Factors Influencing U.S. Military Fighter Jet Flyaway Costs

STAT 383 Final Project

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1 Abstract

This paper investigates the determinants influencing the flyaway costs of United States of America military fighter jets. By meticulously analyzing information about 61 U.S. military fighter jets and employing its data set of ten variables: Aircraft (name of the aircraft), FlyawayCost, FFD (First Flight Date), Year1 (years since 1943), Thrust, Climb, MTOW (Maximum TakeOff Weight), basAvionics (basic avionics - 0/1), advAvionics (advanced avionics - 0/1), and Stealth (0/1). We aim to provide a comprehensive understanding of the variables that impact the flyaway cost of the country's critical defense assets. To better understand the data, and to find answers to our research questions, linear regression and multiple linear regression models are made focusing on the flyaway cost and various explanatory variables. The results of these models yielded that Thrust and FFD are the best independent predictors of flyaway cost, while the categorical variables basAvionics, advAvionics, and Stealth have little to no correlation to the cost. Furthermore, the most accurate prediction model made was the multiple linear regression model using the variables Thrust and FFD obtaining an adjusted R^2 value of 0.9415.

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2 Introduction

After World War II ended in 1944, the aviation industry became dominated by the 'Jet Age' (1945 - 1979) and major advancements in aviation technology, especially within the military, took place during this period [1]. These advancements not only gave rise to increased fighting capabilities of the United States military, but also to the cost it takes to fly these aircraft. Based on the research article "Technological change in U.S. jet fighter aircraft" we now know that the cost escalation of fighter jets is largely due to the increasing performance of these jets[3]. But what variables associated with military fighter jets' performance have the largest impact on the cost of flying these jets? Is the maximum takeoff weight the biggest driving factor of price? Are the jets classified as stealth more expensive to fly? These are the questions that we hope to answer in this report, based on information about 61 U.S. military jet fighters during and beyond the Jet Age.

3 Literature Review

RAND conducted research sponsored by the United States Air Force, tasked with investigating military jet engine acquisition [5]. The objective was to provide updated methodologies for estimating the costs and development time of military jet engines; while also addressing the growing importance of affordability in weapon systems for policymakers in the Department of Defense and the U.S. Congress. Through statistical analysis, RAND examined various factors, including performance, programmatic elements, and technology parameters affecting development and production costs. Utilizing least-squares regression methods, RAND established parametric relationships to forecast future military turbofan engine program costs, development times, and production expenses. Besides the commonality of using a regression model to evaluate cost, in their 'COMPONENT AND RELATED TECHNICAL ADVANCEMENTS' section, RAND highlighted the ongoing impact of technological improvements on military jet engine life-cycle costs. Recognizing the trade-off between enhanced performance and increased costs, the Department of Defense aims to mitigate life cycle costs while maintaining improved engine capabilities.

The article "The Evolution of Military Aircraft Technology: From Propellers to Stealth" by AVI-8 speaks to the different eras of military jets, their improvements in technology and overall capabilities, and how they contributed to the defense of nations around the world [4]. This article is included in this review because it speaks to the technological changes in jets over time. The four major eras identified are 'The Early Days of Military Aviation,' 'The Rise of Propeller-Driven Fighters,' 'The Introduction of Jet-Powered Aircraft,' and 'The Age of Stealth'. The advancements in flight technology, weapons systems, and the engine itself are evident when we look at what the aircraft offered, from the initial propeller-driven biplanes to stealthy fighters.

Looking at another report done by RAND for 'Project Air Force", sponsored by the United States Navy and Air Force [2]. Published in 2008, the report delves into the issue of cost escalation in various types of military fixed-wing aircraft, surpassing commonly used inflation indices such as the Consumer Price Index, the Department of Defense procurement deflator, and the Gross Domestic Product deflator. It investigates the root causes behind the long-term unit cost escalation associated with military aircraft, considering both economy-driven factors beyond the control of the Services and customer-driven factors within their control. These cost increases primarily stem from the pursuit of enhanced capabilities and are anticipated to persist, posing significant challenges to aircraft inventories, especially within the constraints of relatively fixed defense investment budgets. The report highlights a decline in aircraft procurement rates, even during peak funding periods, when compared to previous decades, as revealed through their data analysis.

4 Methodology

This section reviews the materials used throughout the project and examines the statistical processes used to gather results. Our materials are derived from a single data set, originating from a similar study done on the technological change in U.S. fighter jets over time [3]. Furthermore, we use code written in R to run regression models to get results from our data.

4.1 Materials

As stated previously, the data set this project uses is from the paper "Technological change in U.S. jet fighter aircraft" [3]. This set includes our dependent variable, flyaway cost, and eight explanatory variables. Each variable in the data set is expressed as a logarithm, except for the dummy variables. The logarithmic nature of these variables allows for more insightful regression models and shows the linear relationships amongst otherwise exponential data. A description of these variables can be found in Table 1.

Variables	Mean	Min.	Max.
flyaway cost (current dollars)	14.50	11.45	18.96
Thrust (pounds)	9.662	8.294	11.156
Climb rate (feet per minute)	9.929	8.234	11.290
MTOW (pounds)	10.179	9.202	11.324
Basic avionics	0.2295	-	-
Advanced avionics	0.1967	-	-
Stealth	0.03279	-	-
First flight date (year)	-	-	-

Table 1: General description of variables

4.2 Process

To find the correlation between the explanatory variables and flyaway cost, this paper calculates a variety of regression models. These models are all built using an original program coded in R. This program calculates a linear regression model for each variable containing high correlation, as well as a few multiple linear regression models in order to obtain the most accurate prediction model for flyaway cost. These models allow us to compare the statistical significance and percent dependence of each explanatory variable in the context of flyaway cost.

5 Results

5.1 Statistical Overview

To address our research questions, we adopted a dual statistical approach. Initially, we created linear regression models to explore the correlation between certain explanatory variables and the flyaway cost. Subsequently, we conducted two multiple linear regressions, one with all 4 correlated explanatory variables: Thrust, Climb, MTOW, and FFD, and the other with Thrust and FFD. These models are used to analyze their collective impact on the flyaway cost. For both regressions, we will present the coefficients and their values, as well as the correlations between variables.

5.2 Linear Regression Results

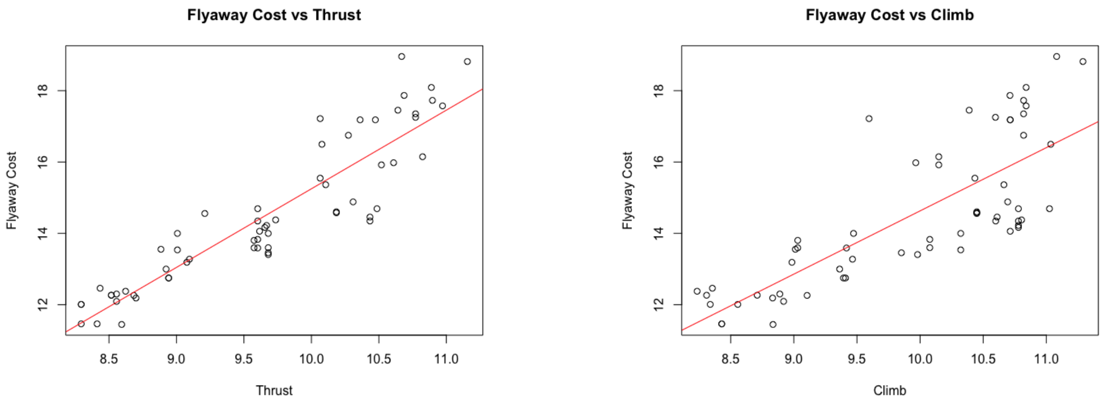
The numerical results of the linear regression models can be found in Table 2. We decided to neglect the categorical variables basAvionics, advAvionics, and Stealth due to a lack of correlation when compared to other explanatory variables. Each categorical variable contained a R^2 value less than .5, which is not a high enough correlation given a data set with low variability. These R^2 values can be found in Table 3.

Variables	Std. Error	P-value	R^2
Thrust	0.1284	<2e-16	0.8333
Climb rate	0.1812	5.75e-14	0.6188
MTOW	0.2891	3.73e-14	0.6243
First flight date	6.772e-03	<2e-16	0.8333

Table 2: Linear regression between explanatory variables and flyaway cost

Variables	R^2
Basic Avionics	0.00876
Advanced Avionics	0.4886
Stealth	0.161

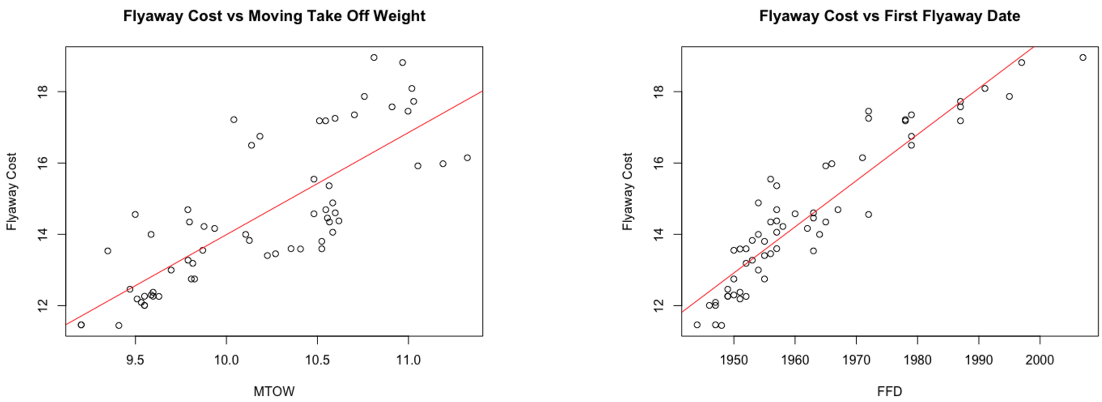
Table 3: R^2 values of categorical variables: basAvionics, advAvionics, and Stealth



(a) Best fit line for Cost Vs. Thrust

(b) Best fit line for Cost Vs. Climb

Figure 1: Linear regression best fit lines for thrust and climb versus flyaway cost



(a) Best fit line for Cost Vs. MTOW

(b) Best fit line for Cost Vs. First Flight Date

Figure 2: Linear regression best fit lines for MTOW and FFD versus flyaway cost

The linear regression plots can be found in Figures 1 & 2. Visually, it is clear that there is a strong correlation between each of the four independent explanatory variables and jet flyaway cost, especially for Thrust and FFD.

5.3 Multiple Linear Regression Results

The data summary for the first multiple linear regression is shown in Table 4. This regression presents the relationship between the four chosen explanatory variables: Thrust, Climb, MTOW, and FFD. The data summary for the second linear regression is shown

Variables	Est. coefficient	Std. error	t-value	p-value
Thrust	1.190	3.595e-1	3.311	0.00163
Climb	-4.213e-2	1.501e-1	-0.281	0.77997
MTOW	-1.319e-2	3.565e-1	-0.037	0.97062
FFD	7.687e-2	7.92e-3	9.698	1.37e-13
Adjusted R-squared value	0.9395			

Table 4: Multiple linear regression for all explanatory variables modeling flyaway Cost

Variables	Est. coefficient	Std. error	t-value	p-value
Thrust	1.148	1.249e-1	9.191	6.43e-13
FFD	7.662e-2	7.212e-3	10.624	3.14e-15
Adjusted R-squared value	0.9415			

Table 5: Multiple linear regression for Thrust and FFD modeling flyaway Cost

in Table 5. This regression only focuses on two of the four variables included in the initial linear regression: Thrust and FFD. We again decided to omit basAvionics, advAvionics, and Stealth in our regressions due to the lack of correlation with flyaway cost. The additional multiple linear regression analysis was performed to demonstrate and verify the significant relationship between Thrust and FFD. Figure 3 shows the residual plot for the initial multiple linear regression. Additionally, Figure 4 shows the Quantile-Quantile (Q-Q) plot and Figure 5 shows the Density plot, both hinting at a normal distribution of the data.

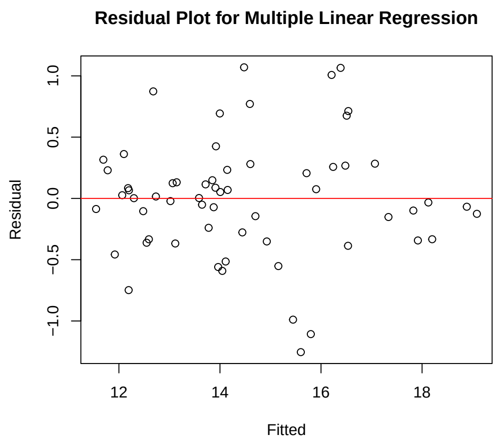


Figure 3: Residual plot for the multiple linear regression

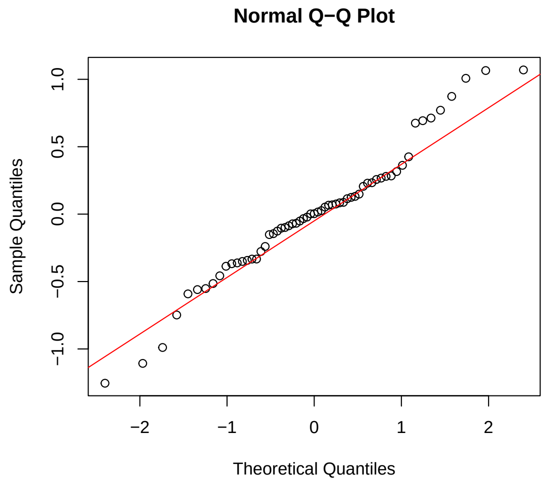


Figure 4: Normal Q-Q plot for the MLR

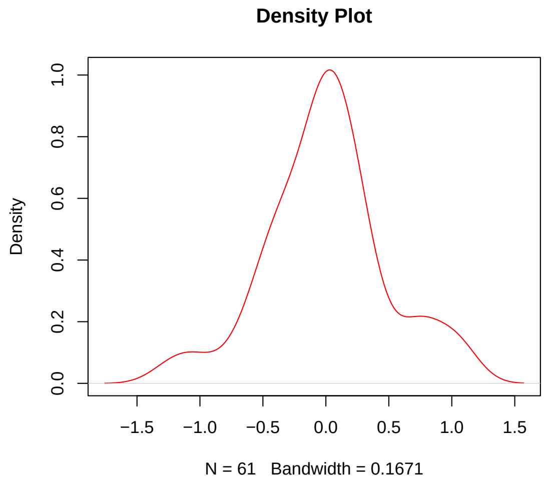


Figure 5: Density plot for the MLR

6 Discussion

6.1 Linear Regression Analysis

Looking at the plethora of linear regression models, many relationships between the explanatory variables and flyaway cost can be explained. To start, it is clear that each of the four tested explanatory variables correlates with the flyaway cost (Table 2, Figures 1 & 2), this is because they all have very small p-values ($p < 10^{-13}$), and each has an R^2 value greater than 0.6. This means the correlations are statistically significant, and the flyaway cost is dependent on each variable, yet some variables are better predictors than others. Notably, both Thrust and FFD have near 0 p-values, with R^2 values above 80%, making these two variables the best independent predictors out of the data set.

It was also found that the categorical variables relating to the type of onboard jet technology had little correlation to the flyaway cost (as seen in Table 3). This lack of correlation could be due to a lack of substantial data regarding the three categorical variables. Out of our sample of 61 fighter jets, only 27 had a value for one of the three categorical variables. An updated data set that contains more values for these variables might lead to a better insight into their correlation to flyaway cost.

Overall, through the linear regression models, we found that Thrust and FFD are the best independent predictors of flyaway cost, and flyaway cost depends the most on these two variables. Furthermore, the categorical variables basAvionics, advAvionics, and Stealth have a weak correlation to the flyaway cost shown by their low R^2 values. Lastly, Climb is the worst statistically significant predictor of the four correlated explanatory variables.

6.2 Multiple Linear Regression Analysis

Shifting the focus to the multiple linear regression models, the most optimized prediction models are found. The first multiple linear regression model we built included all four correlated explanatory variables: Thrust, Climb, MTOW, and FFD (Table 4). This led to a good prediction model with an adjusted R^2 value of 0.9395. However, Climb and MTOW have relatively large p-values in the model, especially when compared to variables Thrust and FFD. Due to this, we created the second multiple regression model omitting Climb and MTOW (Table 5) and obtained the highest adjusted R^2 value of 0.9415. Furthermore, the p-values of Thrust and FFD in this model are both very small, confirming this model is the most accurate in predicting military jet flyaway cost. One can also note that the estimated coefficient of Thrust is much larger than that of FFD. This shows that an increase in thrust power has a much more significant impact on the flyaway cost than a later first flight date of the jet in question.

The dispersion of the data points around the horizontal line (0,0) in the residual plot (Figure 3) shows that the multiple linear regression analysis is a good fit for the data. The Q-Q plot in Figure 4 shows that most data points align with the diagonal. This indicates that the data could be approximately normally distributed. Further, the density plot in Figure 5 also shows the data to have an approximately normal distribution. These facts verify that the use of the two multiple linear regressions in this analysis is a good fit for the dataset.

It is important to note that thrust power is a benchmark of a physical property of the jets, while First Flight Date is a temporal function. Given this, the trend of a higher flyaway cost at a later first flight date ultimately means that newer jets are more expensive. This leads to a limitation of our study, which is the fact that we do not account for inflation or economic status over the years in our data set. Therefore, the correlation between First Flight Date and FlyawayCost can be explained, in part, by factors such as inflation as time goes on. Regardless, the most accurate regression model includes only Thrust and FFD. The equation for this regression is found below.

$$y = -146.9 + 1.148\beta_0 + 0.07662\beta_1 \tag{1}$$

This equation allows us to predict flyaway cost values not included in our data set with high degrees of accuracy. The y-value is the predicted flyaway cost while β_0 is the thrust power, and β_1 is the FFD.

7 Conclusion

In this paper, we evaluated a data set that includes information about 62 U.S. military fighter jets and the factors contributing to the rise in flyaway costs. Through numerous linear and multiple linear regressions, we concluded that Thrust and First Flight Date (FFD) have the biggest impact on the increasing costs of these jets, the three categories variables (basAvionics, advAvionics, and Stealth) have a weak correlation to the flyaway cost, and that Climb is the worst predictor of the flyaway cost. These results indicate that newer technologies and advancements in the aircraft industry contribute to higher production costs. Secondary variables such as Climb and Maximum Takeoff Weight (MTOW) had a similar but lesser effect on the flyaway costs, which displays the complex relationships between these variables and the response variable.

Limitations of this study include the nature of our data set. While the data set served as a strong foundation for our analysis, it should be noted that its scope is limited, concluding in 2007. Given the years since and the rapid technological advancement in the aircraft industry, our study might benefit from an updated and expanded data set. Additionally, factors not assessed in this study, such as inflation and political and global economic conditions, may warrant future exploratory research.

8 Data Availability Statement

The data set and code used in this study can be found publicly at:
`https://github.com/dalesj204/fighter_jet_costs.git`

9 Author Contributions

- RQ: writing, coding, analysis, formatting.
- JD: writing, editing, reviewing, coding, analysis.
- AJ: writing, review, editing, research.

All authors contributed to the article and approved the submitted version.

References

[1] Apr. 2023. URL: https://en.wikipedia.org/w/index.php?title=Post-war_aviation&oldid=1151451677.

[2] Mark V Arena et al. "Why has the cost of fixed-wing aircraft risen? a macroscopic examination of the trends in us military aircraft costs over the past several decades". In: *DTIC Document* (2008).

[3] Aneli Bongers and Jose L. Torres. "Technological change in U.S. jet fighter aircraft". In: *Research Policy* 43.9 (2014), pp. 1570–1581. ISSN: 0048-7333. DOI: https://doi.org/10.1016/j.respol.2014.03.009. URL: https://www.sciencedirect.com/science/article/pii/S0048733314000481.

[4] *The Evolution of Military Aircraft Technology: From Propellers to Stealth*. URL: https://avi-8.com/blogs/the-aviation-journal/the-evolution-of-military-aircraft-technology-from-propellers-to-stealth.

[5] Obaid Younossi et al. *Military jet engine acquisition: technology basics and cost-estimating methodology*. Rand, 2002.