorath [6] which implies the first unit is higher than the second by 22% and the second production model is higher than the third by 22%, etc, etc, until you achieve the full production rate of the “block of aircraft” being manufactured. We understand that two of the three X-1 Bells demonstrators were to do super-sonic flight testing while the third was to establish the Reynolds number or shape of the wing. From several validated sources the “dry weight” of each aircraft varied from source to source.

Other sources included the World Wide Web or internet. Source data analysis concluded that the weight the aircraft could be different by just a few pounds or hundreds of pounds. Back in the day if an aircraft had a hard landing, it was re-purposed or rebuilt and flown again. Often time it was a few feet longer than the original and therefore, the additional weight was accounted for.

Various web site sources also seemed to change. An example is; this project started off years ago “none interference basis” sources gather up one year ~ appeared different than current year. So the Team established and developed a hard copy or catalog system of the data base. The three elements are: *Source or URL*, *Source Collected By*, and *the Date* the data was collected.

Validation of Source Data Version #1:

Why are there 100 aircraft in the data base, yet only 65 aircraft or X-Planes listed? The reason is at this point in the game, we are still collected source data and trying to validate it. An Example is the X-15. The X-15 is listed three time in the data base. One source is from all the hard work performed by Dr. Joseph Hamaker, former Director from NASA Headquarters Cost Analysis Division, most likely from data that was found or used in the early development of NAFCOM. Another source is listed as “Tech Notes”, which can be found in the Technical Research Library at Armstrong. The third source would be the Armstrong Cost Engineering Office (ACE) at Armstrong. The same scenario would be used for the X-38; Dr. Hamaker, GOA, ACE Office.

Cost estimate to develop an X-Plane database: cost per line of data:

Currently there are about 100 aircrafts listed in Armstrong’s X-Plane Data Base. This is due to the fact that the NASA ACE Office is still in the process of validating certain data points. Notional speaking the cost of research has been estimated to be about $1,000 per line item per date. As more people become aware of recording the cost of Flight Research Cost Data and the fact that each CER data needs to be validated, we expect the cost per line of data will go up.

The one parameter, in fact the most important parameter needed for the cost model could not be found in these books and that is the actual cost of the aircraft or X-vehicle. Collecting or data mining cost data continues to be a challenge. Out of hundred line items in the database only twenty-two data points are being used for the predictor. Some of the cost data came from Armstrong’s Technical Library, the Redstone Library, subject matter experts (SME’s) that I have a great deal of confidence and are established members of the cost society. Other sources have come from an activity called “thin slicing the data”. Thin slicing is when you have a conversion with a person and you capture the data you need without going through formal authority like; an indefinite delivery, indefinite quantity (IDIQ) contract which can provide for an indefinite quantity of services for a fixed time.

This project started off two years ago on a "*not to interfere*" basis. As I compiled the data from various sources, I found differences in some of the data, so I developed the following 1.) a **catalog system** for the database, with the following three elements: source of data, source data collected by, and date the data was collected. 2.) I have also established the following **hierarchy** when there is conflicting data: i.e.; government document, contractor document, published book, Wikipedia, etc.) How do we know if the source data is accurate and that the cost is reflective or succinctly identifies that of the schedule and scope towards the development of the CER or predictor? One can find reports for a single X-Plane from the General Accountability Office (GAO), the Subject Matter Expert (SME) and the NASA Technical Libraries (NTL). When all three government sources have a different number, what number do you use? I always believe in the wisdom of crowds, my point is the process should not rely one person selecting the source data for a CER. 3.) Going forward there should be some sort of "configuration control board" that oversees and possible decides what data should be used. That where the new 2016 Summer Intern stepped in and took control. This is discussed in the chapter below called "Version #2" by Mr. Anthony Olguin.

Under NACA leadership, the aircraft procurement contract or acquisition order typically described what the government wanted, i.e. "jet airplane, weighs about 6800 pounds, delta wings, flies fast". One or two aircraft manufacturers would compete for the contract and the aircraft would be built and delivered to either Langley or Dryden for aircraft flight testing. Civil Service labor used in the research and development was paid from a separate government appropriation and facilities costs were paid from yet another. The only way to determine the labor cost was to count how many people were standing in front of Building 4800 and estimate the number of management personnel (about 10%) and the number of laborers (about 90%). According to historical logs there were about three supersonic aircraft in the hangar and 25 to 30 people were the appropriate size for a research flight test project, including contractors. This relationship between number of aircraft and personnel still holds true today for a typical X-Plane Flight Test Program at AFRC. The actual cost to take an aircraft from initial concept to first flight is the sum of these various parts.

As I strove to get validated cost data, I used numerous sources and revisited some sources multiple times with new questions in hand. As an example, I found the original X-1 contract between Bell Aircraft Corporation and the United States Army Air Forces. In 1944, Bell was given a contract to build the first X-1 experimental aircraft at a cost of $6 million. Using the NASA New Start Inflation Calculator, I estimated the cost to be approximately $77 million in FY10 dollars. Several months later I picked up Jay Miller's book, "The X-Planes". While reading the book I found that Bell actually built three X-1 aircraft under the contract. From there I used the Learning Curve Manufacturing Theory developed by Galorath, which implies the first unit is higher than the second by 22% and the second model is higher than the third by 22%. Using this formula I was able to calculate a cost of $3.1 million for the first X-1, $1.7 million for the second (X-1E), and $1.2 million for the third.

There has been numerous papers written that cost is the independent variable (CAIV), implemented in early 1996 by CAIV is a new DoD strategy that makes total life-cycle cost as projected within the new acquisition environment a key driver of system requirements, performance characteristics, and schedules. This is a 180-degree conceptual change in thinking from the days of requirement-, performance-, and sometimes schedule-driven Costs – as sited by Dr. Benjamin C. Rush [7].

National Security concerns were prevalent prior to the 1940s, ‘50s and ‘60s placed the focus on performance over costs and since the end of the Cold War, budgets and costs have moved into a more prominent position for planners as it’s extremely difficult to fine cost data on x-planes within that time period. Then there is a period trending, where it seems only the aircraft manufactures have keep historical costs records. Karl Bender, the Chief Librarian at Armstrong *stated “while I have not seen any official instructions, over the last several years, there has been a stronger emphasis on including budget / cost data both in technical reports and special publications”*.

Managing Historical Cost Data at NASA Aeronautical Research Centers:

On my quest to find and seek out cost data, I’ve come across several Project Manager’s (PM) that have the files of records stored in their office. One PM has burned a complete record of X-43 data stored on volumes of CD’s. While another PM has stored Helios data records into 3-ring binders. These PM are on now within the retirement age and can retire at any-time. Yet more disturbing is two weeks prior to the Christmas holidays 2015 – I found two and half volumes of X-53 data thrown away sitting in the dumpster.

As I searched for two data points: the “wing area” for X-36 and X-43, I received a phone call on September 2nd, 2016 the Chief Librarian at Armstrong stating the “*wing area for those two birds were still classified*”. Karl stated “*a work-order will began next week to release the data point for X-36*” from the other classified material, as the X-36 now sitting in a public museum. Basically, Anthony and I went to the museum with tape measure in-hand and calculated the area of the wing. See the figure below.

Figure 3

We are now in the stage where we are relying more on third-party contractors to scrap up cost data from various sources; 1.) From the Aerospace Industry, and from Subject Matter Experts (SMEs). The concern is with proprietary aspect in obtaining the data and the common practice of "thin slicing" the data – how do we know if the data being used as the predictor is correct?

Peer Reviews:

After several peer reviews, Marc Greenberg, a senior cost analyst within NASA Headquarters' Strategic Investment Division, suggested on June 9th, 2016 in Atlanta, Georgia, to go back and take a hard look at the data collected. As we all know, accurate data is the bedrock for statistical analysis and it is important we establish this basis before we proceed with analysis. Thus, our objective is to produce an X-Plane database that ensures that all the data is as accurate, traceable and far-reaching as possible.

Creating the X-Plane data base involves the demanding task of tracking down, documenting and cross-referencing numerous X-Plane parameters across countless sources. This is especially difficult since X-Planes were acquisitioned by other government agencies (OGA) and tested at NASA, with NASA being the responsible test organization (RTO). X-Planes are designated as such due to their innovative design and their dissimilarity to their predecessors. The data is heterogeneous in nature and some specifications are unquantifiable, but will be of future use to create groupings for potential "dummy variables" or "qualitative discriminators". Examples of these groupings are; composite vs. aluminum bodies, autonomous vs. piloted aircraft and the different "versions" of plane such as the transition of flight controls from stick and rudder to "fly-by-wire".

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Taking a Step Back to Ensure Accuracy & Traceability for a Better NASA X-Plane Cost Model – Version #2

Anthony Olguin, NASA AFRC Summer Intern from Cal Poly University, Pomona, CA.

Building the Data Base:

Once it was clear that there needed to be modifications and revisions to the first version CERs and to the X-Plane data base. There was a number of provisions or standards that were set so that issues from the previous data base could be averted, these included:

- No assumptions, “no thin slicing”. Every single data point that is included in the analysis has to taken from a documented source and that the source is also included in the “master” worksheet.
- No duplicates – There will be no X-plane model that was a variant of another model.
- Dummy variables – The inclusion of aircraft parameters that cannot be described in quantifiable form.
- Multiple Databases – There will be two separate databases, one that will include every X-Plane model from X-1 to X-56 and a secondary database of models that will be candidates for regression and analysis.

Dummy Variables:

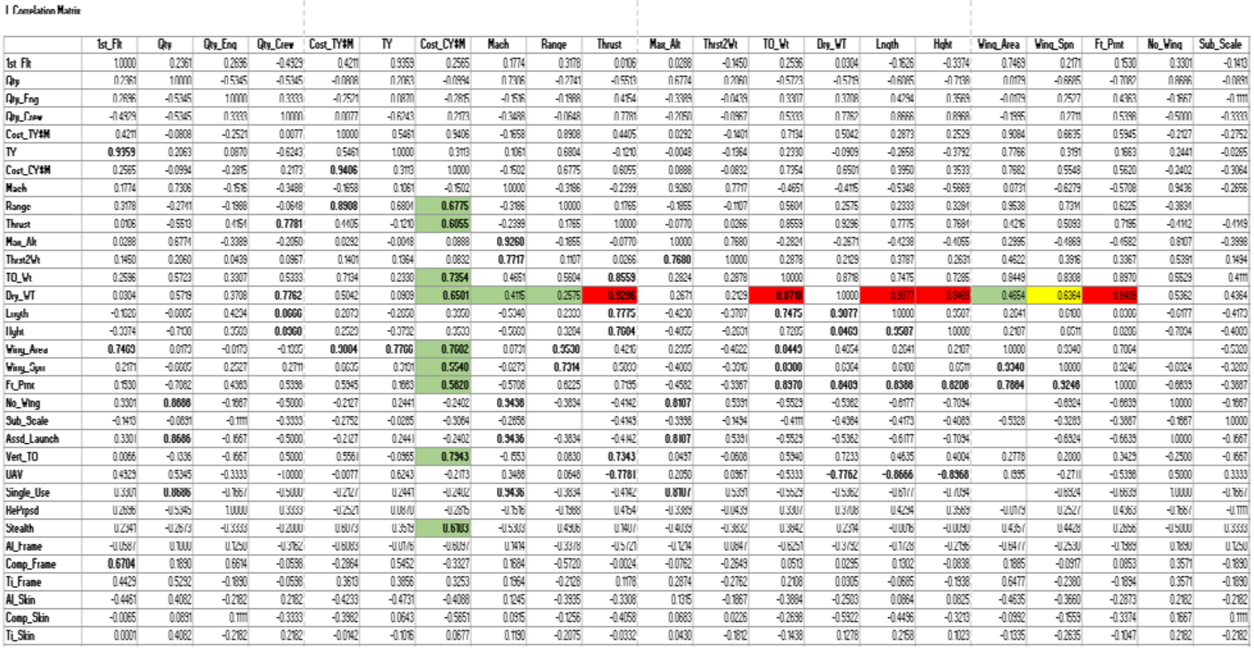
The most obvious difference from the first and second versions of the database is the addition of “dummy” variables. Unlike an aircraft’s weight, mach and range, not all figures can be represented in the form of a quantifiable figure. For example, how does one describe an aircraft as being “stealth” or its skin material on a number scale? Therefore, with the statistical software permitting, the addition of dummy variables (1 equaling “yes” and 0 equaling “No”) is the attempt to better represent the observations in our database.

The selection process for dummy variables ultimately came down to two factors: Which unquantifiable aircraft parameters have at least the possibility of influencing the cost of an X-plane and secondly, which X-plane models have parameters that are staggeringly different from the rest of the data base and can a dummy variable be used to represent that discrepancy? An example of this would be the wing-span or diameter of planes that did not have a traditional wing but was designed to produced lift with is body, or “lifting-body”. In total there are 21 dummy variables listed for every X-plane model, and only the dummies that show improvement to the cost estimates were included in the final CER.

The figure below reflects the 22 X-Planes that met all the standards mention above to be used in the official regression data base. See figure 4.

Figure 4

The figure below simply reflects the methodology in determining the "best fit" from various independent variables and dummy variables. This literally took weeks of analysis as data kept changing as new "verifiable data" kept coming in. It's all about the base!



I Correlation Matrix

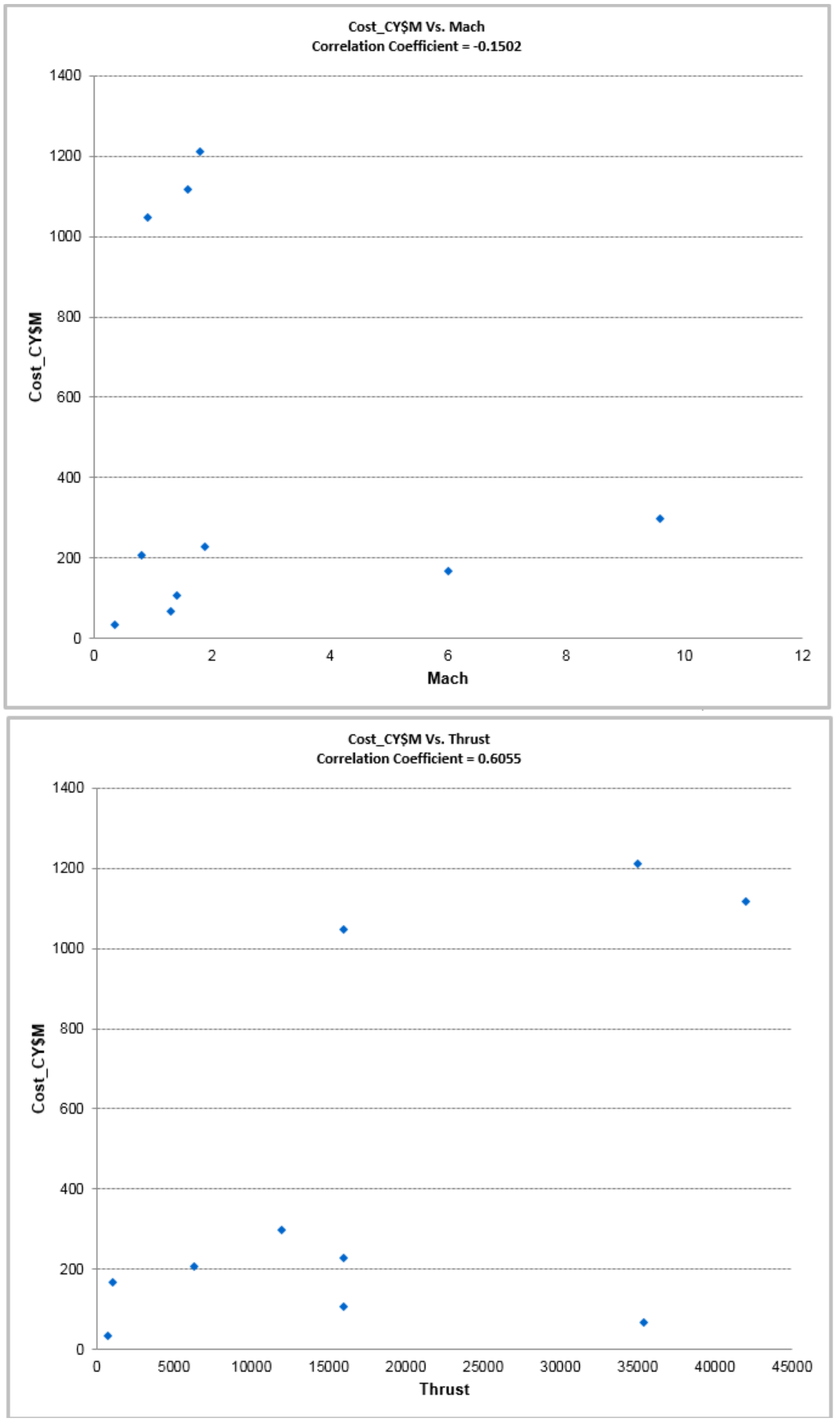
	1st_Flt	Qty	Qty_Eng	Qty_Crew	Cost_TY$M	TY	Cost_CY$M	Mach	Range	Thrust	Max_Alt	Thrst2Wt	TO_Wt	Dry_WT	Lngth	Hght	Wing_Area	Wing_Spn	Ft_Prnt	No_Wing	Sub_Scale
1st Flt	1.0000	0.2361	0.2696	-0.4929	0.4211	0.9359	0.2565	0.1774	0.3178	0.0106	0.0288	-0.1450	0.2596	0.0304	-0.1626	-0.3374	0.7469	0.2171	0.1530	0.3301	-0.1413
Qty	0.2361	1.0000	-0.5345	-0.5345	-0.0808	0.2063	-0.0994	0.7306	-0.2741	-0.5513	0.6774	0.2060	-0.5723	-0.5719	-0.6085	-0.7138	0.0179	-0.6685	-0.7082	0.8686	-0.0891
Qty_Eng	0.2696	-0.5345	1.0000	0.3333	-0.2521	0.0870	-0.2815	-0.1516	-0.1988	0.4154	-0.3389	-0.0439	0.3307	0.3708	0.4294	0.3569	-0.0179	0.2527	0.4363	-0.1667	-0.1111
Qty_Crew	-0.4929	-0.5345	0.3333	1.0000	0.0077	-0.6243	0.2173	-0.3488	-0.0648	0.7781	-0.2050	-0.0967	0.5333	0.7762	0.8666	0.8968	-0.1995	0.2711	0.5398	-0.5000	-0.3333
Cost_TY$M	0.4211	-0.0808	-0.2521	0.0077	1.0000	0.5461	0.9406	-0.1658	0.8908	0.4405	0.0292	-0.1401	0.7134	0.5042	0.2873	0.2529	0.9084	0.6635	0.5945	-0.2127	-0.2752
TY	**0.9359**	0.2063	0.0870	-0.6243	0.5461	1.0000	0.3113	0.1061	0.6804	-0.1210	-0.0048	-0.1364	0.2330	-0.0909	-0.2658	-0.3792	0.7766	0.3191	0.1663	0.2441	-0.0265
Cost_CY$M	0.2565	-0.0994	-0.2815	0.2173	**0.9406**	0.3113	1.0000	-0.1502	0.6775	0.6055	0.0888	-0.0832	0.7354	0.6501	0.3950	0.3533	0.7682	0.5548	0.5620	-0.2402	-0.3064
Mach	0.1774	0.7306	-0.1516	-0.3488	-0.1658	0.1061	-0.1502	1.0000	-0.3186	-0.2399	0.9260	0.7717	-0.4651	-0.4115	-0.5348	-0.5669	0.0731	-0.6279	-0.5708	0.9436	-0.2656
Range	0.3178	-0.2741	-0.1988	-0.0648	**0.8908**	0.6804	**0.6775**	-0.3186	1.0000	0.1765	-0.1855	-0.1107	0.5604	0.2575	0.2333	0.3284	0.9538	0.7314	0.6225	-0.3834	
Thrust	0.0106	-0.5513	0.4154	**0.7781**	0.4405	-0.1210	**0.6055**	-0.2399	0.1765	1.0000	-0.0770	0.0266	0.8559	0.9296	0.7775	0.7684	0.4216	0.5093	0.7195	-0.4142	-0.4149
Max_Alt	0.0288	0.6774	-0.3389	-0.2050	0.0292	-0.0048	0.0888	**0.9260**	-0.1855	-0.0770	1.0000	0.7680	-0.2824	-0.2671	-0.4238	-0.4055	0.2995	-0.4869	-0.4582	0.8107	-0.3998
Thrst2Wt	0.1450	0.2060	0.0439	0.0967	0.1401	0.1364	0.0832	**0.7717**	0.1107	0.0266	**0.7680**	1.0000	0.2878	0.2129	0.3787	0.2631	0.4622	0.3916	0.3367	0.5391	0.1494
TO_Wt	0.2596	0.5723	0.3307	0.5333	0.7134	0.2330	**0.7354**	0.4651	0.5604	**0.8559**	0.2824	0.2878	1.0000	0.8718	0.7475	0.7285	0.8449	0.8308	0.8970	0.5529	0.4111
Dry_WT	0.0304	0.5719	0.3708	**0.7762**	0.5042	0.0909	**0.6501**	0.4115	0.2575	**0.9296**	0.2671	0.2129	**0.8718**	1.0000	0.9077	0.8469	0.4654	0.6364	0.8409	0.5362	0.4364
Lngth	-0.1626	-0.6085	0.4294	**0.8666**	0.2873	-0.2658	0.3950	-0.5348	0.2333	**0.7775**	-0.4238	-0.3787	**0.7475**	**0.9077**	1.0000	0.3507	0.2041	0.0100	0.0300	-0.6177	-0.4173
Hght	-0.3374	-0.7138	0.3569	**0.8968**	0.2529	-0.3792	0.3533	-0.5669	0.3284	**0.7684**	-0.4055	-0.2631	0.7285	**0.8469**	**0.3507**	1.0000	0.2107	0.0511	0.0206	-0.7094	-0.4003
Wing_Area	**0.7469**	0.0179	-0.0179	-0.1995	**0.9084**	**0.7766**	**0.7682**	0.0731	**0.9538**	0.4216	0.2995	-0.4622	**0.8449**	0.4654	0.2041	0.2107	1.0000	0.3340	0.7004		-0.5328
Wing_Spn	0.2171	-0.6685	0.2527	0.2711	0.6635	0.3191	**0.5548**	-0.6279	**0.7314**	0.5093	-0.4869	-0.3916	**0.8308**	0.6364	0.0100	0.0511	**0.3340**	1.0000	0.3246	-0.6324	-0.3283
Ft_Prnt	0.1530	-0.7082	0.4363	0.5398	0.5945	0.1663	**0.5620**	-0.5708	0.6225	0.7195	-0.4582	-0.3367	**0.8970**	**0.8409**	**0.8386**	**0.8206**	**0.7884**	**0.9246**	1.0000	-0.6639	-0.3887
No_Wing	0.3301	**0.8686**	-0.1667	-0.5000	-0.2127	0.2441	-0.2402	**0.9436**	-0.3834	-0.4142	**0.8107**	0.5391	-0.5529	-0.5362	-0.6177	-0.7094		-0.6324	-0.6639	1.0000	-0.1667
Sub_Scale	-0.1413	-0.0891	-0.1111	-0.3333	-0.2752	-0.0265	-0.3064	-0.2656		-0.4149	-0.3998	-0.1494	-0.4111	-0.4364	-0.4173	-0.4003	-0.5328	-0.3283	-0.3887	-0.1667	1.0000
Assd_Launch	0.3301	**0.8686**	-0.1667	-0.5000	-0.2127	0.2441	-0.2402	**0.9436**	-0.3834	-0.4142	**0.8107**	0.5391	-0.5529	-0.5362	-0.6177	-0.7094		-0.6324	-0.6639	1.0000	-0.1667
Vert_TO	0.0066	-0.1336	-0.1667	0.5000	0.5561	-0.0965	**0.7943**	-0.1553	0.0830	**0.7343**	0.0437	-0.0608	0.5940	0.7233	0.4635	0.4004	0.2778	0.2000	0.3429	-0.2500	-0.1667
UAV	0.4929	0.5345	-0.3333	-1.0000	-0.0077	0.6243	-0.2173	0.3488	0.0648	**-0.7781**	0.2050	0.0967	-0.5333	**-0.7762**	**-0.8666**	**-0.8968**	0.1995	-0.2711	-0.5398	0.5000	0.3333
Single_Use	0.3301	**0.8686**	-0.1667	-0.5000	-0.2127	0.2441	-0.2402	**0.9436**	-0.3834	-0.4142	**0.8107**	0.5391	-0.5529	-0.5362	-0.6177	-0.7094		-0.6324	-0.6639	1.0000	-0.1667
HePrpsd	0.2696	-0.5345	1.0000	0.3333	-0.2521	0.0870	-0.2815	-0.1516	-0.1988	0.4154	-0.3389	-0.0439	0.3307	0.3708	0.4294	0.3569	-0.0179	0.2527	0.4363	-0.1667	-0.1111
Stealth	0.2347	-0.2673	-0.3333	-0.2000	0.6073	0.3579	**0.6703**	-0.5303	0.4506	0.1407	-0.4039	-0.3632	0.3842	0.2314	-0.0076	-0.0090	0.4357	0.4428	0.2666	-0.5000	0.3333
Al_Frame	-0.0587	0.1000	0.1250	-0.3762	-0.6083	-0.0176	-0.6097	0.1414	-0.3378	-0.5721	-0.1214	0.0847	-0.6251	-0.3792	-0.1728	-0.2196	-0.6477	-0.2530	-0.1969	0.1890	0.1250
Comp_Frame	**0.6704**	0.1890	0.6614	-0.0598	-0.2864	0.5452	-0.3327	0.1684	-0.5720	-0.0024	-0.0762	-0.2649	0.0513	0.0295	0.1302	-0.0838	0.1885	-0.0917	0.0853	0.3571	-0.1890
Ti_Frame	0.4429	0.5292	-0.1890	-0.0598	0.3613	0.3856	0.3253	0.1964	-0.2128	0.1178	0.2874	-0.2762	0.2108	0.0305	-0.0685	-0.1938	0.6477	-0.2380	-0.1894	0.3571	-0.1890
Al_Skin	-0.4461	0.4082	-0.2182	0.2182	-0.4233	-0.4731	-0.4088	0.1245	-0.3935	-0.3308	0.1315	-0.1867	-0.3884	-0.2503	0.0864	0.0825	-0.4635	-0.3660	-0.2873	0.2182	-0.2182
Comp_Skin	-0.0065	0.0891	0.1111	-0.3333	-0.3982	0.0643	-0.5651	0.0915	-0.1256	-0.4058	0.0683	0.0226	-0.2698	-0.5922	-0.4496	-0.3213	-0.0992	-0.1553	-0.3374	0.1667	0.1111
Ti_Skin	0.0001	0.4082	-0.2182	0.2182	-0.0142	-0.1016	0.0677	0.1190	-0.2075	-0.0332	0.0430	-0.1812	-0.1438	0.1278	0.2158	0.1023	-0.1335	-0.2635	-0.1047	0.2182	-0.2182

Figure 5

Building CERs:

When the database of observations that will be used for analysis was finally “frozen”, it consisted of a total of 22 X-plane models spanning from 1959 to 2012 (as seen above). Once looking at all the observations it was clear to the naked eye that no two X-plane models were the same. When building CERs with such a heterogeneous dataset it was necessary to follow a series of steps to produce a cost estimating equation that would accurately estimate cost. These steps include:

Step 1: Use Correlation Matrix and 2-D plots



Figures 6 and Figure 7

Step 2: Build Equations with non-Dummy variables

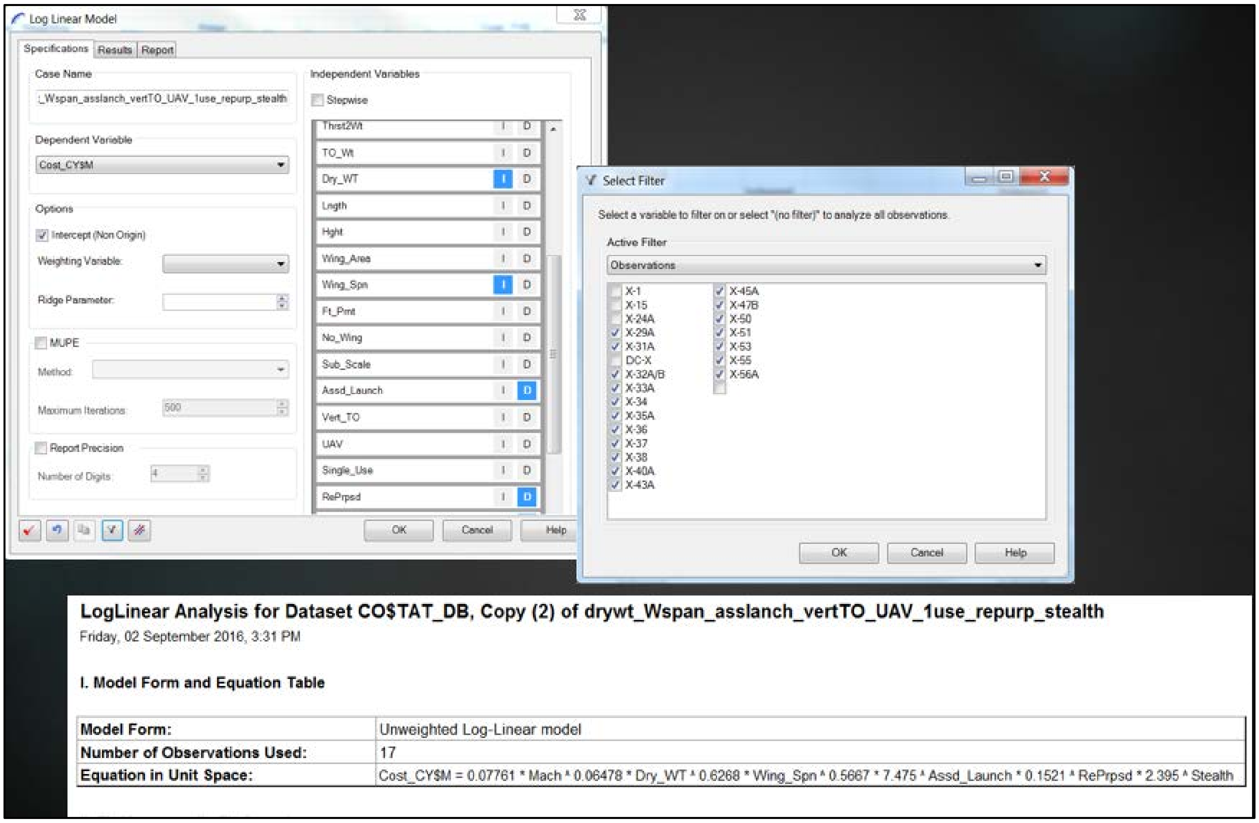
Step 3: Address Outliers

Step 4: Evaluate Overall Equation Statistics

All of which would be completed using "CO$TAT", a very powerful excel Add-in tool that allows statistical analysis and produces an extremely useful report that not only gives the equation form of the CER but also gives stats on the quality of the coefficients and the goodness of fit for the selected variables.

When using such a small sample size it is important to keep in mind that with the addition of every independent variable to the CER, it removes one degree of freedom and can actually begin to artificially correlate your dataset. Therefore, in an attempt to minimize these dangers we set out a rough guideline of: Maximum 3 independent variables and maximum 3 dummy variables.

An example of the selection input of the desired variables in CO$TAT is below:



Case Name: _Wspan_asslanch_vertTO_UAV_1use_repurp_stealth

Dependent Variable: Cost_CY$M

☑ Intercept (Non Origin)

Weighting Variable:

Ridge Parameter:

☐ MUPE

Method:

Maximum Iterations: 500

☐ Report Precision

Number of Digits: 4

☐ Stepwise

Thrst2Wt I D
TO_Wt I D
Dry_WT [✓ I] D
Lngth I D
Hght I D
Wing_Area I D
Wing_Spn [✓ I] D
Ft_Pmt I D
No_Wing I D
Sub_Scale I D
Assd_Launch I [✓ D]
Vert_TO I D
UAV I D
Single_Use I D
RePrpsd I [✓ D]

Select a variable to filter on or select "(no filter)" to analyze all observations.

Active Filter: Observations

☐ X-1
☐ X-15
☐ X-24A
☑ X-29A
☑ X-31A
☐ DC-X
☑ X-32A/B
☑ X-33A
☑ X-34
☑ X-35A
☑ X-36
☑ X-37
☑ X-38
☑ X-40A
☑ X-43A
☑ X-45A
☑ X-47B
☑ X-50
☑ X-51
☑ X-53
☑ X-55
☑ X-56A
☐

LogLinear Analysis for Dataset CO$TAT_DB, Copy (2) of drywt_Wspan_asslanch_vertTO_UAV_1use_repurp_stealth

Friday, 02 September 2016, 3:31 PM

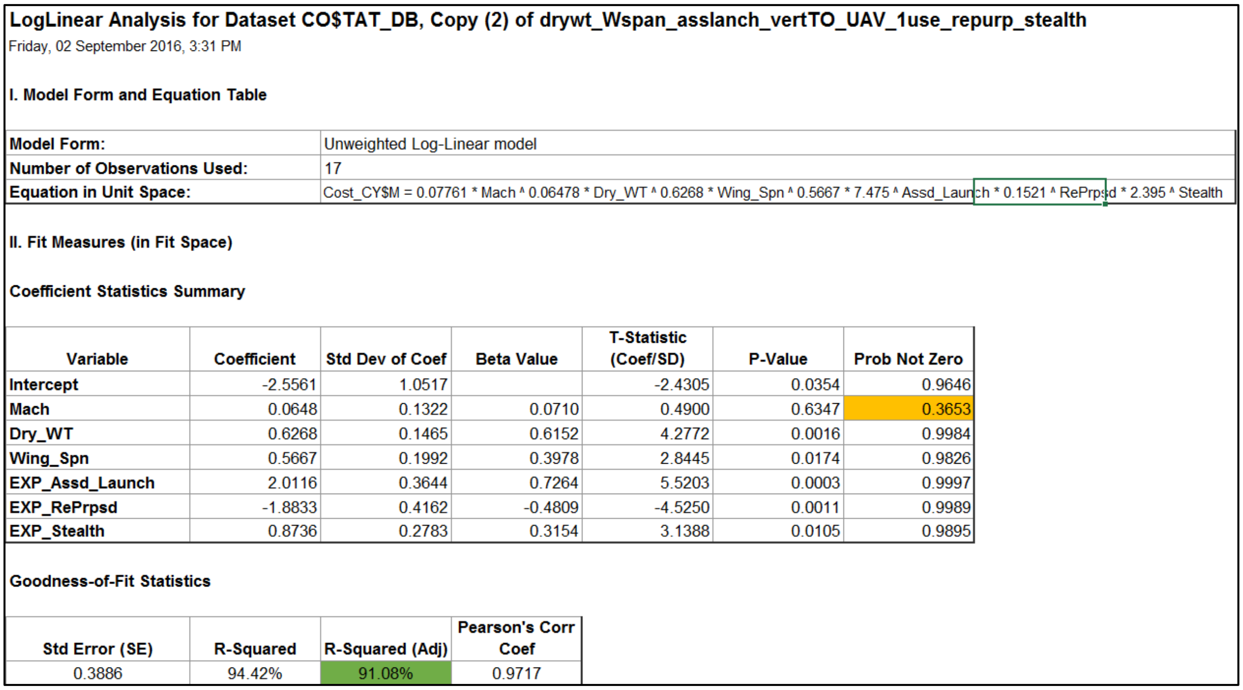
I. Model Form and Equation Table

Model Form:	Unweighted Log-Linear model
Number of Observations Used:	17
Equation in Unit Space:	Cost_CY$M = 0.07761 * Mach ^ 0.06478 * Dry_WT ^ 0.6268 * Wing_Spn ^ 0.5667 * 7.475 ^ Assd_Launch * 0.1521 ^ RePrpsd * 2.395 ^ Stealth

Figure 8

CERs with 17 Observations:

The figures below reflects on of many samples of the statistical report in CO$TAT that was performed:



LogLinear Analysis for Dataset CO$TAT_DB, Copy (2) of drywt_Wspan_asslanch_vertTO_UAV_1use_repurp_stealth

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II. Fit Measures (in Fit Space)

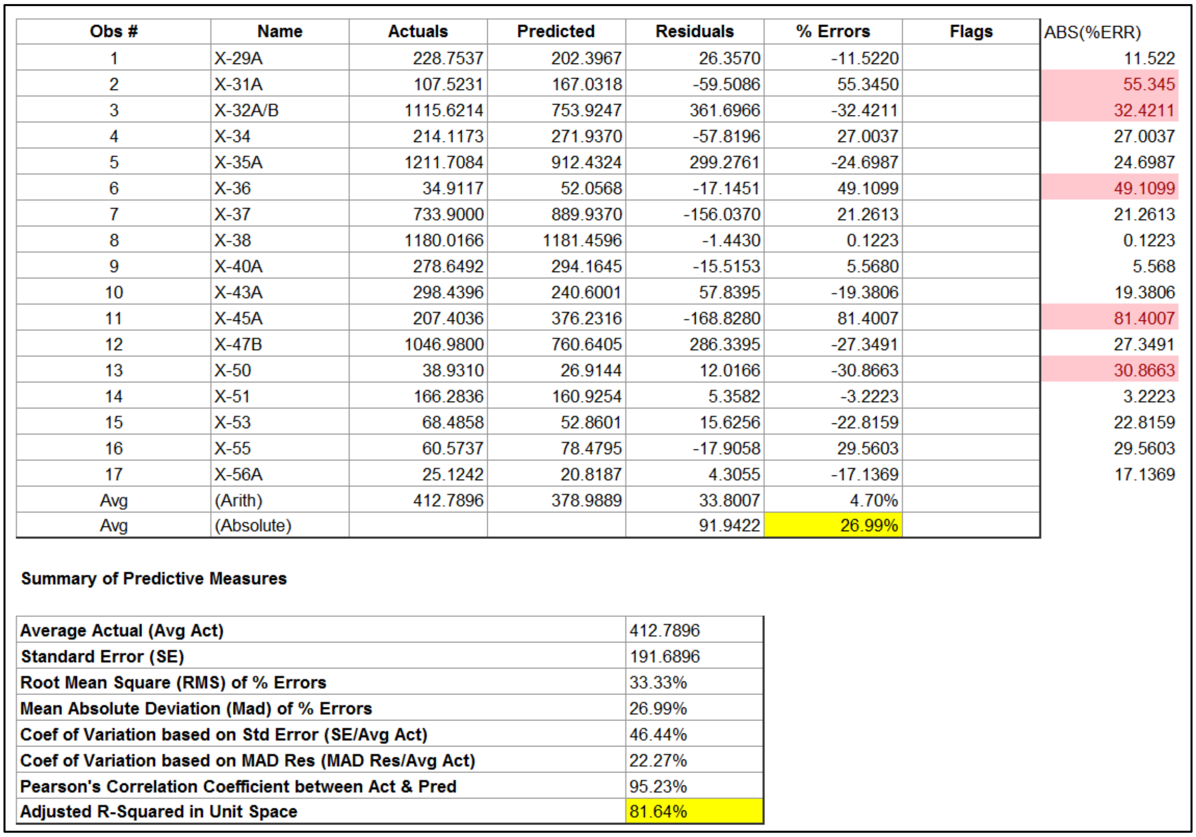
Coefficient Statistics Summary

Variable	Coefficient	Std Dev of Coef	Beta Value	T-Statistic (Coef/SD)	P-Value	Prob Not Zero
Intercept	-2.5561	1.0517		-2.4305	0.0354	0.9646
Mach	0.0648	0.1322	0.0710	0.4900	0.6347	0.3653
Dry_WT	0.6268	0.1465	0.6152	4.2772	0.0016	0.9984
Wing_Spn	0.5667	0.1992	0.3978	2.8445	0.0174	0.9826
EXP_Assd_Launch	2.0116	0.3644	0.7264	5.5203	0.0003	0.9997
EXP_RePrpsd	-1.8833	0.4162	-0.4809	-4.5250	0.0011	0.9989
EXP_Stealth	0.8736	0.2783	0.3154	3.1388	0.0105	0.9895

Goodness-of-Fit Statistics

Std Error (SE)	R-Squared	R-Squared (Adj)	Pearson's Corr Coef
0.3886	94.42%	91.08%	0.9717

Figure 9



Obs #	Name	Actuals	Predicted	Residuals	% Errors	Flags	ABS(%ERR)
1	X-29A	228.7537	202.3967	26.3570	-11.5220		11.522
2	X-31A	107.5231	167.0318	-59.5086	55.3450		55.345
3	X-32A/B	1115.6214	753.9247	361.6966	-32.4211		32.4211
4	X-34	214.1173	271.9370	-57.8196	27.0037		27.0037
5	X-35A	1211.7084	912.4324	299.2761	-24.6987		24.6987
6	X-36	34.9117	52.0568	-17.1451	49.1099		49.1099
7	X-37	733.9000	889.9370	-156.0370	21.2613		21.2613
8	X-38	1180.0166	1181.4596	-1.4430	0.1223		0.1223
9	X-40A	278.6492	294.1645	-15.5153	5.5680		5.568
10	X-43A	298.4396	240.6001	57.8395	-19.3806		19.3806
11	X-45A	207.4036	376.2316	-168.8280	81.4007		81.4007
12	X-47B	1046.9800	760.6405	286.3395	-27.3491		27.3491
13	X-50	38.9310	26.9144	12.0166	-30.8663		30.8663
14	X-51	166.2836	160.9254	5.3582	-3.2223		3.2223
15	X-53	68.4858	52.8601	15.6256	-22.8159		22.8159
16	X-55	60.5737	78.4795	-17.9058	29.5603		29.5603
17	X-56A	25.1242	20.8187	4.3055	-17.1369		17.1369
Avg	(Arith)	412.7896	378.9889	33.8007	4.70%		
Avg	(Absolute)			91.9422	26.99%		

Summary of Predictive Measures

Average Actual (Avg Act)	412.7896
Standard Error (SE)	191.6896
Root Mean Square (RMS) of % Errors	33.33%
Mean Absolute Deviation (Mad) of % Errors	26.99%
Coef of Variation based on Std Error (SE/Avg Act)	46.44%
Coef of Variation based on MAD Res (MAD Res/Avg Act)	22.27%
Pearson's Correlation Coefficient between Act & Pred	95.23%
Adjusted R-Squared in Unit Space	81.64%

Figure 10

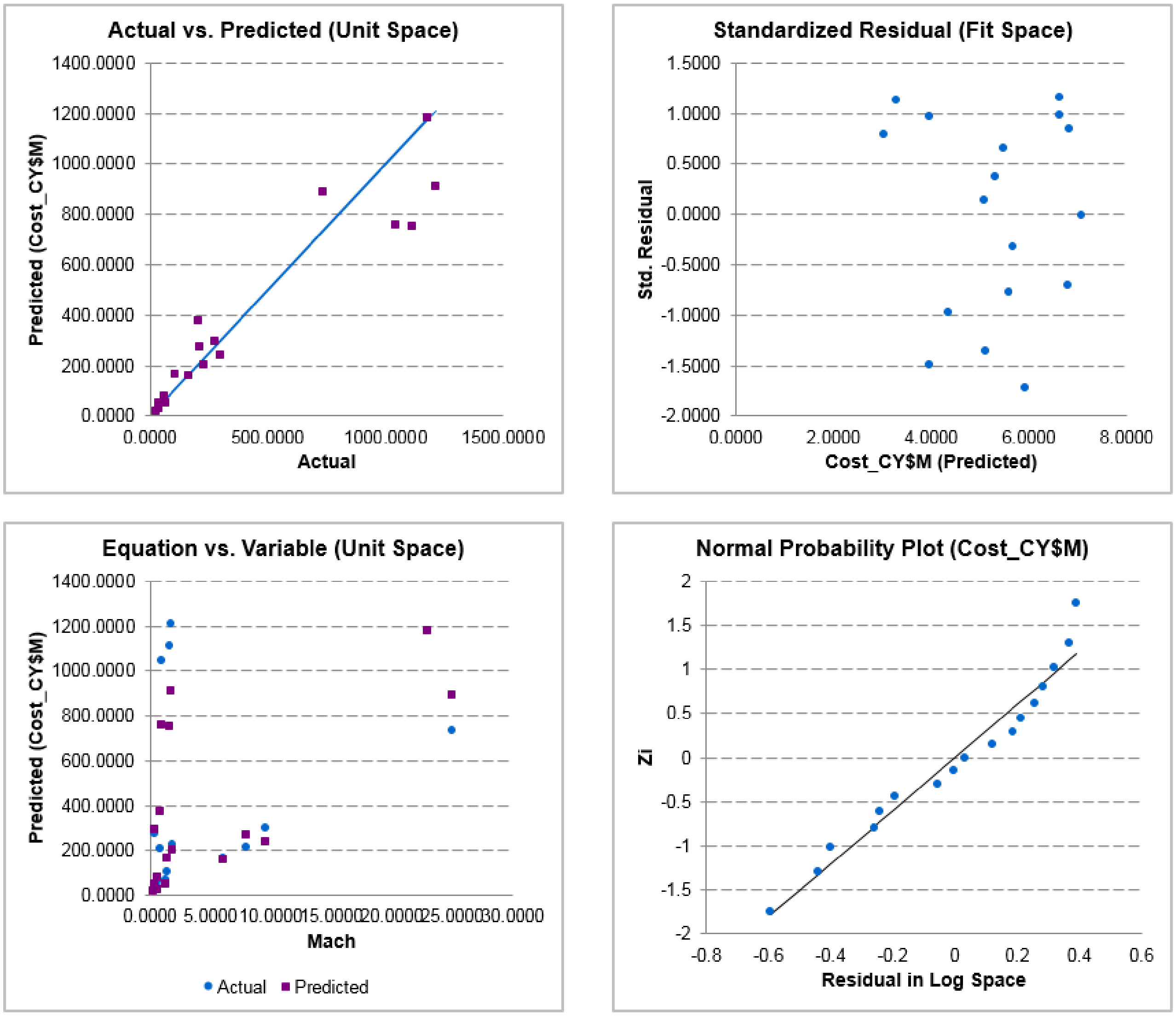
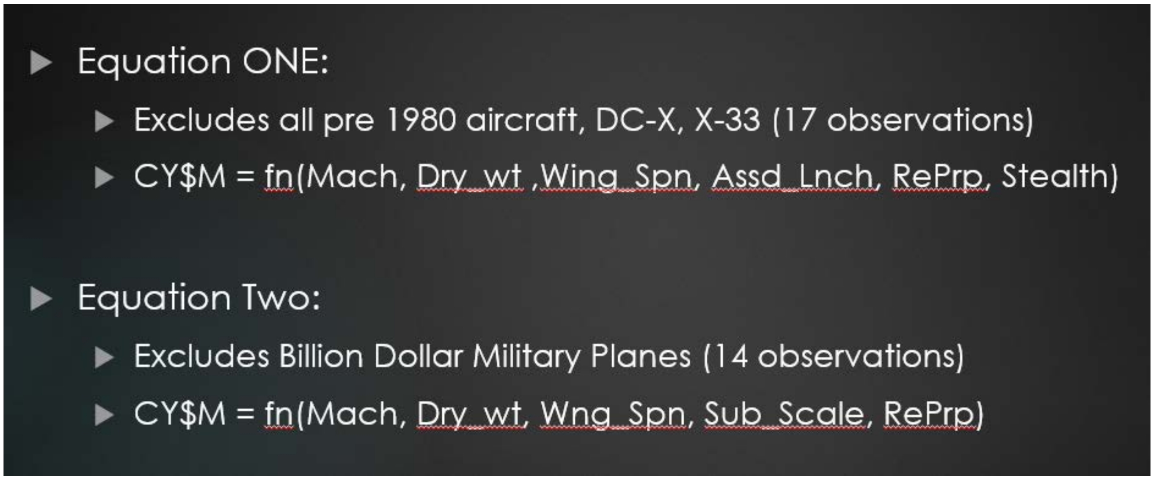


Figure 11

The Top 2 CERS – Version #2:

Equation #1
Excludes all pre 1980 aircraft; DC-X, X-33 17 Observations.
CY$M = fn (Mach, dry weight, wing span, assisted launch, repurposed, stealth)

Equation #2
Excludes billion dollar military planes with 14 observations.
CY$M = fn (Mach, dry weight, wing span, assisted launch, repurposed)
See figure 12 below:



- Equation ONE:
  - Excludes all pre 1980 aircraft, DC-X, X-33 (17 observations)
  - CY$M = fn(Mach, Dry_wt ,Wing_Spn, Assd_Lnch, RePrp, Stealth)
- Equation Two:
  - Excludes Billion Dollar Military Planes (14 observations)
  - CY$M = fn(Mach, Dry_wt, Wng_Spn, Sub_Scale, RePrp)

Figure 12

Culture at NASA Armstrong Flight Research Center:

The culture at NASA is we are very proud of our heritage and the staff is extremely excited that the Office of Management and Budget (OMB) and Congress is augmenting the NASA Budget especially for the advancement of X-Planes. As a Research Flight Center it is our quest to developed and prove out new concepts for Aeronautics Mission Directorate (ARMD).

Figure 13

The Science Technology Mission Directorate (STMD) is currently considering Armstrong's Flight Research Center proposal for the Twin Glider Assisted Launch Systems (TGALS). The TGALS project is currently being evaluated under the Game Changing Initiative (GCI) at Armstrong as a viable option in launching rockets and satellites into orbit. The fuselage and structure for the TGALS is an "all composite" material. It appears the aircraft manufacturers' are trending towards the use of composites.

Figure 14

Advanced Composite Materials:

With the new emerging and popular use of advance composite material used by aircraft industry. Companies like: Scaled Composite and Aurora Science are in the business of producing all composite airframes. Upon a closer examination these "low-cost manufactures" seem to rely on unique aerodynamic analysis and design capability, when combined with a proof-of-concept building experience, provides customers with the most cost-effective composite "hand-layup" fabricator who makes their own "landing gears". On the average 93% of their experimental aircraft uses "composite material including their spars. Composite material is oven cured at 140 degrees using "low cost" methods. The words "computational fluid dynamics" (CFD) came up often. On the average build – it takes 6-9 months of CFD to validate a new design, based on a library of earlier design models. Low cost fabricators "puts a lot faith in their CFD". A typical aircraft design build is around $9M for the first aircraft, $6M for the second or a 30% reduction for the second – based on tooling and learning curve models, etc. They take pride in "Concurrent Engineering", meaning they don't have all the engineering completed when they go for build. The typical schedule from "Design to 1st Flight" is 2 to 2-1/2 Years. *"Double the math" from weight to cost ratios* . . . . For 27,500 lb. with 88' span you are talking $55M (maybe a little more) and done in 2-3 years. Historical example is 15,000 pound empty weight airplane and a $25M program. They like to be done in 2 years to first. They can cut tooling to a .030 tolerance. 5 Axis CNC cutter for tooling. The estimate: 15-20% of the cost of the airplane is the propulsion system and tend to use a commercial propulsion systems rather than surplus government propulsion systems. From lessons learned they found that the initial cost may be cheaper, but getting spare parts and the time waiting to get the spare parts out way the difference in simply using commercial-off-the-self (COTS). They have found that building the 2nd airplane is often 30-35% cheaper than the first, thus having improved the manufacturing learning curve. The current manufacturing learning curve from the larger aerospace manufactures are around 15% to 20%. I've used the 22% algorithm (known as standard at the time of Aluminum Aircraft builders) to determine the cost of the second X-1 Bell.

Composite aircraft manufactures do not use rivets. Historically about 30,000 rivets are used to tie in the structural foundation of an aluminum aircraft. Several papers suggest that an all composite aircraft can save up to 30% of the manufacturer's costs. More analysis needs to done in this area that might change the predictor CER if an all composite airframe were to be used.

As of April 2015, the Air Force Research Laboratory (AFRL) Aerospace Systems Directorate intends to execute a technology development and demonstration initiative to reduce the scope of the technical effort required to establish both the initial, and the continuing airworthiness of airframe structure manufactured from advanced composite materials. The program will identify and select, develop, and demonstrate technology which will improve our ability to assess, predict, and control the structural integrity of composite structure as a function of its constituent materials, configuration, features, and manufactured state, and as influenced by its known history and expected future service environment and loads [8], thus also reducing the cost of the airworthiness process.

In Summary:

Now the X-planes are back: NASA has unveiled a new 10-year experimental program, aimed at developing aircraft which are quieter, greener, and much, much faster. Among their plans is a supersonic jet so tranquil, its supersonic boom has been likened to the sound of a neighbor forcefully shutting their car door (pictured, below).

Figure 15

To ensure we have the right skills and tool sets within several months over two year effort, the Armstrong Cost Engineering Team has gone through the full process in developing a parametric cost model from version #1 to version #2. With the identification and collection of x-plane key parameters, such as; dry weight, length, wing span, manned vs unmanned, altitude, mach and thrust and taking a step backwards to ensure accuracy and traceability for a better X-Plane Cost Model.

Out of the 57 X-Planes and other one-of-a-kind aircrafts of interest, only 14 observations (at the time of publishing this paper) have cost data that is accurate and traceable which is currently being used as the CER or predictor as reflected in equation #2.

With the recent interest among the NASA Technical Community from the four Aeronautical NASA Centers it now appears there is a sustaining amount of interest in collecting cost data – when flight research has been completed.

From another NASA internal process improvement team exercise, the OCFO Reimbursable Policy Office, “Project Close-out” seems to be gaining attention among NASA’s Leadership Teams. The findings from both of these exercises is there is not one file draw nor electronic historical repository for X-Planes. However with the new interest from the Aeronautics and the Science Technical Community it is hopeful that this new energy will change the culture within NASA to at least start developing these skills in-house from a non-interference basis to standing-up a full-on cost engineering office(s) at one of the NASA Aeronautical Centers.

Langley Research Center seems to be right on track by taking the initiative lead by; Craig Nickol and David Richwine to start various studies for a future x-plane, including a supersonic low-boom flight demonstrator. Steve Jacobson, Mike Frederick and Jason Lechniak at Armstrong and Dr. John Melton at Ames have also done an extraordinary amount of work in developing all the requirements for the new series of X-Planes to the Cost Engineering Community. We now have the option to cross-check the outcomes from various parametric cost models, as mentioned from Andy Prince, Director of the Cost Engineering Office at Marshall, from the recent proceeding "*Dangers of Parametric*", which received "Best Paper Overall" at the ICEAA Annual Conference held in Atlanta, Georgia, June 2016. Andy goes on to say "*it is a good practice to cross-validate the outcome of parametric cost models and benchmark a model against new data*". I believe we have successful completed both of those steps listed above i.e. from going from version #1 to version #2 and taken a step backward to revalidate the data base.

Armstrong's Parametric Cost Model (APCM) has caught the attention from the Department of Defense (DoD) officials; including Pamela Melroy, Deputy Director of DARPA's Tactical Technology Office at Defense Advanced Research Projects Agency (DARPA) in Arlington, Va. DARPA has recently announced a $10 million contract four various aircraft fabricators to design, fabricate and fly a new X-Wing project. Within a six-month phase, four companies are in the designed conceptual phase to; define subsystems, identify propulsion systems, define the layout of the aircraft, estimate the aircraft performance, compute the size, weight, fuel, and power requirements, and defined control systems. The DARPA X-Plane initiative is a four-year $130 million effort to fly an experimental aircraft that flies faster than 300 knots with a hover efficiency of 75 percent or better and a cruise lift-to-drag ratio of 10 or more. This is a prime example were both government and industry is headed. This is also the target zone in which NASA would like to play-in. That is to design, build and fly a new x-plane every two to three years. At the $130M to $460M price range.

The Armstrong Parametric Cost Model (ACPM) using version #2 CERs was harvested within a three month period commencing September 9th, 2016. The APCM is currently producing estimates with a high degree of confidence thanks to Summer Intern, Anthony Olguin and Marc Greenberg at NASA Headquarters. With that said we can now go forward in revealing the NASA X-Plane Cost Calculator ™ pictured below.

Figure 16

Technology Transfer - Patient Pending DFC-016-037
NASA X-Plane Cost Calculator ™

KEY TERMS - Provided from the NASA Thesaurus (see SP-7501)

1.) Cost Estimation
2.) Life Cycle Cost
3.) Predictive Analysis Technics
4.) Monte-Carlo Methods
5.) Regression
6.) Mathematical Models

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ACKNOWLEDGMENTS

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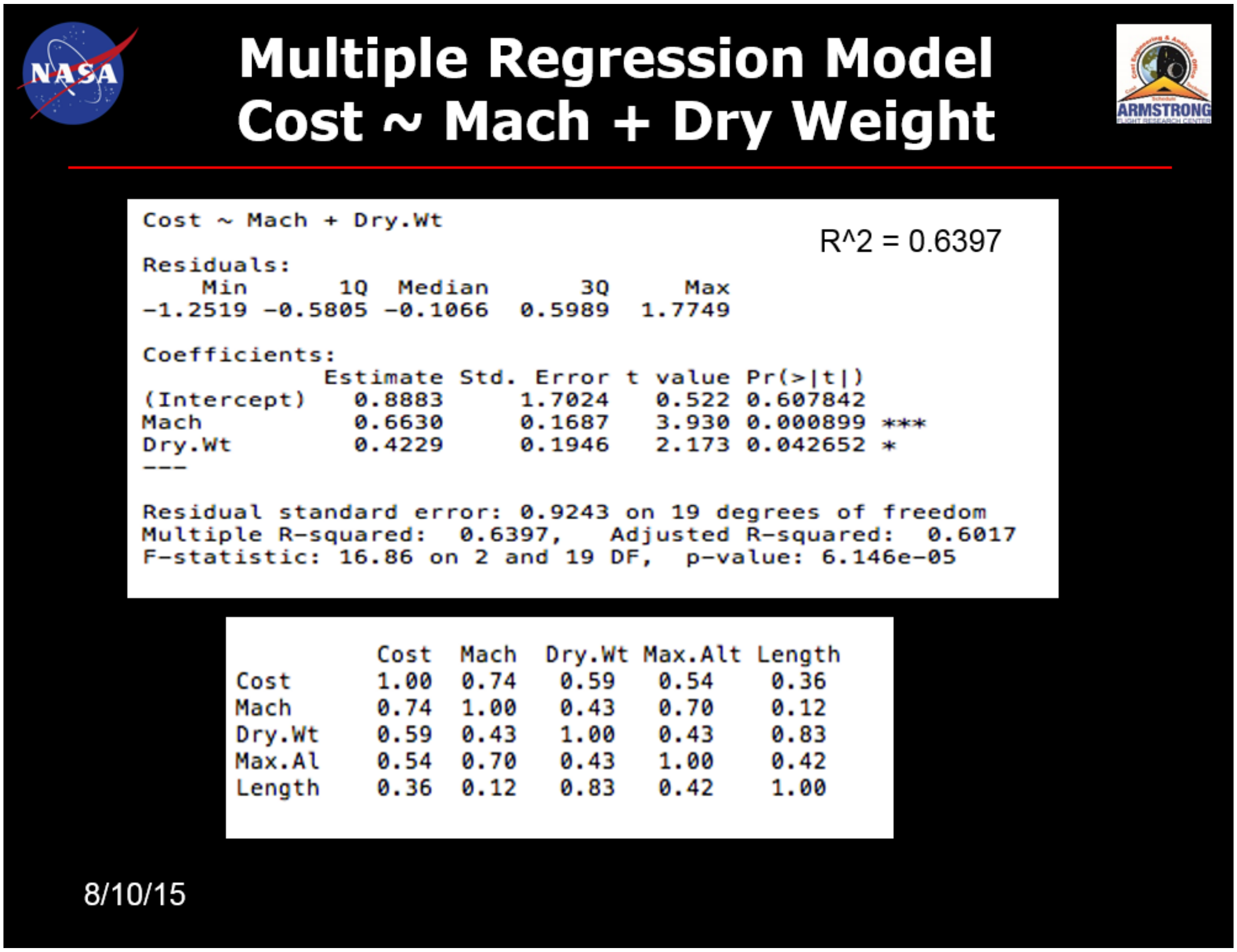
ACRONYMS

ACE – Armstrong Cost Engineering
AFRC – Armstrong Fight Research Center
AFRL - Air Force Research Laboratory
AIAA – American Institute of Aeronautics and Astronautics
APCM - Armstrong's Parametric Cost Model
ARMD – Aeronautics Research Mission Directorate
CER – Cost Estimation Relationship
CFD - Computational Fluid Dynamics
COTS – Commercial Off The Self
DARPA – Defense Advance Research Project Agency
DOD – Department of Defense
ERAST - Environmental Research Aircraft and Sensor Technology
GAO - General Accountability Office
GCI - Game Changing Initiative
IDIQ - Indefinite Delivery, Indefinite Quantity
MOD - Ministry of Defense
NACA – National Advisory Committee for Aeronautics
NAFCOM – NASA Air Force Cost Model
NASA – National Aeronautics and Space Administration
NTL - NASA Technical Libraries
OGA – Other Government Organizations
PM – Project Manager
ROM - Rough Order of Magnitude
RTO – Responsible Test Organization
SER – Schedule Estimation Relationship
SME – Subject Matter Expert
STMD - Science Technology Mission Directorate
TGALS - Twin Glider Assisted Launch Systems

APPENDICES

Appendix #1

Aaron's CER Table, now called version #1 concluded that NASA's X-Planes are too complex for simple linear regression. We have to use more than one predictor in model. We are limited by the number of data points in database. We are cautious not to over fit the data ~ if we use too many predictors. On the other side of the equation we have a higher R2 but lower predictive accuracy. Final model on 8/10/16: Cost vs Mach + Dry Weight as shown below:



Multiple Regression Model Cost ~ Mach + Dry Weight

R^2 = 0.6397

```
Cost ~ Mach + Dry.Wt

Residuals:
    Min      1Q  Median      3Q     Max
-1.2519 -0.5805 -0.1066  0.5989  1.7749

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   0.8883     1.7024   0.522 0.607842
Mach          0.6630     0.1687   3.930 0.000899 ***
Dry.Wt        0.4229     0.1946   2.173 0.042652 *
---

Residual standard error: 0.9243 on 19 degrees of freedom
Multiple R-squared:  0.6397,   Adjusted R-squared:  0.6017
F-statistic: 16.86 on 2 and 19 DF,  p-value: 6.146e-05
```

```
         Cost  Mach  Dry.Wt Max.Alt Length
Cost     1.00  0.74   0.59   0.54    0.36
Mach     0.74  1.00   0.43   0.70    0.12
Dry.Wt   0.59  0.43   1.00   0.43    0.83
Max.Al   0.54  0.70   0.43   1.00    0.42
Length   0.36  0.12   0.83   0.42    1.00
```

8/10/15

Figure 17

Version #1 R^2 and Coefficients, dated: 8/10/15