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Price vs. Performance: The Value of Next Generation Fighter Aircraft

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PRICE VS. PERFORMANCE:

THE VALUE OF NEXT GENERATION FIGHTER AIRCRAFT

THESIS

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Abstract

The United States Department of Defense (DoD) is currently recapitalizing its aging fighter aircraft inventory with the F-22A and F-35. While the DoD may consider cost and performance issues, it does not use a quantitative model that effectively measures the tradeoffs between the two. This thesis constructs a hedonic model of the fighter aircraft market to measure the implicit price on fighter performance characteristics and specifically applies it to next-generation aircraft.

Data from 50 aircraft from 1949-present were used to construct two models – one based on procurement costs and one based on research, design, test, and evaluation (RDT&E) costs. The models, based on a linear Box-Cox transformation, demonstrated that the unique F-22A trait, the ability to super-cruise, has the highest per-unit implicit price ($68.5M), followed by the stealth technology ($58.7M) and large-scale integrated circuitry ($55.3M). The high marginal value for the super-cruise trait implies that, depending on how super-cruise is used operationally, the F-35A may be a more effective purchase in terms of resource allocation than the F-22A.

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I. Introduction

The U.S. Department of Defense (DoD) periodically recapitalizes its equipment, and aging aircraft are no different. Conceptually, the aircraft modernization decision can be divided into two schools of thought: modernization based on financial criteria and modernization based on operational criteria. Often, financial criteria (such as increasing life-cycle costs) drive the recapitalization of support aircraft, as several RAND studies indicate (Victoria A. Greenfield and David M. Persselin 2002;Edward G. Keating and Matthew Dixon 2003) . Operational replacement models – typically for fighter or bomber aircraft – depend more on technological upgrades and increased performance characteristics. However, the DoD still operates with a limited budget, and must still account for costs and weigh tradeoffs of these aircraft. Currently, no framework exists within the DoD for evaluating cost and performance trade-offs between major weapon systems. This paper proposes to create such a framework for evaluating costs and performance, and specifically apply it to the US fighter aircraft market.

The current state of the US fighter aircraft market presents a unique opportunity to apply this model. The US Air Force is upgrading its fleet to include a new air superiority fighter, the F-22A, as well as a new multi-role fighter, the F-35A. Critics have contended the F-22A is overly expensive, and some of its performance attributes can be found in the less expensive F-35 (Jim Winchester 2004). No empirical models exists that weigh price versus capabilities, so decision makers do not have a quantitative framework to make the optimal modernization decision.

One possible method to evaluate costs and performance is a hedonic price model. This model, formalized theoretically by Sherwin Rosen (1974), assumes different heterogeneous goods are composed of bundles of characteristics, and it is the supply and demand of these characteristics that ultimately determine the price of a good (Mark Dickie, Charles Delorme, and Jeffrey Humphries 1997). These models are built with aggregate data for a given market. To evaluate the cost and performance tradeoffs of the F-22A and F-35, two hedonic models will be constructed – one valuing the characteristics based on procurement costs and one based on research and development costs. This technique illustrates the implicit price the United States Government places on attributes, thus creating a framework to assess value and capabilities.

The fighter aircraft hedonic models include several different categories of variables. Aircraft procurement costs and research, design, test, and evaluation (RDT&E) costs are used for aircraft cost data. The performance variables are divided into two general categories – traditional performance variables (e.g., speed) and next generation variables (e.g., stealth technologies). The traditional performance variables include characteristics like speed and range that previous researchers such as Robert Morehead (1973) and Jenny Herald (2006) have included in similar models. The next generation variables include characteristics such as stealth and radar advancements that subject matter experts such as Thomas Hampton (1998) and Loren Thompson (2004) have identified as important.

This report is organized as follows: Section 2 summarizes the current literature on the subject, including the current decision-making framework, a discussion of hedonic modeling, and the rationale for selecting independent variables in the model. Section 3 describes the data and coding procedures. Section 4 presents the model results, while Section 5 discusses implications of the results and any conclusions that can be drawn about current DoD recapitalization initiatives pertaining to fighter aircraft.

II. Literature Review

As noted, this paper creates a hedonic framework to evaluate costs and performance of the US fighter aircraft market to help in procurement and modernization decisions. To establish the appropriate conceptual context, the following section analyzes relevant literature on several issues. First, the paper details how the Department of Defense currently makes modernization decisions. Then, it examines the concepts behind a hedonic model and how the model applies to the F-22A and F-35. Finally, it discusses what characteristics will be included in this particular model.

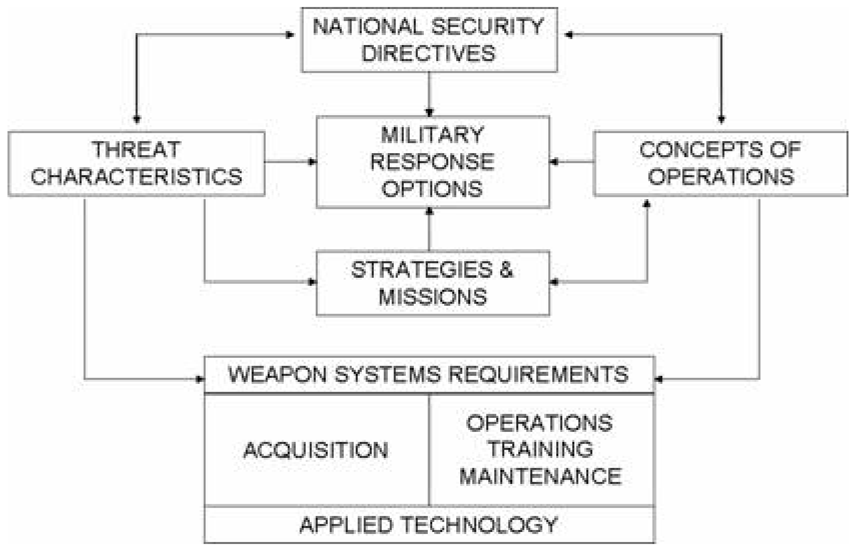
The Current Air Force Modernization Framework

As suggested, decisions to update and modernize military equipment are made in two distinct ways: through financial criteria or mission-needs criteria. The former is similar to corporate capital budgeting decisions and the latter is based on battlefield experience where certain technologies demonstrate some level of obsolescence in battle. The U.S. Air Force has sponsored a number of studies on the use of financial criteria. In particular, Greenfield and Pesserlin (2002) developed a mathematical framework to optimize when an aircraft should be replaced based on age and increasing maintenance costs. Keating and Dixon (2003) also developed a decision system to replace aircraft and specifically apply it to the C-21A transport and KC-135 tanker. Both works address the issue from a financial perspective – they find the optimal point where the cost of repairing old aircraft begins to exceed the annualized cost of buying new aircraft.

Neither builds performance characteristics into the model. Moreover, these financial models are only applied to support aircraft.

For front-line aircraft (primarily fighters and bombers), performance becomes more of an issue, and the decision process becomes more complicated. The focus shifts from when the most economical time to replace an aircraft is to what the performance requirements for a new system are once a need has been identified. Conceptually, Harold McCard (1991) envisions the requirements and decision process for a weapon system as a top down series of feedback loops beginning at the strategic level with National Security Policy, evaluating a number of factors such as enemy threat data and operational concepts, and ending at the operational level with performance requirements for new weapon systems (see Figure 1). William Gregory (1989) defines a more bottom up and direct process. Gregory states field commanders identify a problem, the requirements to overcome this problem are debated between agencies such as branch headquarters and the intelligence community, and these requirements emerge as capabilities in new weapons. Both authors identify a system that is capabilities-based, not financially based. Also, the decision when to modernize is based on the response to a battlefield problem, not when it is most economically appropriate. The replacement decisions of the F-15 and F-16 reflect this logic, as both will be replaced before the optimal time financially (Committee on Aging of U.S. Air Force Aircraft 1997).

Figure 1. Weapon Security Requirements as a Function of National Security Policy



Even though weapon system modernization decisions are primarily capabilities based, cost is still an important factor. The DoD has a finite budget, and must face the same fiscal constraints as other federal organizations. A framework that weighs both costs and capabilities is absent from the literature. Anecdotal evidence suggest such a framework is desirable – Thomas McNaugher (1989) notes the F-15's excessive top speed cost the Air Force over 1 billion dollars during its production run. A hedonic model incorporates both cost and capabilities and may provide a structure to evaluate price and performance tradeoffs.

A Hedonic Model as a Decision Making Framework

Hedonic modeling gained popularity with Griliches (1961) to counter upward bias in price indexes due to quality changes, but Rosen (1974) laid the theoretical groundwork still in use today. Rosen's approach concerns markets with heterogeneous goods – goods that can be divided into utility-bearing characteristics. From this perspective, the good is essentially a bundle of attributes, and the price reflects the supply and demand of the underlying characteristics. Regressing these characteristics against the good's price can reveal the marginal value the consumer places on each attribute. Rosen also states that demand functions for each attribute are attainable. Deriving these demand functions has proved highly problematic and is ultimately beyond the scope of this work (Patrick Bajari and C. Lanier Benkard 2005). Instead, I focus on the marginal value the DoD places on fighter aircraft attributes.

In formalizing the hedonic method, Rosen made a number of assumptions, two of which will have to be relaxed to apply the method to fighter aircraft. First, Rosen specified a market should have an extremely large multitude of goods, creating a continuum of products. In practice, this assumption is usually eased . Many of the markets where a hedonic model is applied only have a few hundred products at the most, and most markets have far less (N. M. Arguea, C. Hsiao, and G.A. Taylor 1994; William Boulding and Devavrat Purohit 1996; Joanna Stavins 1997). The fighter aircraft market only has a few different airframes operating at any one time, so the product spectrum is limited. Second, Rosen applies his theory to a market in perfect competition. Like the first assumption, this assumption is usually relaxed in application. Often the hedonic method is applied to monopolistically competitive or oligopolistic markets (David Prentice and Xiangkang Yin 2004). The fighter aircraft market is far removed from perfect competition, as it has a few suppliers and typically only one consumer.

Hedonic models have been applied in numerous situations, from testing markets for monopoly power to valuing the safety features in automobiles (William Boulding and Devavrat Purohit 1996; Frank Verboven 2002). It has not been used as a decision-making framework, but because notionally the government is paying for a bundle of performance characteristics in each fighter aircraft, a hedonic model can determine the marginal value the government places on each characteristic. Military planners can then decide if the implicit value is worth the cost, weighing both value and performance. The caveat to a hedonic model as a decision-making tool is that it does not focus on when to modernize, and the government must have a firm understanding of the costs and capabilities of the products it is evaluating.

Model Variable Selection

Many of the attributes used in the hedonic models are those identified as important by either previous research or subject matter experts. In particular, many characteristics from legacy aircraft are derived from past studies. Characteristics used in the model from next-generation aircraft are those identified as important by experts, as little quantitative research has been conducted on these systems.

Traditional fighter performance variables include those variables previously identified as significant in legacy aircraft. This study will use maximum speed, service ceiling, combat radius, weight, and relative measures of the sophistication of electronic components. Herald (2006) explained 91% of the variation in fighter aircraft prices from 1945-1986 with many of these variables (she did not use weight, and used total range instead of combat radius). Maximum speed and service ceiling describe how fast and how high the aircraft can fly. Combat radius accounts for the combat area of operations. Herald's study used total flying range with refueling tanks instead of combat radius, but the addition of fuel tanks affects the stealth ability of next generation fighters.

Many authors have outlined the critical capabilities that the next generation of fighters will bring to the DoD. Both Thomas Hampton (1998) and Michael Costigan (1997) identified the F-22A's stealth and super-cruise abilities as important to the next generation of warfare. Super-cruise denotes an aircraft's ability to sustain speeds in excess of Mach 1 without the use of afterburner. Devin Cate (2003) indicates the next generation of fighters will have an Active Electronically Scanned Array radar, which will allow for greater radar range, lower probability of interception, and the ability to track multiple targets at once. Finally, the DoD is in the process of acquiring the F-35B, a plane that can perform vertical take-off and landing (STVOL) maneuvers (Christopher Bolkcom 2004). Therefore, this variable will be incorporated as well.

This study uses one additional variable not used in other studies. The F-35, designed subsequent to F-22A research, directly benefited from research and development performed on the F-22A. One additional variable is added to attempt to control for this effect.

Functional Form

There is no definitive guidance on the appropriate functional form for hedonic models. As such, a number of forms have been used in past research. Maureen Cropper, Leland Deck, and Kenneth McConnell (1988) explored six different forms: the linear, semi-log, log-log, quadratic, linear Box-Cox transformation, and the quadratic Box-Cox transformation. Cropper, Deck, and McConnell simulated housing market equilibria with data from the Baltimore area. By comparing consumers' actual marginal bids for each characteristic with those determined by the models, they found that while complex quadratic models perform well when every attribute is observable, the simpler forms greatly outperform the others when either attributes are missing or are replaced by proxy variables. The linear Box-Cox transformation performed well in cases where all attributes are observed and in cases where some attributes are not represented. Thus, their recommendation is to use the linear Box-Cox transformation when estimating the marginal value of characteristics. In line with this recommendation, this study will use the linear Box-Cox functional form to estimate values. Appendix A and B give a more in-depth analysis of comparisons among the simpler functional forms (linear, semi-log, log-log, and linear Box-Cox).

Literature Review Summary

McCard (1991) and Gregory (1989) have theorized on how the modernization decision occurs for the Department of Defense, but there has been little quantitative work on these decisions for fighter aircraft. In particular, no previous work exists on price and performance tradeoffs. A hedonic price model, as described by Rosen (1974), weighs both costs and capabilities and may provide a proper decision-making framework. This model will demonstrate the marginal values the Department of Defense places on aircraft attributes. In this model, the independent variables range from traditional performance characteristics such as maximum speed to next-generation characteristics such as super-cruise. Since economic theory cannot provide guidance on the functional form of the model, the linear Box-Cox form is used, following the recommendation of Cropper, Deck, and McConnell (1988). By calculating the implicit prices of attributes with this model, policy makers can use the marginal value of aircraft characteristics as a tool to make modernization decisions.

III. Data and Methods

The primary goal of this research project is to create an empirical model that evaluates the price and performance characteristics of fighter aircraft. This chapter outlines this procedure, first by describing data used in the model, then by detailing coding techniques used in this study.

Data

This study builds two models – one aimed to determine the attribute values for procurement costs, and one for research, design, test, and evaluation (RDT&E) costs. A separate model for each phase of aircraft acquisition allows for comparisons across phases. We may gain certain insights into price and performance if these two models vary greatly. Also, two models allow for the inclusion of different variables for each stage.

All aircraft data comes from three sources: Ted Nicholas' and Rita Rossi's *U.S. Military Aircraft Data Book* series, Paul Jackson's, Kenneth Munson's, and Lindsay Peacock's *Jane's All the World's Aircraft* series, and Marcelle Knaack's *Encyclopedia of US Air Force Aircraft and Missile Systems, Volume I*. The data to construct the hedonic model are from the domestic US fighter market, and does not consider foreign aircraft, nor does it consider domestic aircraft that will only be sold to foreign nations (i.e. the F-16C Block 60). The data set includes characteristics from 50 aircraft, ranging in age from the 1949 F-84E Thunderjet to the currently-in-development F-35 series of fighters. In some cases, fighter characteristics from two sources conflict – for example, the two sources may list different top speeds for the same aircraft. In these instances, the characteristic in question is averaged. While this technique may not be ideal in finding the true value of the attribute, it hedges against listing a value that is either too high or too low.

For the purposes of this study, procurement cost is defined as weapon system cost – the physical system itself – plus any extra costs for initial spares and parts. In several aircraft, procurement costs could not be obtained and flyaway cost is used instead. In aircraft where both flyaway cost and procurement cost are available, the flyaway cost is usually lower by 2-3% (Nicholas and Rossi, 1991). The RDT&E costs include all costs for the research and development of the aircraft, and do not overlap with procurement costs. Any RDT&E costs for later modifications to the aircraft are also included. Together these two cost brackets can be thought of as total system cost. All costs are average unit costs over the life of the system except for the F-35, in which case predicted costs are used. All aircraft costs are base year 2005 dollars.

Variable Coding

The independent variables include both continuous and categorical variables. The continuous variables include maximum take-off weight (measured in lbs), combat radius (miles), maximum speed (mph at 30,000 ft), and service ceiling (ft). The variables for the integrated circuitry, large-scale integrated circuitry, AESA radar, STVOL, stealth technologies, super-cruise, and F-35 research benefits are binary categorical variables. As Table 1 illustrates, both maximum take-off weight and average combat radius possess a high variance relative to their mean. Maximum speed and service ceiling are much less disperse. To form the RDT&E model, all variables are used. For the procurement model, all variables with the exception of F-35 RDTE DUMMY are incorporated.

Table 1. Summary Statistics – Independent Variables

SUMMARY STATISTICS				
Variable	Mean	Std. Dev.	Min	Max
Max TO Weight (lbs)	45463.06	20367.81	15710	85406
Max Speed (mph)	1102.85	323.81	517.5	1650
Combat Radius (mi)	674.66	300.09	180.55	1239
Ceiling (ft)	50726.00	4929.28	33000	65000
Int Circuitry	0.16	0.37	0	1
LS Int Circuitry	0.34	0.48	0	1
AESA Radar	0.12	0.33	0	1
STVOL	0.04	0.20	0	1
Stealth	0.10	0.30	0	1
Supercruise	0.02	0.14	0	1
F-35 RDTE Dummy	0.06	0.24	0	1

Several variables deserve special mention. In particular, STEALTH, SUPERCRUISE, and F-35 RDTE DUMMY all have nuances that may aide in the interpretation of any results. Almost all aircraft denoted by STEALTH also posses the next generation of aircraft computer technology, the integrated avionics suite. While STEALTH primarily identifies aircraft as possessing radar-absorbent technologies, as a rough proxy it additionally includes value associated with the integrated avionics suite due to collinearity between the two characteristics (see Appendix C). SUPERCRUISE is intended to capture the ability to cruise above Mach 1 without afterburners, but the F-22A is the only plane with this technology. Thus, SUPERCRUISE acts as an F-22A dummy variable and, from a modeling standpoint, it captures anything possessed by only the F-22A. However, research failed to identify anything unique to the F-22A beyond super-cruise ability. The variable F-35 RDTE DUMMY, only present in the RDT&E model, acts in much the same way SUPERCRUISE acts. It captures anything unique to F-35 RDT&E spending. For the purposes of this study, it is assumed that this is the benefit gained from past F-22A research.

IV. Analysis and Results

The following section provides the results of the two hedonic models based on the linear Box-Cox transformation. First, the untransformed models are provided with an initial assessment of model performance. Then, the marginal values based on model coefficients are presented for further analysis. All marginal values are based on mean procurement and RDT&E costs and mean performance characteristics.

Model Results

The Box-Cox-transformed procurement model explains approximately 88.5% of the variation in procurement costs, with a number of variables significant at $\alpha = .1$. STVOL fell just outside the this significance level ($p > .118$). Among the non-transformed categorical variables, both LS INT CIRCUITRY and SUPERCRUISE have the largest magnitude, with every categorical variable demonstrating some degree of significance. At this level of analysis, care must be exercised in interpreting the magnitude of the continuous variables due to the effect of the transformation. The sign of every significant variable met *a priori* expectations.

Table 2. Model Estimate: Procurement

PROCUREMENT MODEL ESTIMATE

Variable	Coefficient		Chi-sq
Max TO Weight	59490.03	***	17.50
Max Speed	1035.52	**	5.61
Combat Radius	-29.61		0.09
Ceiling	-2804.55		0.32
Int Circuitry	0.47	**	3.93
LS Int Circuitry	1.43	***	30.29
AESA Radar	0.63	**	3.84
STVOL	0.59		2.44
Stealth	1.15	***	10.05
Supercruise	1.41	**	5.63
Cons	-55128.13		--

λ	-1.05
θ	0.05
n	50
R-sq	0.908
Adj R-sq	0.885

*** .01 Level of Significance
** .05 Level of Significance
* .1 Level of Significance

The RDT&E model enjoyed similar results – the model captured 85.9% of research and development cost variance, with almost every variable statistically significant. Of the categorical variables, SUPERCRUISE (4.72) had the largest coefficient, closely followed by STEALTH (4.23). F-35 RDTE DUMMY met *a priori* expectations with respect to sign, with a statistically significant negative coefficient (-3.23). CEILING was the only variable not demonstrating any significance.

Table 3. Model Estimate: RDT&E

RDT&E MODEL ESTIMATE

Variable	Coefficient		Chi-sq
Max TO Weight	1.90E-41	***	9.11
Max Speed	-6.40E-27	***	9.14
Combat Radius	5.50E-26	*	3.56
Ceiling	7.12E-41		0.26
Int Circuitry	0.45	***	7.77
LS Int Circuitry	2.66	***	18.80
AESA Radar	2.49	***	8.09
STVOL	0.38	***	7.77
Stealth	4.23	***	11.50
Supercruise	4.72	***	9.37
F-35 RDTE Dummy	-3.27	***	9.27
Cons	0.15		--

λ	8.54
θ	0.29
n	37
R-sq	0.902
Adj R-sq	0.859

*** .01 Level of Significance
** .05 Level of Significance
* .1 Level of Significance

Marginal Values

Model coefficients alone do not lend themselves well to in-depth analysis. This requires calculation of the implicit marginal value of each attribute (see Appendix D for implicit price equations). This section reveals the value of each characteristic based on the linear Box-Cox model. All marginal values are in millions of dollars.

The marginal values for the procurement model cover a wide range, and while some initially appear trivial, all may have a significant impact. The incremental value for MAX TO WEIGHT is approximately $500. However, this is on a per-pound basis, so a 1000 lb weight increase results in a $500,000 increase in price per aircraft. Likewise, each mile/hour increase raises the value of the aircraft by $20,000. The largest changes in value are attributed to LS INT CIRCUITRY and SUPERCRUISE, with respective increases of $37.4M and $36.8M. STEALTH raises the value another $30M, and the other categorical variables increase value to a lesser degree.

Table 4. Marginal Values: Procurement

PROCUREMENT MODEL MARGINAL VALUES

Variable	Marginal Value	
Max TO Weight	0.0005	***
Max Speed	0.02	**
Combat Radius	-0.001	
Ceiling	-0.00002	
Int Circuitry	12.29	**
LS Int Circuitry	37.42	***
AESA Radar	16.58	**
STVOL	15.54	
Stealth	30.18	***
Supercruise	36.75	**

*** .01 Level of Significance
** .05 Level of Significance
* .1 Level of Significance

The RDT&E cost model marginal values differ slightly from their procurement model counterparts. The single largest value driver is the inclusion of SUPERCRUISE ($31.8M), with STEALTH ($28.5M) second. LS INT CIRCUITRY and AESA RADAR capability also demonstrate large value increases, as the inclusion of these abilities lead to changes of $17.9 and $16.8M, respectively. According to this model, the F-35 inherits $22M in RDT&E value from the F-22A. Contrary to a priori expectations, maximum speed appears to be a disamenity, as every mph increase leads to a $4,000 decrease in RDT&E value.

Table 5. Marginal Values: RDT&E

RDT&E MODEL MARGINAL VALUES

Variable	Marginal Value	
Max TO Weight	0.00002	***
Max Speed	-0.004	***
Combat Radius	0.001	*
Ceiling	0.0001	
Int Circuitry	3.03	***
LS Int Circuitry	17.93	***
AESA Radar	16.78	***
STVOL	2.57	***
Stealth	28.51	***
Supercruise	31.78	***
F-35 RDTE Dummy	-22.05	***

*** .01 Level of Significance
** .05 Level of Significance
* .1 Level of Significance

These models demonstrate the relative value the DoD is placing on aircraft attributes by agreeing to certain costs. In both models, SUPERCRUISE acts as a large value driver, with STEALTH and circuitry components following to lesser degrees. The combined models paint the picture that SUPERCRUISE and electronics are the most intrinsically valuable. The implications of these models are discussed in the following section.

V. Conclusions and Recommendations

The two hedonic models presented may have certain implications with regard to the purchase of next-generation fighter aircraft. However, this study has certain limitations. In the remaining section, these limitations are discussed, as well as conclusions drawn from the results.

Caveats and Limitations

These models represent one of the few hedonic analyses performed on the Department of Defense aircraft market, and like others, they are subject to several limitations. These caveats include an atypical market setting and the inclusion of categorical and proxy variables that attempt to capture aircraft characteristics. To fully understand the meaning of the marginal values, any potential shortfalls must be understood.

Much economic theory rests on the assumption that the market in question has an abundance of buyers and sellers, or at the very least, many buyers and several competitive sellers. Hedonic theory is no different. However, the DoD domestic aircraft market has only one buyer and a few (sometimes only one) sellers. This monopsonist vs. oligopolist setting is not prevalent in economic literature, so the ramifications of this relationship and its impact on hedonic modeling are not fully understood. One issue that has developed from this situation is the use of cost data to approximate price. Many major weapon systems are now bought on cost-based contracts, where the government reimburses the contractor for all costs incurred. This procurement method differs from a more typical market, where prices adjust to an equilibrium through the interaction of buyers and sellers. However, one may argue that cost contracts are rarely as simple as contractors reporting cost numbers and getting reimbursed, and in fact, a lot of negotiation occurs over what the true "costs" are. From this perspective, the negotiated cost could be viewed as an equilibrium price point. No matter the point of view, this economic situation remains unexplored and its impact unknown.

In the same way the cost data of the dependent variable is a proxy for price, a number of independent variables are modeled by categorical and proxy variables. Ideally, there are more finely tuned parameters to model these characteristics. For instance, the model currently uses a categorical variable to denote stealth ability. A more appropriate measure may be the actual radar cross-section of the aircraft. Similarly, highest attainable speed without the use of afterburners may more adequately model super-cruise ability, and some measure of processing power may more precisely model the circuitry variables. Unfortunately, aircraft radar cross-section data are classified, the highest attainable speed without afterburners is not reported, and no single yardstick exists that measures the spectrum of plane electronics. All variables were modeled as such due to lack of data.

The cost data used in this report for the F-35 deserves special mention. As the plane is still in development, the most recent reported estimates for the final cost were used. If the aircraft follows the trend of its predecessors, costs will increase before it enters steady-state production. The DoD is purchasing the plane under the Cost as an Independent Variable acquisition strategy, and ideally this should limit cost growth. However, some degree of cost growth is likely.

Discussion of Results

In light of these limitations, the results merit some discussion. More precisely, the statistical significance of model variables allows us to determine what is important to the DoD, while marginal values derived from the models allow side-by-side comparisons of aircraft.

The two models demonstrate relative similarities in what is statistically significant. Considering the variable STVOL in the procurement model is weakly significant ($p > .118$), the only variable to demonstrate a strong difference in significance is COMBAT RADIUS. The RDT&E model shows this attribute to be significant, while the procurement model does not. This indicates the aircraft's combat radius is minimally valuable ($1,000 per additional mile) during initial development, and subsequently becomes less valuable during actual procurement. This finding casts doubt on the arguments of Costigan (1997) that aircraft with extended combat radii such as the F-22A are inherently more valuable to the DoD. It is not that range is unimportant, but rather not strongly valued.

The marginal values derived from the models allow for certain comparisons between aircraft. Of particular interest to this paper are the conclusions that can be drawn between the next-generation fighter aircraft (see Table 6). The F-22A and F-35A share many similar traits of the variables found statistically significant. They weigh approximately the same, share similar radar types and circuitry, and possess some level of stealth capability. The difference in procurement value stems from the F-22A's marginally faster top speed and ability to super-cruise. Of the $38.3M in increased value the procurement model identifies, super-cruise composes $36.8M. The RDT&E model shows a different pattern – while SUPERCRUISE is valuable ($31.8M), the $22M inherited by the F-35 drives the value increase down to approximately $10M.

Inter-generational comparisons can be made as well; however, the interpretation of these comparisons must be kept in the appropriate context. Technical aspects of aircraft change over time, so implicit value comparisons are time-sensitive. For instance, the DoD values the F-22A $28M more today than it valued the F-15E in its procurement period (1986-2001). Similar comparisons show the DoD values the next generation of multi-role fighter, the F-35, $10.6M more than the F-16C during its buying cycle. The RDT&E model demonstrates the value the DoD places on super-cruise and stealth, as the F-22A shows a $60.9M increase over the F-15E.

Table 6. Select Marginal Price Comparisons

COMPARISON OF IMPLICIT VALUES BETWEEN SELECT AIRCRAFT ($M)

PROCUREMENT

Aircraft	Increase
F-22A over F-35A	38.32
F-22A over F-15E	27.98
F-35A over F-16C	10.58
F-15E over F-16C	20.41

RDT&E

Aircraft	Increase
F-22A over F-35A	9.97
F-22A over F-15E	60.93
F-35A over F-16C	6.13
F-15E over F-16C	-0.82

The real-life difference in procurement cost of the F-22A and F-35A is approximately $123M. The difference between the actual cost difference and the implicit cost difference stems from the inability to “untie” the bundled good in question and move an attribute to another good without any reassembly costs. However, this is not the case with most goods, including aircraft. This discrepancy can then be thought of as extra transaction and reassembly costs associated with non-divisible products (Rosen 1974).

Study Implications

While this study does not attempt to resolve any conflicts over the next-generation aircraft, certain insights can be drawn from the hedonic models. Specifically, these models imply increasing costs have very definite value trade-offs, that trivial differences in many attributes do mean trivial differences in value, and that the DoD's current acquisition strategy with next generation fighter aircraft may be inefficient from a "best-value" perspective.

The original plans for the F-22A did not include such a high price-tag. Due to both requirements increases and cost over-runs, F-22A procurement costs grew 55% from 1991 to 2005, while total system costs grew 129% (David Walker 2006). Increasing costs can have implicit-value consequences, especially on those characteristics unique to the aircraft in question. For instance, the ability to super-cruise is unique to the F-22A. If the procurement cost of the F-22A was closer to $109M (the 1991 projected price) instead of $170M, then super-cruise loses some of its statistical significance ($p>.137$ instead of $p>.018$). Additionally, the marginal value of super-cruise diminishes ($20.7M instead of $36.8M). This is a rough estimation, as it does not account for any changes in other performance characteristics over the time period, but it demonstrates the effect increasing costs have on value. Any system with large cost increases (all else held constant), will see a sharp rise in implicit prices on system-unique traits.

In comparing attributes that the F-22A and F-35A share, it becomes apparent the two aircraft are remarkably similar. Of the statistically significant variables, the only variables demonstrating any change are maximum speed and combat radius. Other characteristics, such as stealth and radar types, are largely the same. The difference in speed accounts for a $1.4M value increase in procurement dollars and the difference in combat radius creates a $1.0M increase in RDT&E dollars. These small changes in aircraft performance characteristics lead to small changes in value. This fact is due in part to the size of the changes and the attributes' relatively small implicit values. To see a large increase in value of one aircraft over the other, large changes in attributes would be needed, and that is not the case when comparing the next generation fighters.

If a goal of the DoD acquisition system is efficiency in spending, this study indicates current next-generation fighter acquisition may not be efficient in dollar/ performance trade-offs. By agreeing to certain costs, the DoD has implicitly placed certain values on characteristics. In comparing the difference in total system (procurement and RDT&E) values of next-generation fighter aircraft, the DoD places a $48.3M value premium on the F-22A – less than the $60.5M total system cost of the F-35, but slightly more than the $47M procurement cost. This difference is primarily due to one attribute, super-cruise, coupled with the high price of an F-22A. As mentioned previously, the value placed on super-cruise is $36.8M in procurement dollars and $31.8M in RDT&E dollars. If the DoD truly feels that super-cruise is worth at least $68.6M per plane, then the DOD is being efficient in spending. However, that may be a tough sell in our current fiscal environment since the F-35A's procurement cost ($47M) is only $10M more than the procurement value of super-cruise alone. Other than super-cruise, the differences between the aircraft are trivial. This leads to an interesting hypothetical scenario for the DoD: What is worth more, the ability to super-cruise in an F-22A plus $10M or a whole F-35 aircraft? According to this model, at the current aircraft costs they are about equal. Depending on how super-cruise is used operationally, some may feel the DoD is paying a high premium for the F-22A.

Future Study Recommendations

While this study attempts to identify certain value and performance tradeoffs, it may benefit from other research on unexplored areas of the economics pertaining to the Department of Defense. In particular, more research should be conducted investigating the cost/price relationship, the cost over-run value linkage, and the inclusion of more data to fine-tune this relationship.

Much of the theoretical economic groundwork employed in this research effort (and others) assumes the existence of markets where the buyers and sellers act in a particular way. However, the DoD does not operate in a typical market and cost data is used to approximate price. Many studies would benefit from a closer examination of this market, an examination of the cost/price relationship, and any theoretical and practical implications of using cost data.

This study implies increasing costs affect value. The DoD and others may profit from more in-depth studies linking cost over-runs with value consequences or over-runs with a dollar-per-utility measure. This avenue of research may help identify current inefficiencies in spending or cost-growth patterns where spending efficiency drops greatly.

A natural extension of this study could take into account more variables or cost relationships. This study used average procurement and RDT&E costs over the life-cycle of the aircraft. Other areas of research could examine the effect learning curves have on marginal values or they could incorporate complete life-cycle costs, to include maintenance and logistics. Part of the value of certain aircraft may be hidden in lower maintenance costs.

Perhaps another research project could examine a more fundamental question: How do two similar systems (in terms of performance attributes), such as the F-22A and F-35A, have such different costs? This fact also brings into question the operational nature of the aircraft. The F-22A was initially designed as an air-superiority fighter and later converted to accept more roles. The F-35A was designed from the ground up as a multi-role fighter. An operational study may examine if the (mostly small) differences in the aircraft have a large operational effectiveness. These findings may later be linked to differences in cost.

Final Remarks

This study originally set out to build a hedonic model of the US fighter aircraft market and apply its findings to the acquisition of next-generation fighter aircraft. With a few caveats, it reveals the implicit price placed on the F-22A's ability to sustain speeds in excess of Mach 1 to be in excess of $60M (total system cost) per aircraft. The DoD is now in a position to evaluate both price and performance. If the DoD feels the benefit gained from the difference in performance characteristics the F-22A possesses over other aircraft is worth at least its implicit cost, then F-22A acquisition should continue as is. However, if benefits gained from the F-22A (and in particular super-cruise) are trivial, then the DoD should modify its acquisition plan accordingly.

Appendix A. Comparison of Functional Forms

Cropper, Deck, and McConnell (1988) found the more mathematically simple models – the Box-Cox, linear, semi-log, and log-log, outperform the more complex models in situations where attributes are omitted or proxy variables are used. The Box-Cox transformation was their functional form of choice, but the others are not without merit.

In comparing functional forms on procurement costs, all models explained at least 80% of the variation in costs, with the highest R^2 belonging to the Box-Cox transformation (adj R^2 = .885). The Box-Cox model also enjoyed more significant variables than the other forms. Both the semi-log and log-log forms were plagued with heteroskedasticity (according to the Breusch-Pagan/Cook-Weisberg test).

The RDT&E models demonstrated a higher range of explained variation of the dependent variable, with the linear form possessing the highest R^2 (.926). The RDT&E models show a striking difference across forms when comparing significant variables. Almost all the variables of the Box-Cox model were significant at the 1% level, while other models demonstrated only one or two significant variables.

COMPARISON OF FUNCTIONAL FORMS

PROCUREMENT

	Box-Cox		Linear		Semi-Logǂ		Log-Logǂ	
Variable	Coeff.	Chi-sq	Coeff.	t	Coeff.	t	Coeff.	t
Max TO Weight	59490.03 ***	17.50	0.0005 ***	2.77	0.0000175 **	2.49	0.89 ***	3.34
Max Speed	1035.52 **	0.09	-0.005	-0.44	0.001	1.5	-0.01	-0.05
Combat Radius	-29.61	5.61	0.01	1.3	-5.75E-06	-0.01	0.87	1.22
Ceiling	-2804.55	0.32	-0.0004	-1.2	-0.00001	-0.36	-0.17	-0.11
Int Circuitry	0.47 **	3.93	12.99 *	1.79	0.57	1.53	0.45	1.2
LS Int Circuitry	1.43 ***	30.29	28.17 ***	4.19	1.15 ***	2.92	1.11 ***	2.9
AESA Radar	0.63 **	3.84	26.58 ***	2.85	0.61	1.59	0.50	1.27
STVOL	0.59	2.44	4.32	0.37	0.68	0.64	0.65	0.62
Stealth	1.15 ***	10.05	16.31	1.5	1.03	1.55	1.00	1.37
Supercruise	1.41 **	5.63	103.12 ***	6.03	1.12	1	1.10 **	2.19
Cons	-55128.13	--	4.78	0.31	0.75	0.67	-11.48	-0.78
R-sq	0.908		0.862		0.860		0.883	
Adj R-sq	0.885		0.826		0.825		0.853	

RDT&E

	Box-Cox		Linearǂ		Semi-Log		Log-Log	
Variable	Coeff.	Chi-sq	Coeff.	t	Coeff.	t	Coeff.	t
Max TO Weight	1.90E-41 ***	9.11	0.0002	1.15	0.00002	1.19	0.83	1.39
Max Speed	-6.40E-27 ***	9.14	-0.01	-0.85	-0.0003	-0.19	-0.51	-0.47
Combat Radius	5.50E-26 *	3.56	0.006	0.53	-0.0005	-0.55	-0.44	-1.07
Ceiling	7.12E-41	0.26	0.0003	0.53	0.0000001	0	-0.51	-1.17
Int Circuitry	0.45 ***	7.77	3.19	0.54	-0.11	-0.2	0.03	0.06
LS Int Circuitry	2.66 ***	18.80	9.10	1.56	2.11 ***	3.98	2.48 ***	4.71
AESA Radar	2.49 ***	8.09	13.18 *	2.04	0.90	1.32	0.80	1.24
STVOL	0.38 ***	7.77	-1.80	-0.34	0.11	0.14	-0.07	-0.09
Stealth	4.23 ***	11.50	30.53	0.84	1.33	1.04	0.77	0.61
Supercruise	4.72 ***	9.37	121.19 **	2.29	2.63	1.45	3.52 *	1.92
F-35 RDTE Dummy	-3.27 ***	9.27	-35.29	-0.91	-0.16	-0.1	0.72	0.41
Cons	0.15	--	-9.16	-0.48	0.03	0.01	3.15	0.38
R-sq	0.902		0.949		0.806		0.818	
Adj R-sq	0.859		0.926		0.720		0.737	

*** .01 Level of Significance

** .05 Level of Significance

* .1 Level of Significance

ǂ Heterskedastistic; robust standard errors used

Appendix B. Marginal Values Between Functional Forms

Marginal values between models identified as most appropriate by Cropper, Deck, and McConnell (1988) show a relative amount of stability in the procurement models, and a higher degree of variation in the RDT&E models. Three procurement models – the Box-Cox, the semi-log, and the log-log – identify marginal values that are in close agreement, with the linear model only in agreement on a few variables. This is most evident with the "super-cruise" variable, where the linear form shows a $103M marginal value and the other three are closely clustered in the mid $30M range. The RDT&E models show no discernable pattern among marginal prices. This lack of consistency may be due to the infrequency of significant variables in the additional models.

COMPARISON OF MARGINAL VALUES BETWEEN FUNCTIONAL FORMS

PROCUREMENT

Variable	Box-Cox		Linear		Semi-Log[Ŧ]		Log-Log[Ŧ]	
Max TO Weight	0.0005	***	0.0005	***	0.0006	**	0.0006	***
Max Speed	0.02	**	-0.0047		0.03		-0.0003	
Combat Radius	-0.0013		0.01		-0.0002		0.04	
Ceiling	-0.00002		-0.0004		-0.0003		-0.0001	
Int Circuitry	12.29	**	12.99	*	17.92		14.22	
LS Int Circuitry	37.42	***	28.17	***	36.23	***	35.07	***
AESA Radar	16.58	**	26.58	***	19.33		15.71	
STVOL	15.54		4.32		21.51		20.62	
Stealth	30.18	***	16.31		32.64		31.49	
Supercruise	36.75	**	103.12	***	35.35		34.76	**

RDT&E

Variable	Box-Cox		Linear[Ŧ]		Semi-Log		Log-Log	
Max TO Weight	0.00002	***	0.0002		0.0003		0.0003	
Max Speed	-0.004	***	-0.01		-0.0038		-0.01	
Combat Radius	0.001	*	0.01		-0.01		-0.0097	
Ceiling	0.0001		0.0003		0.000002		-0.0002	
Int Circuitry	3.03	***	3.19		-1.63		0.51	
LS Int Circuitry	17.93	***	9.10		31.55	***	37.04	***
AESA Radar	16.78	***	13.18	*	13.39		12.01	
STVOL	2.57	***	-1.80		1.62		-1.04	
Stealth	28.51	***	30.53		19.81		11.44	
Supercruise	31.78	***	121.19	**	39.23		52.56	*
F-35 RDTE Dummy	-22.05	***	-35.29		-2.38		10.71	

*** .01 Level of Significance

** .05 Level of Significance

* .1 Level of Significance

Ŧ Heterskedastistic; robust standard errors used

Appendix C. Correlation Between Variables

Below is the correlation matrix for all independent variables used in this study, plus two more that were originally included. INT AV SUITE (Integrated Avionics Suite) represents the progression of the circuitry variables in the next generation fighter aircraft. However, this variable is highly collinear with STEALTH (r = .88). Thus, from a modeling standpoint, these variables capture the same information. YEAR, denoting the year the first operational aircraft was delivered to the DoD, was included to capture the increase in price not explained by independent variables (Manuchehr Irandoust 1998) . It was dropped due to the correlation between itself, STEALTH, and AESA RADAR. F-35 RDTE DUMMY, while demonstrating a degree of collinearity with both AESA RADAR and STEALTH, was ultimately left in the model due to the large preponderance of evidence suggesting the F-35 directly benefited from the RDT&E of the F-22A.

CORRELATION MATRIX

	Max TO Weight	Combat Radius	Max Speed	Ceiling	Int Circuitry	LS Int Circuitry	Int Av Suite	AESA Radar	STVOL	Stealth	Supercruise	Year	F-35 RDTE Dummy
Max TO Weight	1												
Combat Radius	0.42	1											
Max Speed	0.63	0.05	1										
Ceiling	0.33	0.26	0.37	1									
Int Circuitry	-0.03	-0.35	0.36	0.14	1								
LS Int Circuitry	0.58	0.52	0.35	0.26	-0.31	1							
Int Av Suite	0.21	0.05	-0.03	-0.04	-0.13	-0.21	1						
AESA Radar	0.30	0.18	0.01	-0.03	-0.16	-0.01	0.80	1					
STVOL	0.00	-0.06	-0.16	-0.02	-0.09	0.07	0.32	0.24	1				
Stealth	0.21	0.07	-0.13	-0.18	-0.15	-0.10	0.88	0.70	0.27	1			
Supercruise	0.10	0.17	0.01	0.01	-0.06	-0.10	0.48	0.39	-0.03	0.43	1		
Year	0.56	0.32	0.29	0.12	-0.18	0.48	0.67	0.77	0.32	0.65	0.28	1	
F-35 RDTE Dummy	0.18	-0.04	-0.04	-0.14	-0.11	-0.18	0.86	0.68	0.38	0.76	-0.04	0.60	1

Appendix D. Box-Cox Transformation Equations

Box-Cox Transformation

$$\tau(P,\lambda)=\begin{cases}\left(P^{\lambda}-1\right)/\lambda & if\ \lambda\neq 0\\ \ln(P) & if\ \lambda=0\end{cases}$$

Marginal Price for Box-Cox Transformation: Continuous Variables

$$B_i\, z_i^{\lambda\text{-}1}\, P^{1\text{-}\theta}$$

Marginal Price for Box-Cox Transformation: Categorical Variables

$$B_i P^{1\text{-}\theta}$$

Appendix E. Sample Data Set

Airframe	Proc Cost	RDTE Cost	Max TO Weight	Combat Radius	Max Speed	Ceiling
F-35B	65.22	13.41	60000	679	1056	48000
F-35A	47.82	13.41	60000	518	1056	48000
F-35C	65.22	13.41	60000	679	1056	48000
F-22	170.27	172.53	60000	1024	1122	50000
F/A-18 E	89.54	30.1	66000	1001.18	1188	50000
F/A-18 F	89.67	30.1	66000	1001.18	1188	50000
F/A-18 A-D	53.06	7.35	56000	391.26	1188	50000
F-15E	62.91	9.84	81000	788.28	1650	60000
F-15 A-D	51.2	11.85	68000	1220.98	1650	65000
F-16C	31.80	6.044	48000	970.49	1320	50000
F-16D	31.81	6.044	48000	970.49	1320	50000
F-14D	121.47	50.87	74349	1239	1240.8	53000
F-14 A-C	58.3	9.71	74349	1239	1240.8	53000
AV-8B	41.1	11.41	30990	503	646.8	50000
F-117A	86.69	46.48	52000	795	594	33000
F-5F	15.29	22.24	24018	656	996.6	52500
F-5E	8.14	3.18	24018	656	996.6	52500
F-4E	12.41	0.13	41135	422.05	1478.4	57200
F-4D	11.13	1.37	38706	455.4	1425.6	54950
F-4C	11.61	0.71	38606	484.15	1425.6	55400
F-111F	49	12.84	85161	920	1584	58500
F-111D	40.44	20.46	85406	920	1584	55150
F-111E	48.85	15.14	84433	920	1584	53300
F-111A	46.69	20.5	82632	920	1452	57900
F-106B	31.3	0.38	36500	727.95	1265	51400
F-106A	30.83	4.33	38700	727.95	1265	52000
F-105B	37.06	1.72	52500	230	1372.8	49000
F-105D	13.35	1.76	52500	230	1372.8	49000
F-105F	13.44	4.29	54300	230	1346.4	49000
F-104A	11.55	N/A	24804	402.5	1320	55200
F-104B	15.74	N/A	24294	216.2	1320	48600
F-104C	9.84	2.54	27853	351.9	1320	58000
F-104D	9.58	2.46	23725	180.55	1320	53000
F-102A	8.28	1.73	31276	650.9	778.55	51400
F-101A	19.75	N/A	48000	793.5	1000.5	50300
F-101C	8.37	N/A	49000	603.75	1000.5	50300
F-101B	11.2	0.42	45461	693.45	1092.5	50700
F-100A	7	0.79	32500	586.5	816.5	49000
F-100C	4.56	1.54	37000	575	923.45	49000
F-100D	4.81	0.76	39750	529	908.5	47700
F-100F	5.28	0.69	40100	517.5	908.5	47300
F-94A	2	N/A	15710	1077.55	604.9	46000
F-94B	1.51	N/A	16000	1077.55	587.65	48000
F-94C	3.72	N/A	24200	1200	639.4	51400
F-89D	5.53	N/A	45575	500.25	517.5	43500
F-86F	1.5	N/A	20650	287.5	690	45000
F-86H	4.02	N/A	21800	419.75	747.5	47200
F-86D	2.39	N/A	19952	269.1	691.955	49600
F-84E	1.63	N/A	18000	849.85	599.15	45000
F-84F	5.31	N/A	24200	431.25	690	44300

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14. ABSTRACT

The United States Department of Defense (DoD) is currently recapitalizing its aging fighter aircraft inventory with the F-22A and F-35. While the DoD may consider cost and performance issues, it does not use a quantitative model that effectively measures the tradeoffs between the two. This thesis constructs a hedonic model of the fighter aircraft market to measure the implicit price on fighter performance characteristics and specifically applies it to next-generation aircraft.

Data from 50 aircraft from 1949-present were used to construct two models – one based on procurement costs and one based on research, design, test, and evaluation (RDT&E) costs. The models, based on a linear Box-Cox transformation, demonstrated that the unique F-22 trait, the ability to super-cruise, has the highest per-unit implicit price ($68.5M), followed by the stealth technology ($58.7M) and large-scale integrated circuitry ($55.3M). The high marginal value for the super-cruise trait implies that, depending on how super-cruise is used operationally, the F-35A may be a more effective purchase in terms of resource allocation than the F-22A.

15. SUBJECT TERMS

Cost analysis, econometric modeling, hedonic model, Box-Cox transformation, F-22A, F-35, F-35A, aircraft performance characteristics

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