X-1 to X-Wings
Developing a Parametric Cost Model

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NASA - Armstrong Flight Research Center

Introduction

- In today's cost constrained environment NASA needs a X-Plane data base and parametric cost model that can quickly provide a rough order of magnitude cost predictions for experimental aircraft.

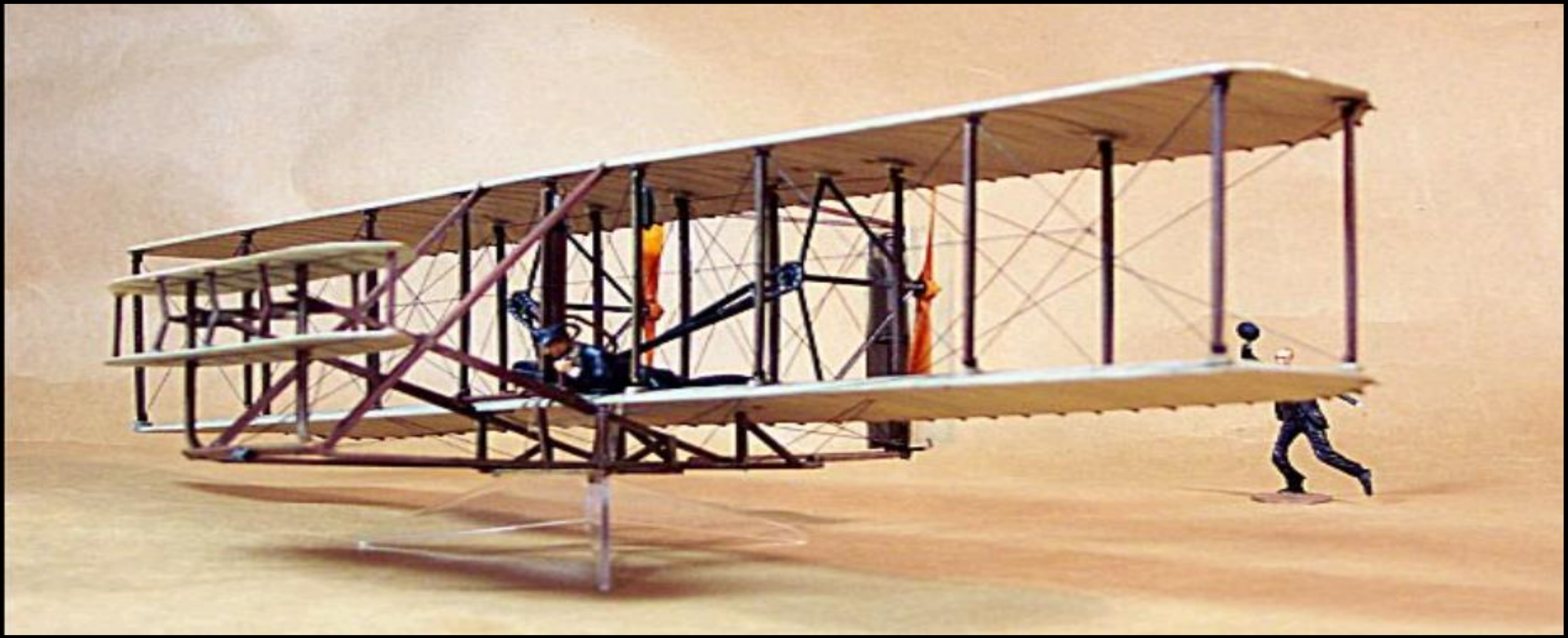
- The model should be based on critical aircraft design parameters, such as weight, size, and speed, as well as some sort of complexity factor..

- It's commonly known among cost engineering professionals, both government and industry that weight based CERs have the highest correlation.

- Last fall 2014 - the authority was given on a non-interference basis to develop an X-Plane Parametric Cost Model.

- Then early spring 2015 – I was given opportunity to hire a Summer Internship to assist in developing CERs using Regression Analysis.

Challenges in getting cost data



Throughout history every aircraft manufacturer, starting with the Wright brothers, has weighed their aircraft. The original Wright Flyer (Flyer I) weighed 604.1 pounds. A military version of the aircraft (Flyer III), capable of carrying one passenger, was procured by the Army Signal Branch for $30,000, thus establishing the first CER at $49.66 per pound.

The Story behind the X-1 Bell

I walked into work everyday for 10 years. One day I took the initiative to put my thoughts and my training into action with the question; what was the cost to design, build and fly the 1952 Bell X-1E ?

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

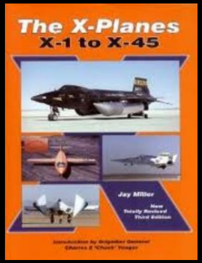
Challenges in getting cost data

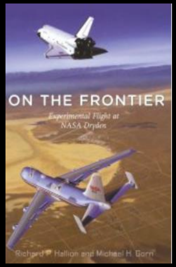
Timeline

- 1940's 50's, 60's & 70's. . . Were basically joint-funded Programs;
  - National Advisory Committee for Aeronautics (NACA)
  - National Aeronautics and Space Administration (NASA)
  - U.S. Army, and various U.S. Air Force
- Salary Dollars were paid under a different "Appropriation".
- NASA Dryden/Armstrong was under Ames until January 1994.
- Full Cost Accounting did not go into affect until 2002.
- Some Project Managers (PM) have volumes of cost data stored away in their cabinets.
  - Organized in 3-ring binders
  - Organized by burning; technical, scope, schedule, and cost data onto CDs
- NASA has a Cost Analysis Data Requirement (CADRe) for projects subject to NPR 7120.5E.
- In general, CAD and NASA Aeronautic Centers will cover CADRe for 7120.8 Research and Technology Program and Projects i.e. X-Planes.

Source of the Data

- NASA Technical Libraries
  - Armstrong's Technical Reference Library
  - Marshall Space Flight Center – Library "Redstone"
- Various publications "Books" specifically written on X-Planes
  - "The X-Planes"; written by Jay Miller
  - "On the Frontier"; written by Richard Hallion & Michael Gorn.





- Subject Matter Experts
  - Dr. Joseph Haymaker
  - 3rd Parties "Cost Research" Companies
- Government Accountability Office (GAO)
  - Various Cost Reports on X-Planes
- Industrial Partners or various Aeronautical Manufactures
  - Proprietary and "thin-slicing" the data
- Wikipedia and other "on-line" sources
  - Beware of the information and document the source, date, and URL

Hierarchal Cataloging of the data

- Some of the X-planes had three or mores sources of Cost Data
  - For Example: NASA Technical Data, GAO, Hamaker; for the same plane
  - How does the Cost Engineer know who's data is correct?
- The entire set of X-Planes parameters are now catalog in an Excel data base with a word document linked in a separate folder serving as the source document.
- Source documents are in Word format
  - **Name** of the person collecting the data
  - **Date** the source was collected
  - **URL** name 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 1 year time span.
- Hierarchy currently being used for Source Data

1.) Government Source (Technical Libraries) go first-in-line.

2.) People associated in collecting Cost for NASA or for the Government.

3.) Thin-slicing, Wikipedia and other on-line forums.

Advance Composite Materials

- Advance Composite Materials (ACM) have gone a long way since the creation of carbon fiber and epoxy.
- Hand Lay-up versus Auto-Clave composite “Sandwich” Manufacturing
  - ➢ Hand-layup - is the process were resins are impregnated by hand in the form of woven, knitted, stitched or bonded fabrics. Hand-lay up process usually accomplished by rollers or brushes and cooked in a warm “unpressured oven”, cured under standard atmospheric conditions.
  - ➢ Autoclave - eliminates voids by placing the layup within a closed mold and applying vacuum, pressure, and heat.

- ACM aircraft manufactures are replacing 30,000 or more rivets and other components that were used by earlier aircraft manufacturing processes.

Cost of using Advance Composite Materials for prototyping X-Planes

- Large and small aircraft manufactures are using Advance Composite Materials.
  - Reports are coming in with a 30% cost saving from aircraft companies using Composites rather than Aluminum and Rivets.
  - Yes, there were known problems with adhering process in the past – which now seems to be fixed.
- The current vision at NASA's Aeronautical Research Centers are to **D**esign, **B**uild and **F**ly "One-of-a kind" research X-Planes every 2 to 3 years.
- Rapid Prototyping from Design to 1st Flight is expected.
- NASA needs to build-in "concurrent system engineering" into the process including; Preliminary Design Reviews (PDRs), Critical Design Reviews (CDRs), "Air-worthiness", and Flight Readiness Reviews (FRRs)
- Eliminate the need for "Unidentified Future Expenses (UFE).

Future State

- Twin Glider Assisted Launch System (TGALS) has currently been priced using the earlier algorithms of Armstrong's Parametric Cost Model.

- Show a 2 minute conceptual flight demo video
- https://www.youtube.com/watch?v=0hEnYyykaL8

Parametric Cost Modeling

- Assumptions
  - Cost can be predicted by a few design parameters.
  - Cost includes the initial design to first flight.
- Parameters
  - Technical and performance parameters for 22 experimental aircraft
    - Dry Weight, Takeoff Weight
    - Length, Wing Span, Wing Area
    - Mach, Thrust, Speed Regime
    - Maximum Altitude, Range
    - Material, Number of Engines, Crew size
- Goal
  - Identify the best parameters
  - Develop the "best fit" R2 value greater than .80

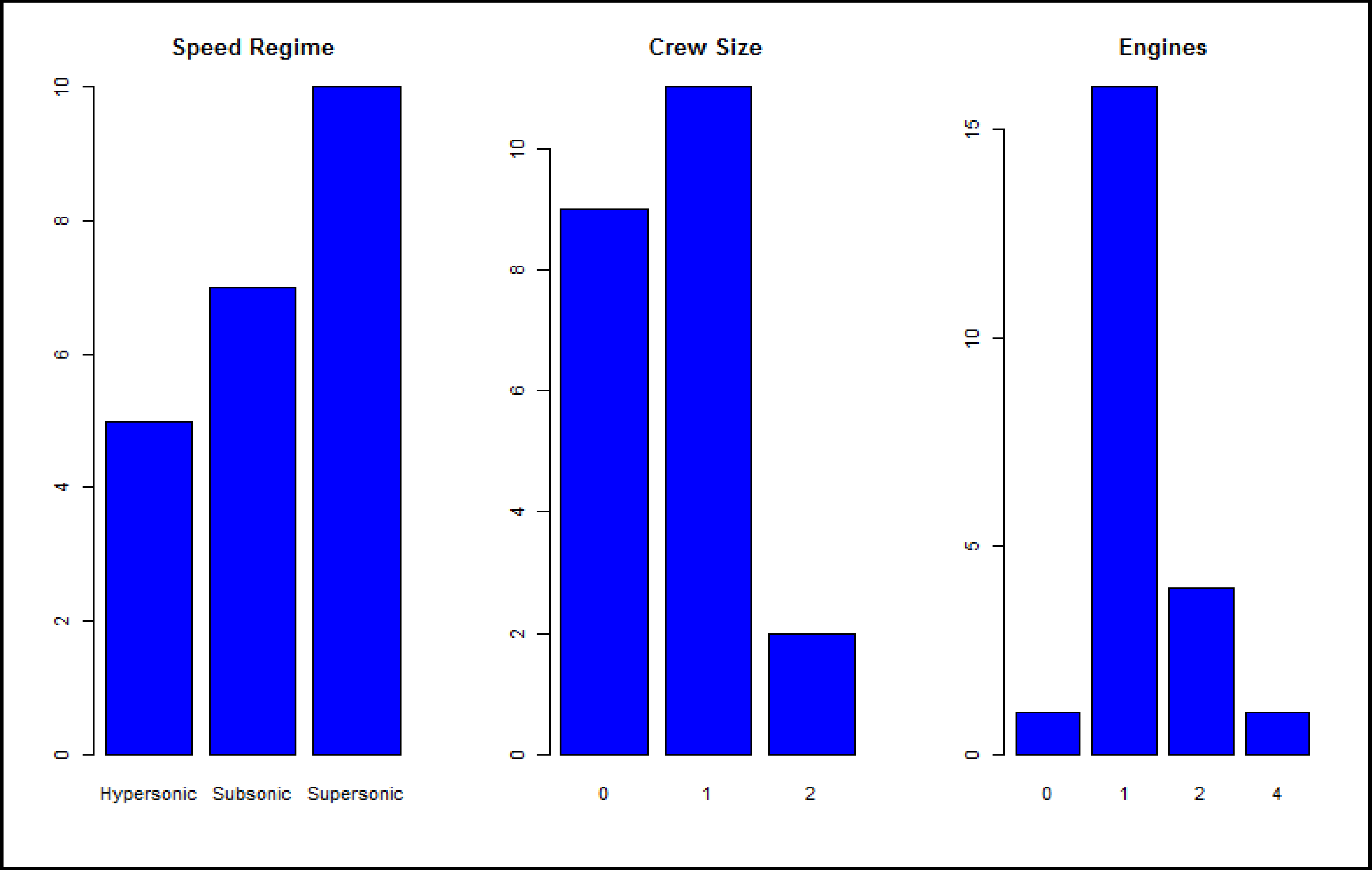
Linear Regression

- Supervised learning
- Conceptually simple
- $Y_j = \beta_0 + \beta_1 X_{1j} + \beta_2 X_{2j} + \ \ldots + \beta_n X_{nj} + \varepsilon_j$
- Assumptions
  - Expected value of Y is a linear function of the X’s
  - Unexplained variations in Y are independent and normally distributed
  - All errors in Y measurements have the same variance

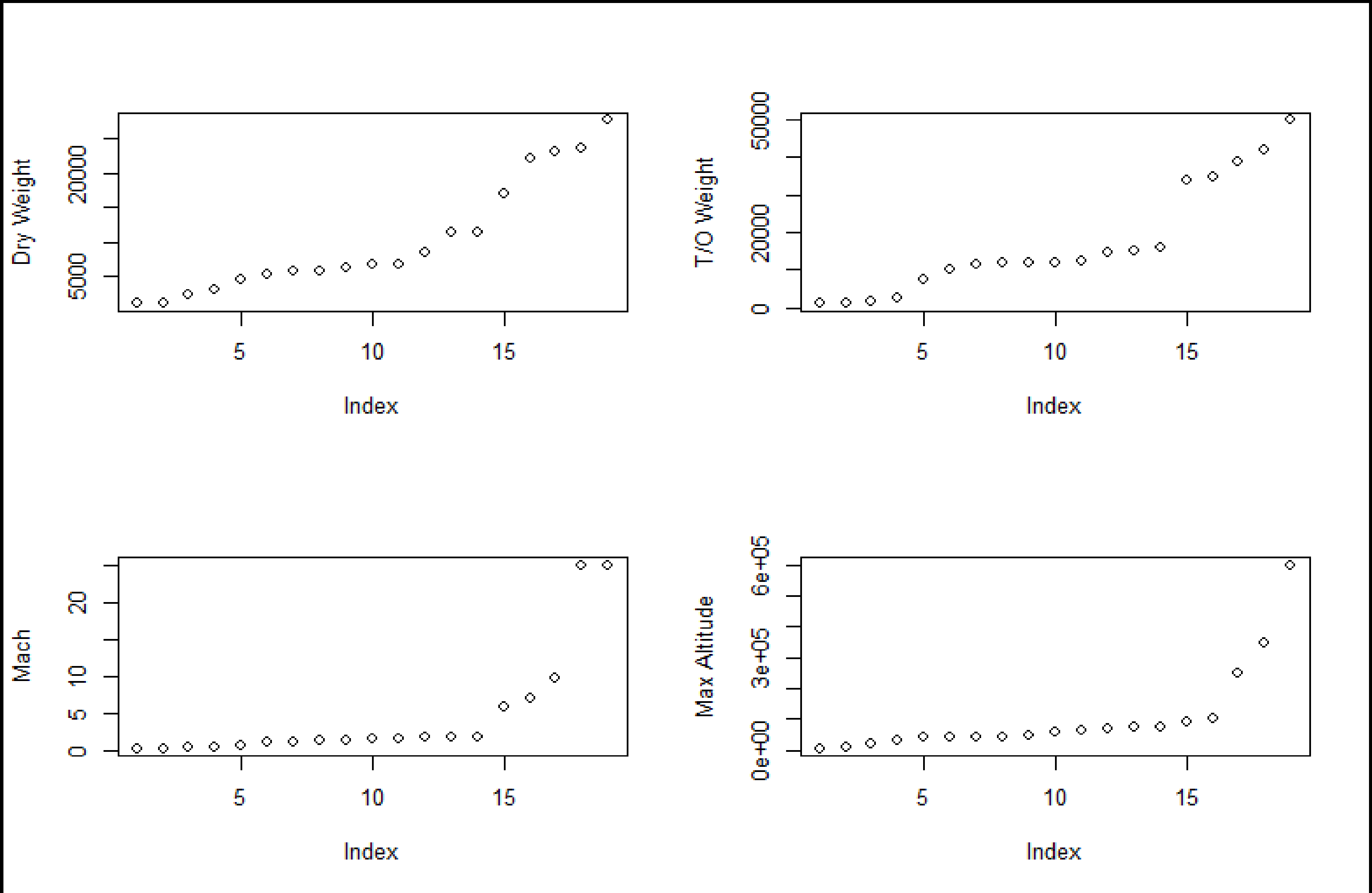
Summary of Variables

Statistic	Mean	St. Dev.	Min	Max
Cost	357.97	489.77	12	1,600
Dry.Wt	11,102.36	9,222.96	377	28,814
Length	34.56	16.86	7.42	69.25
Height	11.26	4.39	3.13	23.75
TO.Wt	17,583.54	15,296.72	480	50,000
Range	1,784.05	5,307.26	1	25,000
Max.Speed	2,284.76	4,169.56	172.50	19,030
Mach	4.12	7.17	0.23	25
Max.Altitude	94,489.54	138,593.20	5,000	599,808
Thrust	18,385.14	19,559.06	0.50	60,000
Wing.Span	23.97	18.93	0.50	77.58
Wing.Area	207.10	160.65	0.50	590

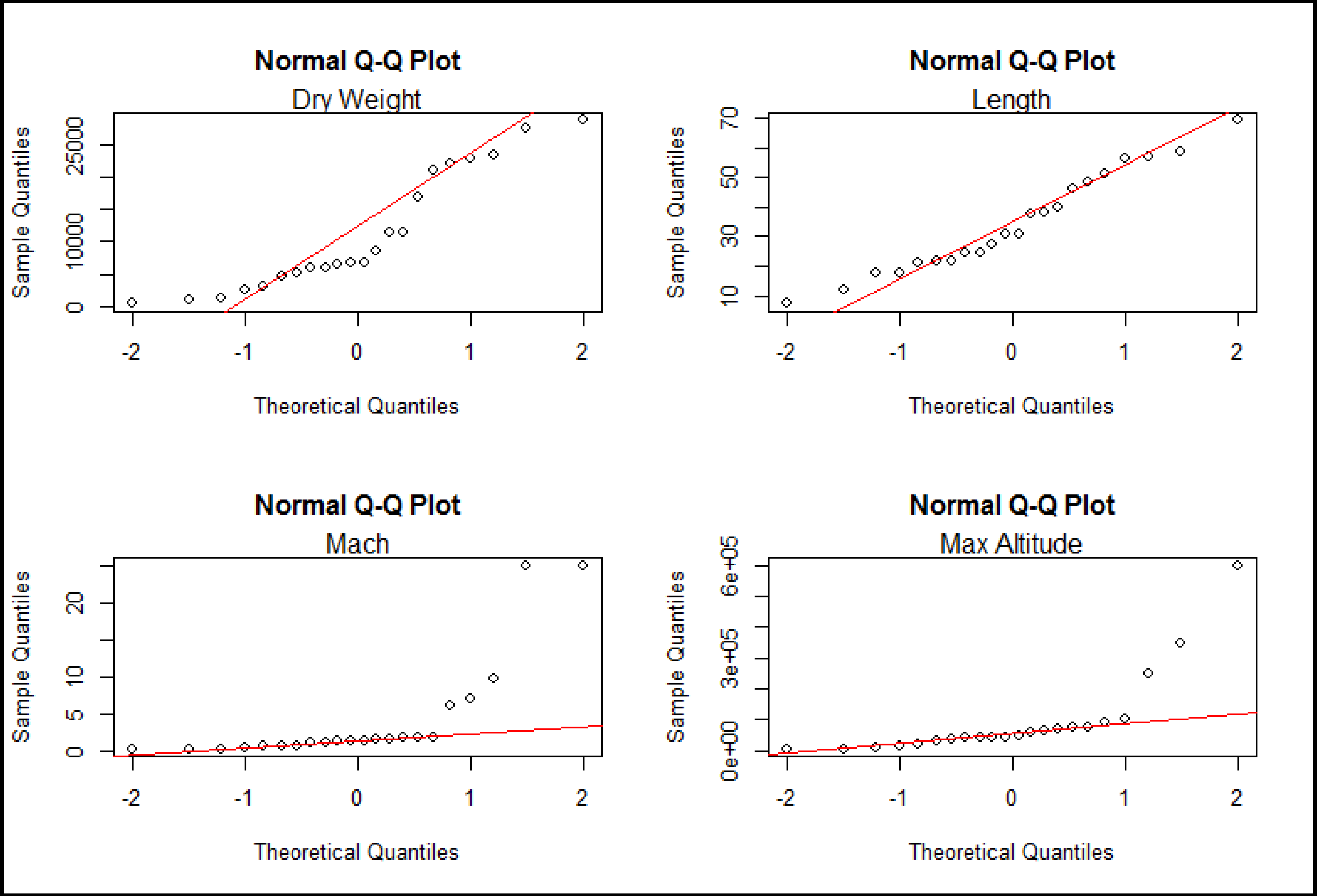
Categorical Predictors



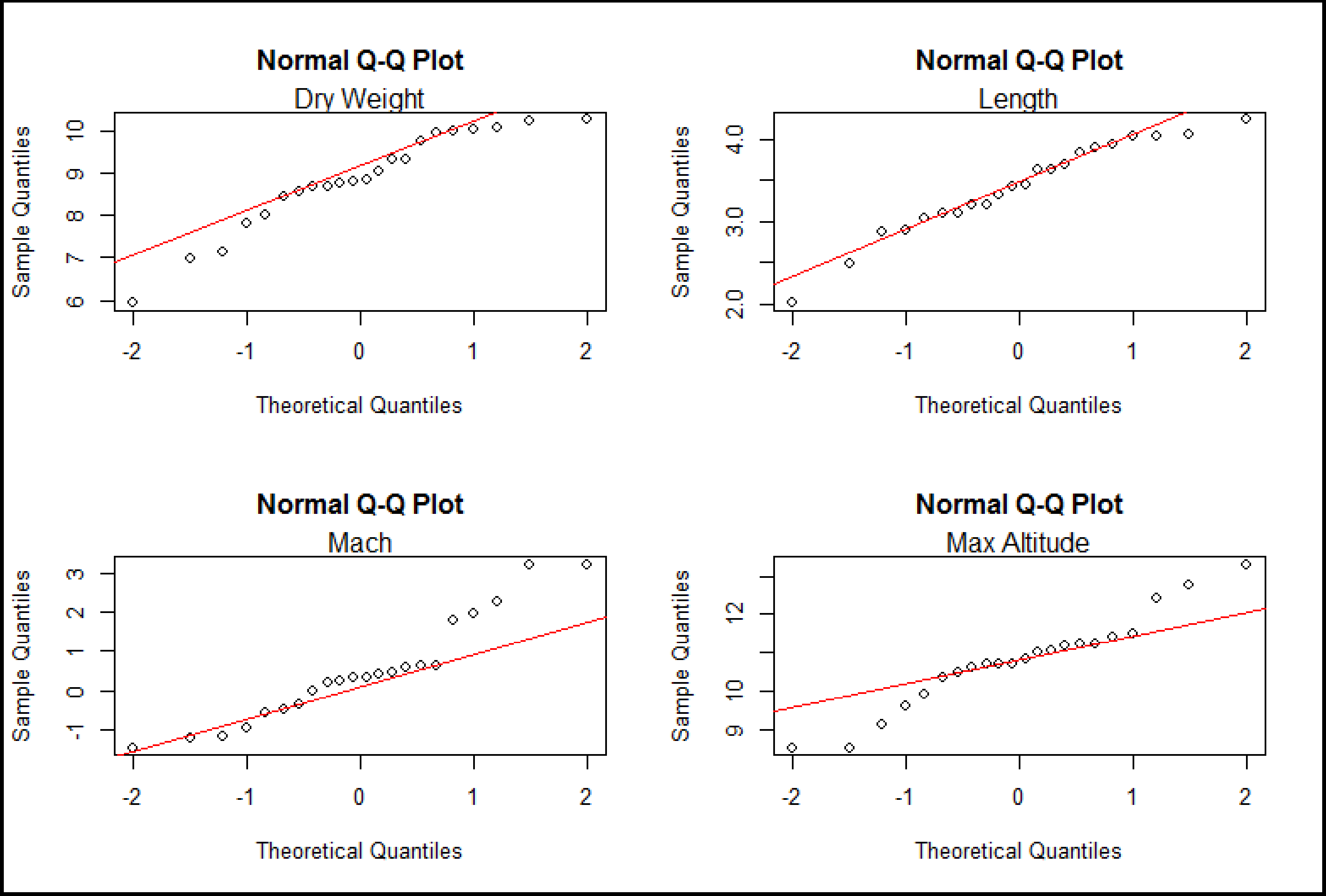
Continuous Predictors



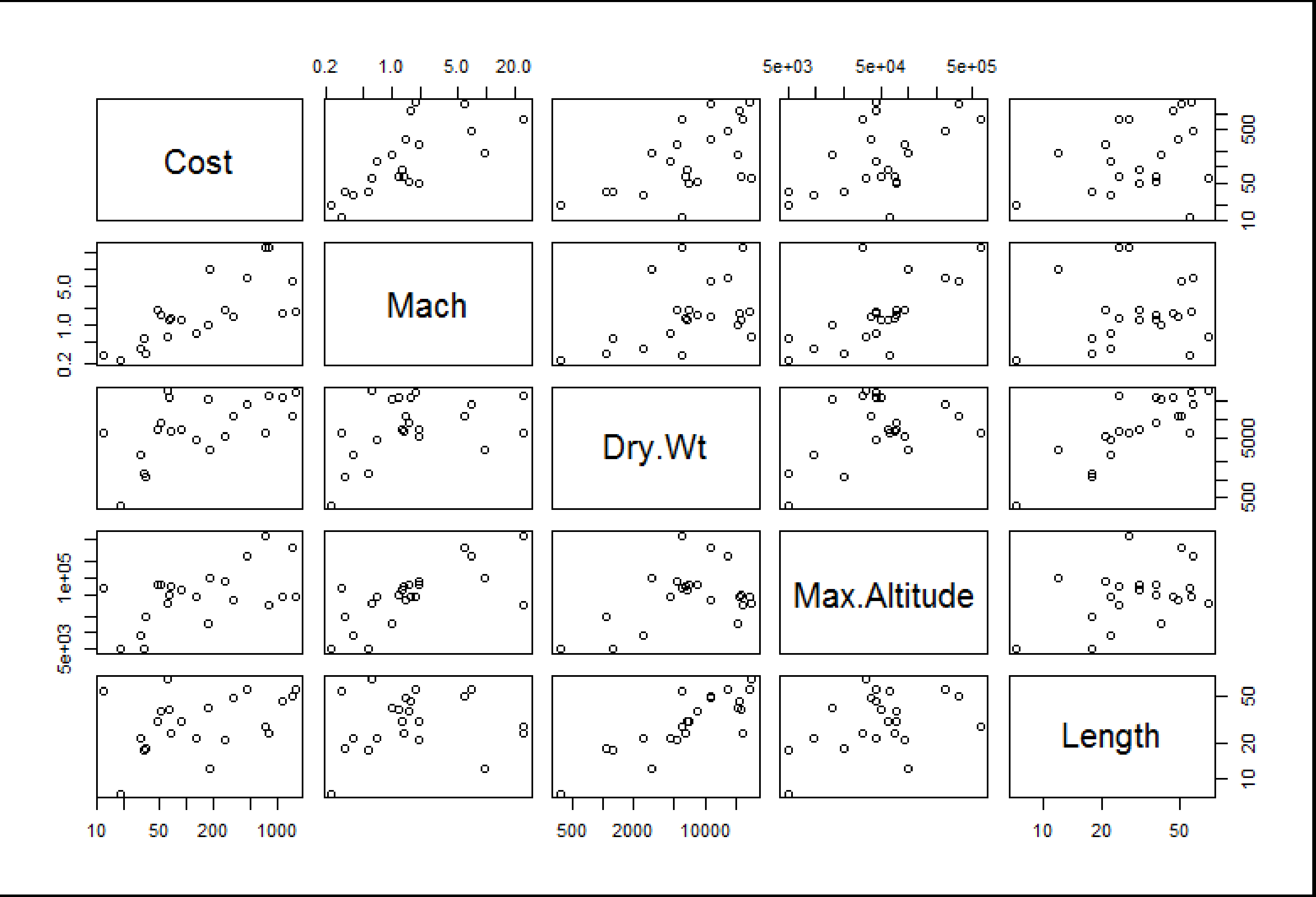
Distribution: Original Data



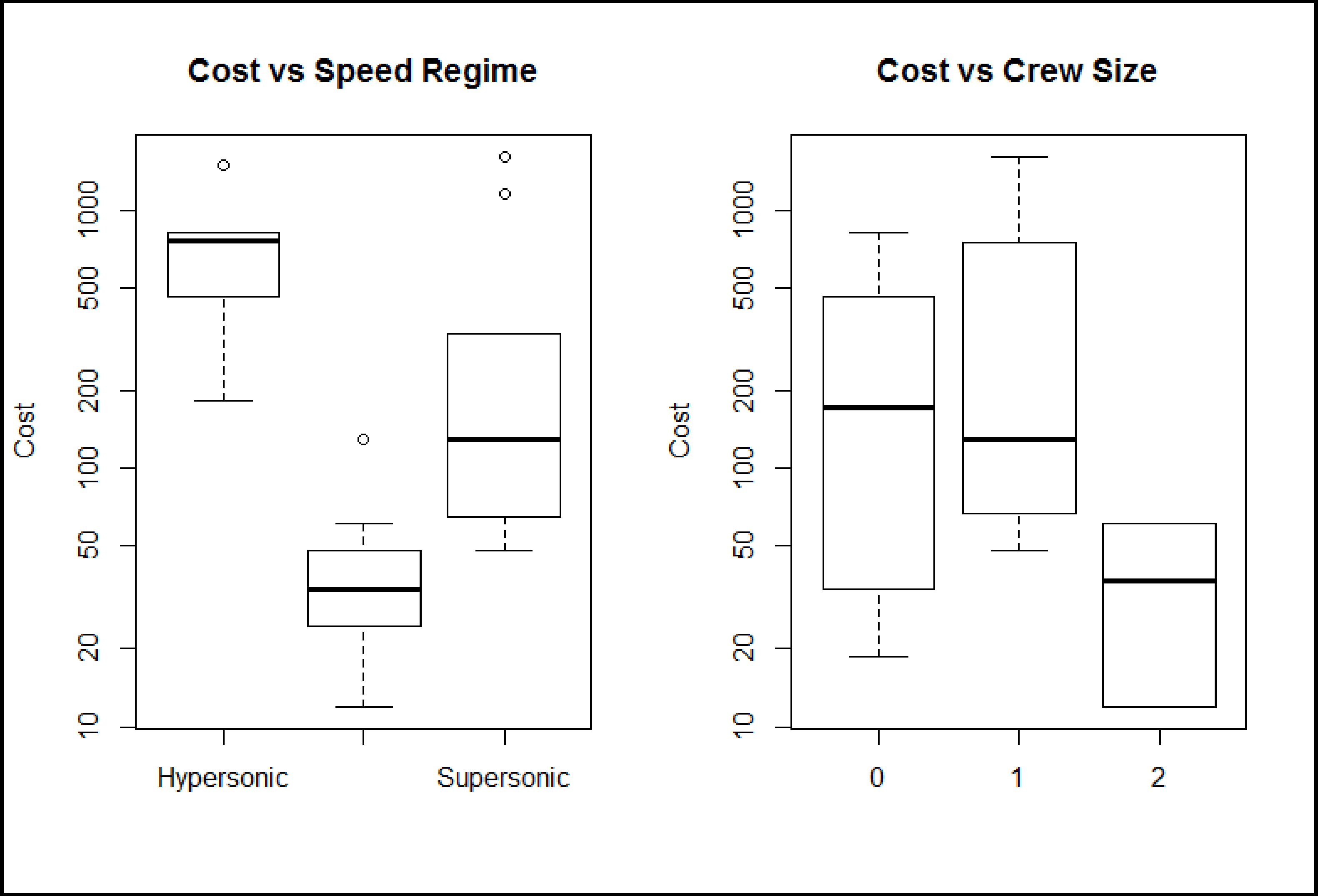
Distribution: Log-Transformed Data



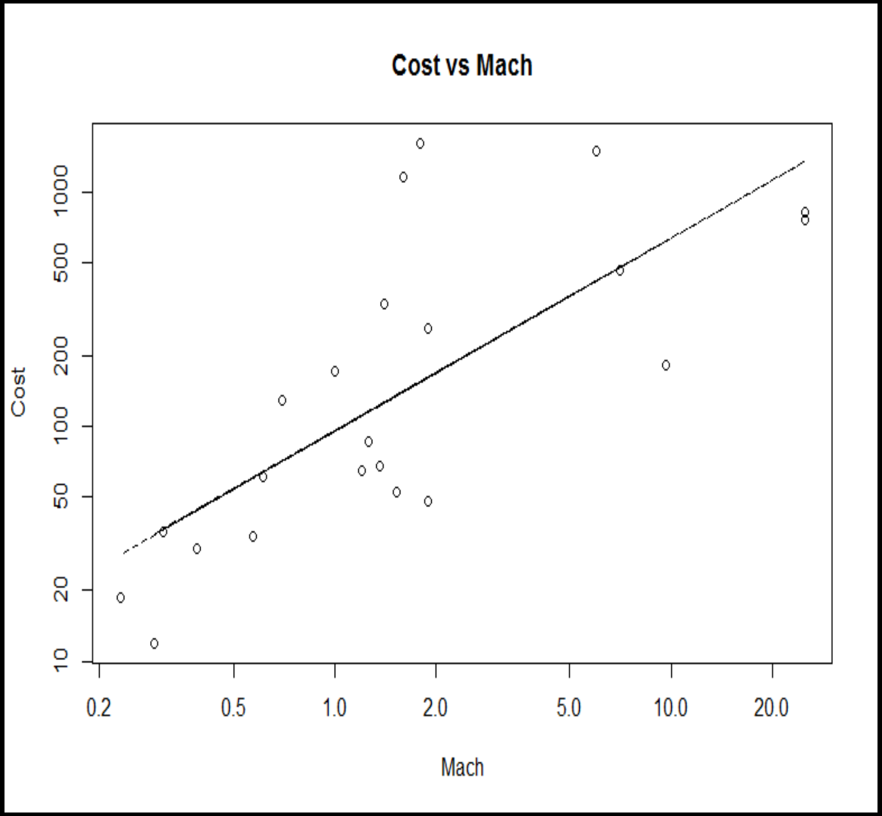
Pairwise Scatter Plots



Cost vs Categorical Predictor

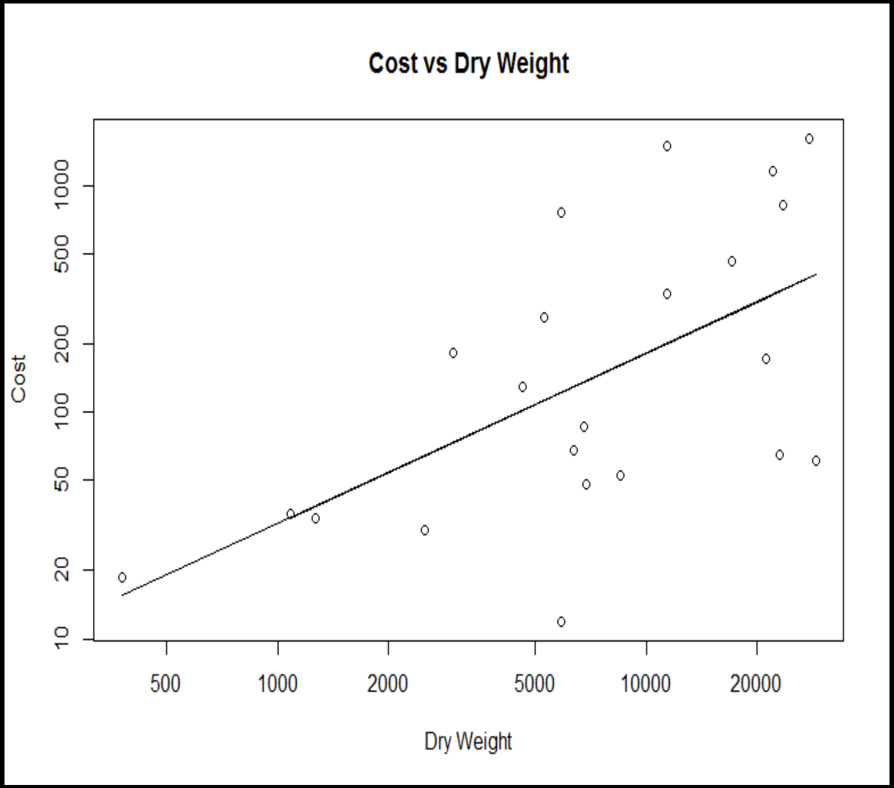


Cost vs Mach




```
Cost ~ Mach

Residuals:
    Min      1Q  Median      3Q     Max
-1.2106 -0.5649 -0.3293  0.5581  2.3363

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)   4.5592     0.2276  20.034 1.05e-14 ***
Mach          0.8205     0.1659   4.946 7.79e-05 ***
---

Residual standard error: 1.007 on 20 degrees of freedom
Multiple R-squared:  0.5501,    Adjusted R-squared:  0.5276
F-statistic: 24.46 on 1 and 20 DF,  p-value: 7.79e-05
```

Cost vs Dry Weight



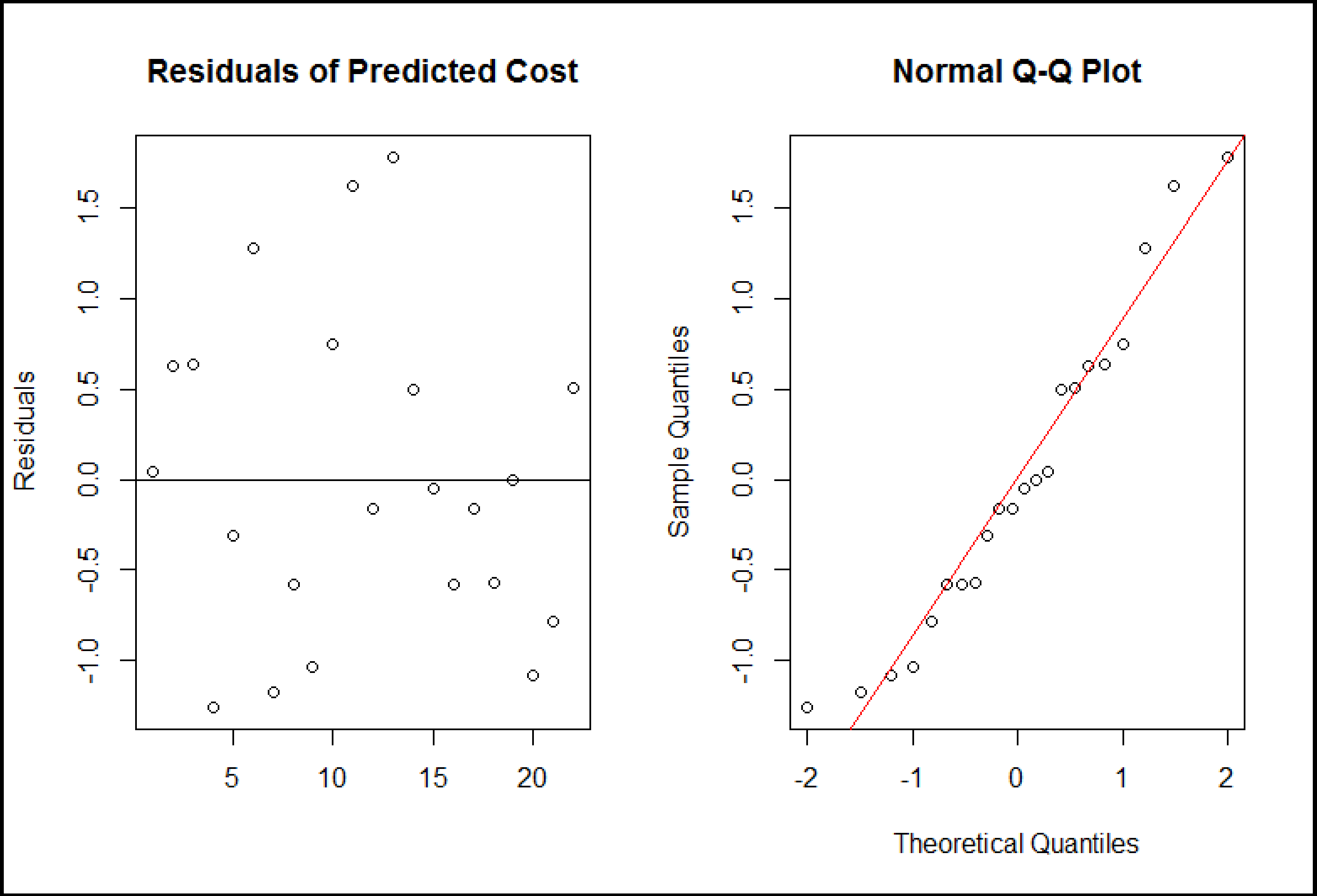

```
Cost ~ Dry.Wt

Residuals:
    Min      1Q  Median      3Q     Max
-2.3180 -0.7239  0.1129  0.8535  2.0023

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept)  -1.7177     2.0576  -0.835  0.41369
Dry.Wt        0.7516     0.2307   3.258  0.00393 **
---

Residual standard error: 1.213 on 20 degrees of freedom
Multiple R-squared:  0.3468,    Adjusted R-squared:  0.3141
F-statistic: 10.62 on 1 and 20 DF,  p-value: 0.003934
```

Multiple Regression Model

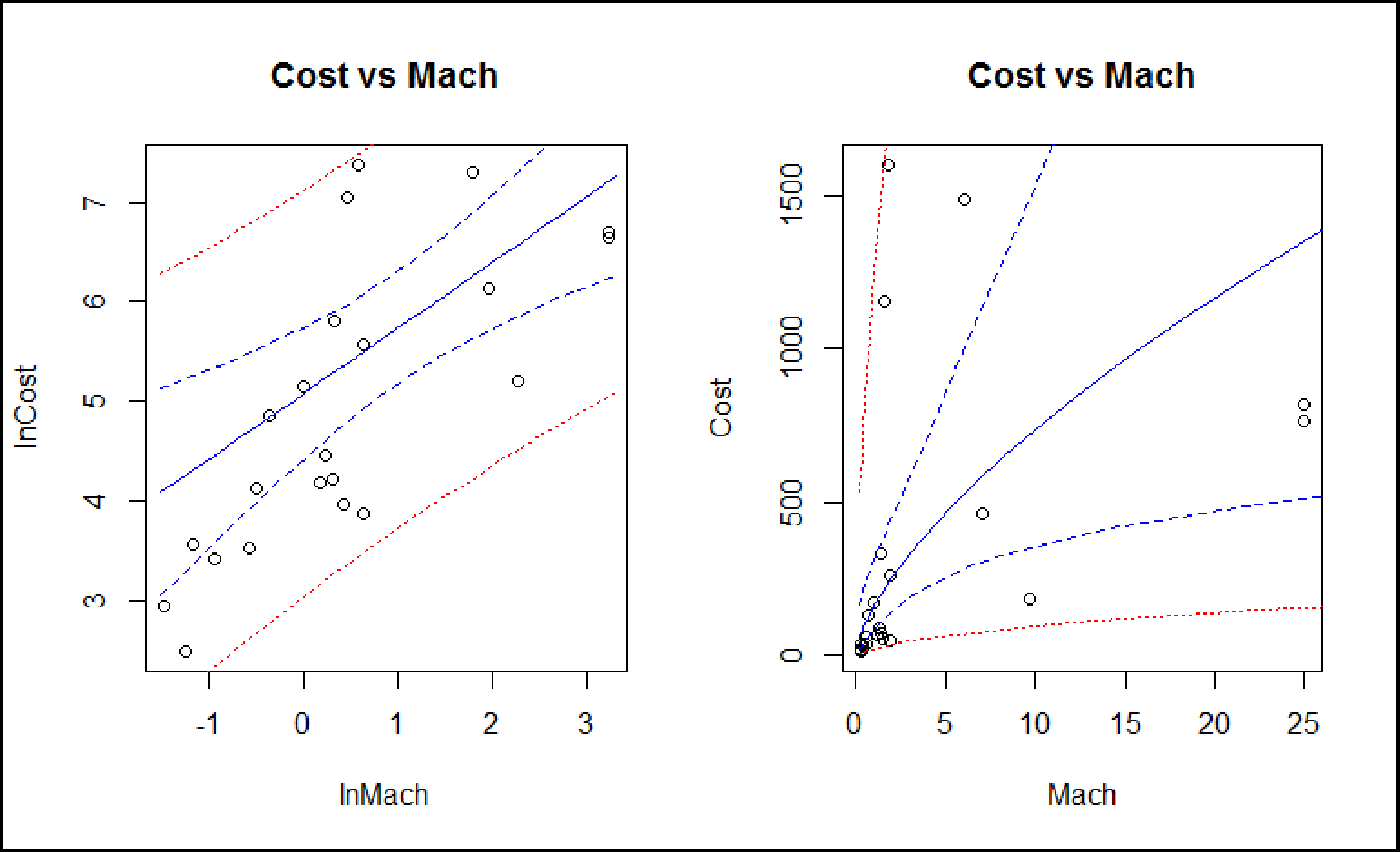
```
Cost ~ Mach + Dry.Wt

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

Model Assumptions

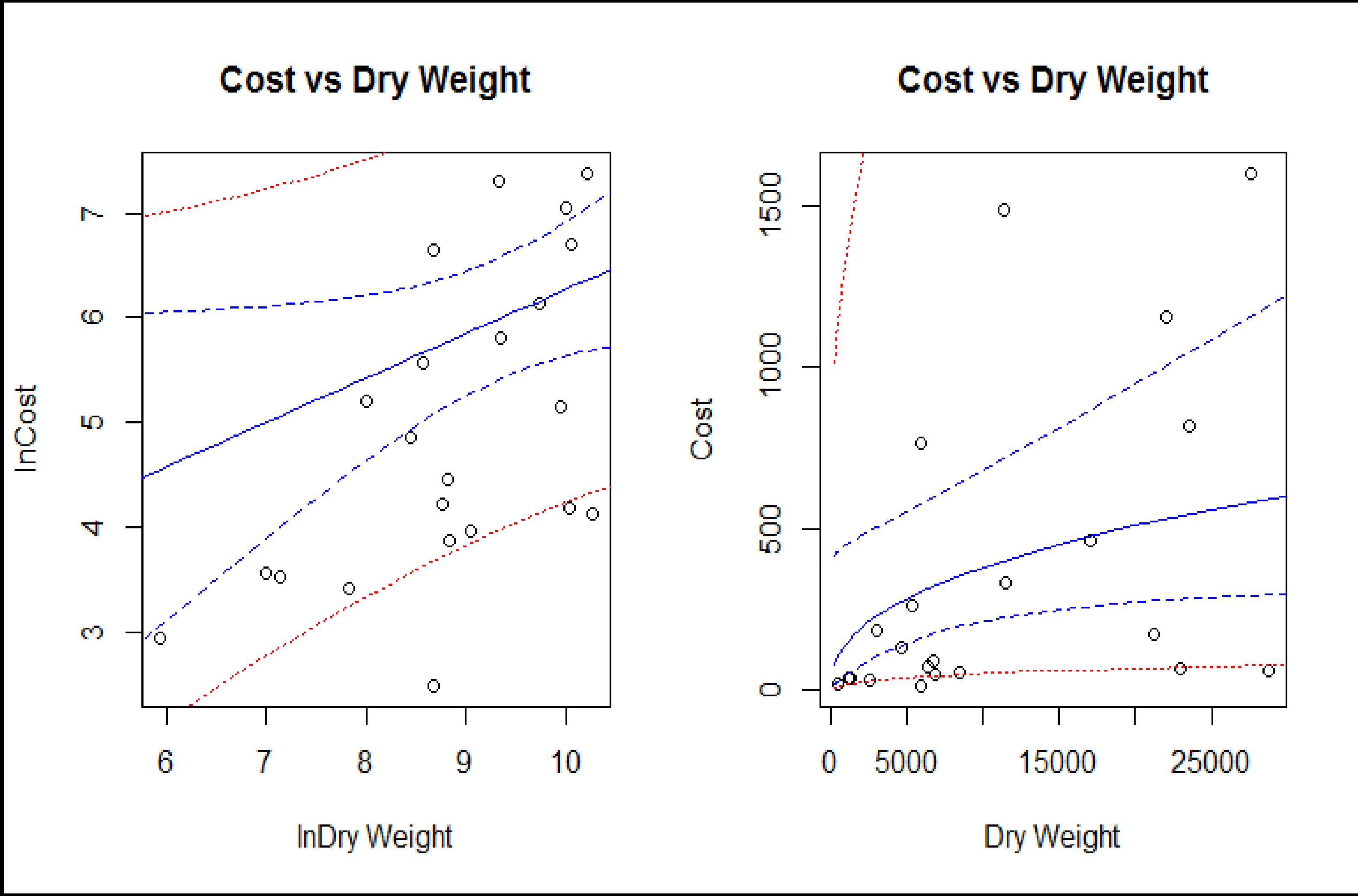


Final Model



Cost vs Mach
lnCost
lnMach
3
4
5
6
7
-1
0
1
2
3
Cost vs Mach
Cost
Mach
0
500
1000
1500
0
5
10
15
20
25

Final Model


Cost vs Dry Weight
lnCost
7
6
5
4
3
6
7
8
9
10
lnDry Weight
Cost vs Dry Weight
Cost
1500
1000
500
0
0
5000
15000
25000
Dry Weight

Future X-Planes

Table 3. Predicted Cost for Future X-Planes

Configuration	Point Estimate	Lower Estimate	Upper Estimate
HWB	251.62	96.84	653.79
ND8	159.89	76.22	335.41
TBW	164.52	82.12	329.57
LBFD	179.98	121.40	266.84

Future X-Planes and X-Wings

Summary

- Within a two-month effort the Armstrong Cost Engineering Team has gone through the full process in developing a parametric cost model.
- We have identified and collected key parameters, such as; dry weight, length, wing span, manned vs unmanned, altitude, Mach and thrust.
- We have summarized the Variables.
- We created a regression analysis on 22 CERs of the 65 X-Planes that are currently in the data base.
- We have gone through the initial stages in determining the “best fit” for R2 values.
- We have parametrically priced out several future X-Planes.
- More work needs to be done !
  - One recommendation is to stand-up a NASA Armstrong Cost Engineering Office on a non-interference basis.

Questions

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