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Quantifying the Effects of Aircraft Engine Upgrades on Operating and Support Costs

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QUANTIFYING THE EFFECTS OF AIRCRAFT ENGINE UPGRADES ON OPERATING AND SUPPORT COSTS

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Abstract

As research into Operating and Support (O&S) costs matures, the focus can narrow. This research represents a first of its kind for the Air Force; it is an empirical study to analyze the effects of new engines on fuel efficiency and maintenance over those engines they replace. Within this research, new engines are those with distinct Type Series Modification (TMS) designators that appear within categories of Mission Designation System (MDS) aircraft. The only new engines appear on C-5s, C-130s, and C-135s. The inclusion of retired engines brings in two fighter aircraft, F-15s and F-16s. The data source is the Air Force Total Ownership Cost (AFTOC) database, which collects flying hours and gallons of fuel and is available by engine. Using this data, the realized fuel efficiencies of the new engines can be effectively graphed, quantified and tested. Maintenance costs are not tracked by engine but are approximated from ratios determined by AFTOC. Of note, these costs do not include Contractor Logistics Support (CLS) which may weaken the analysis for estimating future engine maintenance costs. From the data available, the potential savings that can be realized in fuel and maintenance are significant and do not come at a trade-off in engine performance.

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Bradford A. Myers

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QUANTIFYING THE EFFECTS OF AIRCRAFT ENGINE UPGRADES ON OPERATING AND SUPPORT COSTS

I. Introduction

1.1 Background

Despite Operating and Support (O&S) costs accounting for an average of 55 percent of total life cycle costs (Jones, et al., 2014), no study to date has attempted to quantify the effects of new engines on sustainment costs. This thesis fills that void by analyzing before and after effects on O&S costs based on three new engines and seven retired engines across 38 aircraft platforms and one additional new engine on a helicopter platform. O&S consists of all sustainment costs, including manpower, fuel, supplies, maintenance, upgrades, etc. (CAPE, 2016), but this thesis examines the fuel performance and maintenance costs of engines only.

The B-52H re-engine cost estimate motivated this research. The analysts at the Air Force Life-Cycle Management Center (AFLCMC) were tasked to brief what the new B-52H O&S costs would be after the engines were upgraded. Unfortunately, the cost community does not have available or published Cost Estimating Relationships (CERs) for how to account for O&S effects after an engine modification. Therefore, to have a defendable estimate, the analysts turned to the analogous C-5 RERP (Reliability Enhancement and Re-engining). Using programmatic data for the C-5 and the B-52 as well as the historical costs per Flying Hours the cost analysts derived the estimate.

This work broadens those efforts by more holistically examining the effects of engine upgrades on ongoing O&S costs across a variety of aircraft systems. Future cost analysts for major modifications may be able to use these findings to help formulate cost estimates with the results of this research. The impact of these better refined estimates will be found in the improved decision support process by program managers competing for Air Force resources.

1.2 Problem Statement

Put succinctly, how do engine upgrades impact ongoing O&S costs? The first step entails finding comparable aircraft with data on at least two different engines. As further discussed in Chapter III, a different engine is defined here as of those engines with a separate Type Series Modification (TMS) designator. For the purpose of this thesis, a major engine modification is one that is applicable to the O&S Cost Management Guidebook published by Department of Defense (DoD) whose glossary defines a modification as “any modification that is of sufficient cost and complexity that it could itself qualify as an Acquisition Category (ACAT) I through ACAT III program for acquisition management purposes (2016, pg 151).” This includes any modification that is itself a Major Defense Acquisition Program (MDAP) or qualifies as an ACAT III or higher.

Effectively solving ongoing engine costs improves O&S cost estimates. This is particularly important since O&S costs are historically some of the most difficult costs to correctly capture (Ryan, et al., 2012). Better estimates arm decision makers with better information. Properly informed decision makers can then decide between alternatives balancing the cost or performance of an engine modification. Decision makers will likely value improved O&S estimates as evidenced by the recent increase in the focus of getting O&S costs estimates correct (GAO, 2010).

1.3 Method of Analysis

Further described in Chapter III, this thesis descriptively compares the actual maintenance costs and calculated fuel efficiencies characteristics of new engines against the actual observations of those engines that are being replaced. The observed differences are displayed visually and are statistically tested. Actual data for engine inventory on aircraft is used to find engine pairings. Engines put into place after Fiscal Year (FY) 2017 do not have at least two years of new O&S costs for statistical comparison. By the same logic, only those engines that have been in place since FY1998 allows for two years of pre-modification O&S data using Air Force Total Ownership Cost (AFTOC) stand-up-date of FY1996. In short, only those engines which entered the service between FY1998 through FY2017 are considered, for a total of 19 years of O&S data. Discussed further in Chapter II, not all weapon systems account equally in O&S costs and this research focuses solely on Air Force aircraft.

To be useful, the structural break comparing the –pre and –post modification cost data must have statistically significant relationships. In order to mitigate against a Type II error, which is a failure to find a relationship where one exists, a chosen alpha (α) level of 0.1 applies. An alpha of 0.1 is appropriate for exploratory analysis where the desire is to minimize missed opportunities that show statistically significant relationships.

1.4 Research Questions

Using the methods just described, the scope of this analysis addresses the following research questions:

1. What are the quantifiable effects of an engine upgrade to the ongoing O&S costs of a weapon system? To what effect can these be measured and how useful are they in analysis for the future?

2. How do these effects vary across different weapon systems? Specifically, do different platforms or categories of aircraft behave the similiar ways? Is a new engine to a heavy transport analogous to a new engine in a fighter jet?

3. To what extent do historical data have predictive capacity for future O&S cost estimates? What are the corresponding confidence levels? What does the empirical data reveal?

1.5 Thesis Organization

The remainder of this thesis is divided into four chapters. Chapter II covers a review of the literature pertaining to O&S cost estimates as well as a description of the statistical methods applied to the empirical data. Chapter III focuses on the methodology of the data collection sources and the limits of the data. Additionally, this chapter explains the statistical method applied. Within Chapter IV, the analysis and results of the statistical tests address the research questions posed. Lastly, Chapter V formally concludes the thesis with the interpretation and summarization proposed to answer the research questions as well as provide recommendations on further areas of study.

II. Literature Review

2.1 Chapter Overview

This chapter discusses what the current state O&S research reveals. We first examine what exactly O&S is and how it is recorded. We then discuss some of the research concerning O&S, which has benefited from an increased focus in recent years (Ryan, et al., 2012) as Congress and the DoD have tried to control what is frequently the highest portion of a weapon system life cycle. In addition to peer reviewed journals, interested parties that have analyzed O&S costs include the Congressional Budget Office (CBO), the Government Accountability Office (GAO), Federally Funded Research and Development Centers (such as the RAND Corporation), and DoD schools such as the Naval Postgraduate School or the Air Force Institute of Technology. Finally we discuss some characteristics of engines and what the research suggests should happen as they are upgraded.

2.2 What Qualifies as Operating and Support Costs?

The rules and definitions for O&S costs are defined in the Cost Assessment and Program Evaluation (CAPE) O&S Cost Estimating Guide, the DoD O&S Cost Management Guidebook, DoD Instruction 5000.02, and Air Force Instruction 65-508. The Guidebook defines O&S costs as "sustainment costs incurred from the initial system deployment through the end of system operations. Includes all costs of operating, maintaining, and supporting a fielded system. Specifically, this consists of the costs (organic and contractor) of personnel, equipment, supplies, software, and services associated with operating, modifying, maintaining, supplying, and otherwise supporting a system in the DoD inventory (DoD, 2016, pg 5)." Costs also occur before initial system deployment, as well as disposal costs after a system's useful life. Taken together these costs constitute a weapon systems Life Cycle Costs (LCC). LCCs consist of four overlapping phases of support which include: Research and Development, Investment, O&S, and Disposal. This relationship is demonstrated in Figure 1.

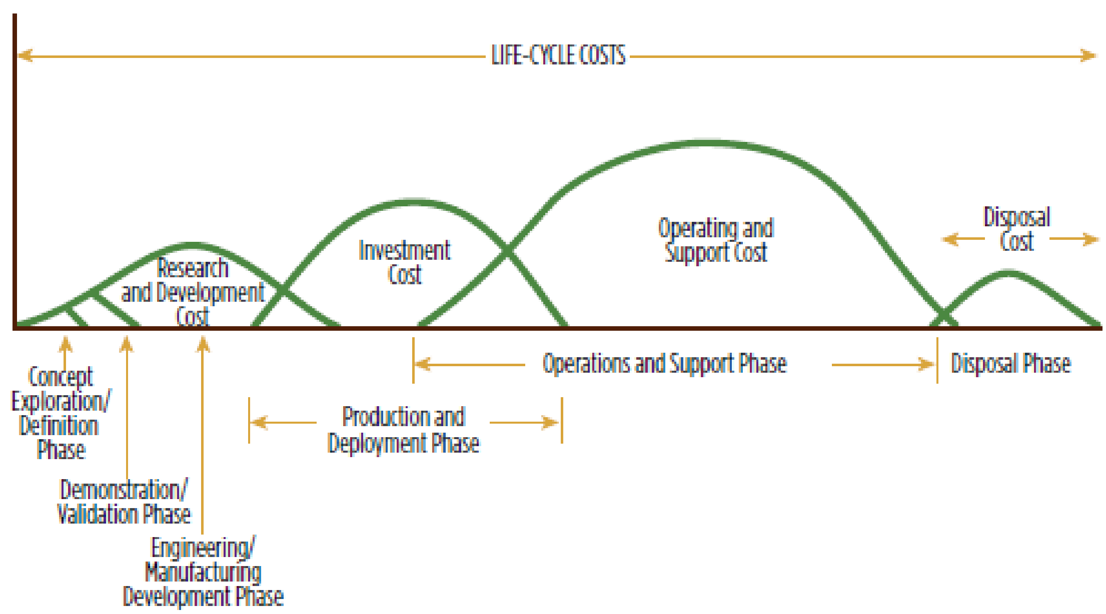


Figure 1: Life-Cycle Costs for a DoD Weapon System (Jones, et al. 2014)

Research and Development includes activities such as creating and testing prototypes. Investment costs can be viewed synonymously as production costs. Disposal costs tend to be minimal, and can usually be simplified into O&S costs (O'Hanlon et al., 2018; Hewitson, et al., 2018). For the purposes of this thesis, we are concerned only with O&S costs. CAPE directs O&S costs are categorized into six main categories as shown in Table 1. Each category also has sub-hierarchies underneath them which further categorize costs into lower levels.

Table 1: Main Categories of O&S Costs from CAPE

Level	Title	Description
1.0	Unit-Level Manpower	Cost of operators, maintainers, and other support manpower assigned to operating units. May include military, civilian, and/or contractor manpower.
2.0	Unit Operations	Cost of unit operating material (e.g., fuel and training material), unit support services, and unit travel. Excludes material for maintenance and repair.
3.0	Maintenance	Cost of all system maintenance other than maintenance manpower assigned to operating units. Consists of organic and contractor maintenance.
4.0	Sustaining Support	Cost of system support activities that are provided by organizations other than the system's operating units.
5.0	Continuing System Improvements	Cost of system hardware and software modifications.
6.0	Indirect Support	Cost of support activities that provide general services that lack the visibility of actual support to specific force units or systems.

The current cost element structure shown in Table 1 originated in 2014. The 2014 change was mostly to the titles with the exception of changing how contractor support was combined under Maintenance (for a detailed analysis of each of the different categories and subcategories and definitions see Chapter 6 of the CAPE O&S Cost estimating guide). While there is natural variation, people, parts and fuel account for 70 to 90 percent of O&S costs (OSD, 2016). For the purpose of this thesis it is important to realize that many factors affecting the costs reported. For instance, Unit-Level Manpower includes operator and maintenance crews, such as air crews. Manpower billets can act more of a function of the total overall budget rather than only tied to the costs of maintaining an engine. Similarly, changes to overall Air Force budget can affect unit operation costs as expenses such as temporary duty travel become subject to higher scrutiny and justification.

Indirect Support costs do not tie directly to any particular weapon system or piece of equipment. Some examples would include base operations support, personnel management, family housing or general training and education such as Professional Military Education. Since these costs are indirect, if they vary after an engine modification, those costs would not tie directly to that engine change; therefore indirect support costs are excluded from this analysis. This approach is also consistent with the Boito et al. (2015) recommendation to include only elements one through five when comparing O&S costs.

Complicating O&S costs, when evaluating modifications is that O&S costs sometimes include continuing system improvements to hardware or software that could be coded as either Research, Development, Test and Evaluation (RDT&E), Procurement or simple O&S costs (OSD CAPE, 2014). Within the same guidance, life cycle estimates for O&S should include a note about assumptions for mid-life upgrades or Service Life Extension Programs (SLEP) associated with the planned system life (OSD CAPE, 2014). The methodology section of Chapter III expands on these concepts and how it is handled where it is relevant.

2.3 How much are O&S costs?

For many programs, the system O&S costs will be the largest of the four cost categories, which is a key reason why there is renewed emphasis on O&S affordability and cost management (OSD CAPE, 2014). Although overall costs did decline somewhat under sequestration around 2013, O&S costs on average are rising (Ferry, 2013). In constant 2019 dollars O&S costs went from $13.5 billion dollars in 1999 to $39.6 billion in 2019 as recorded in AFTOC. Given that the effects of inflation are removed from Figure 2, we would expect the slope of costs to be relatively flat if O&S only kept pace with inflation.

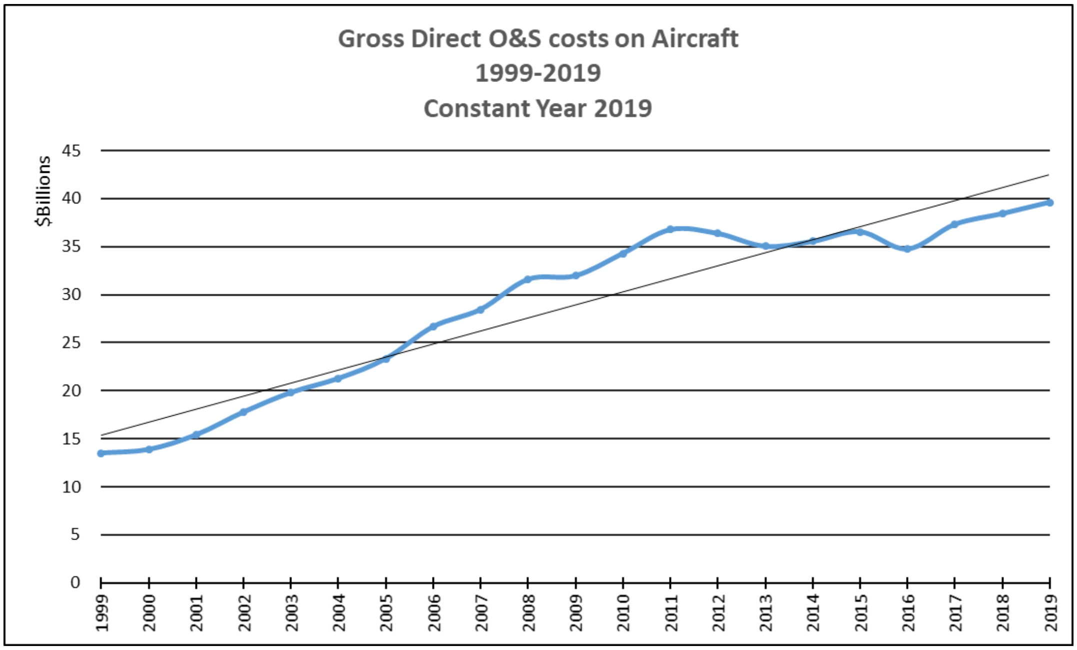


Figure 2: O&S Costs 1999-2019

Conventional wisdom used to hold that O&S, as the longest phase of the life cycle costs, accounted for approximately 70% of total costs. This was coined the "golden ratio." However, Jones, White, Ryan and Ritschel (2014) investigated the accuracy of the golden ratio and discovered that the true cost of O&S varies based on weapon system, with a low of 16% for Space Systems, to a high of 70% for Automated Information systems. The calculated overall average O&S costs across the DoD was around 55%. Even using those more conservative figures, it still holds that O&S costs consist of the majority of a weapon system costs over the life cycle. Jones, et al. (2014) also stated that the tendency to reduce the life-cycle costs of a weapon systems to a single ratio with respect to acquisition costs is impractical.

What remains practical are initiatives to reduce O&S costs. GAO (2010) highlighted the lack of initiatives to reduce O&S costs, and the Air Force pointed to the Expeditionary Logistics for the 21st Century program which had the goal (among others) of reducing O&S costs by 10 percent. The extent to which that happened is unknown. RAND (Boito, et al., 2016) also made a recommendations to senior leadership to place more attention on O&S costs to increase visibility of these costs and their drivers in order to make cost savings improvements. Modifications are one of those O&S cost drivers and the answers to the research questions are designed to help meet this goal.

2.4 Prior O&S Cost Research

Traditionally, the DoD focused cost research on the acquisition component of a system's life cycle instead of O&S costs. Because of this focus, DoD research has managed to gain valuable insights into acquisition costs and how those costs behave over time. These insights formed the framework for acquisition process revisions and cost saving improvements (Ryan, 2012). Ryan, et al. made the further observation that: "Between 1945 and 2009, there were over 130 separate studies and commissions focused on the acquisition of DoD systems, dozens of which involved the nature of acquisition cost behavior. During this same time period, there appears not to be a single published study pertaining to how system costs behave during the O&S phase (2012, pg 363)." Ryan's observations would be supported by the GAO's 2010 conclusion that the DoD lacks key information to effectively manage and reduce O&S costs on most military weapon systems. Further support from GAO came in 2012 that also concluded that weapon system O&S cost estimating and reporting were inconsistent, unreliable, and lacked effective oversight. A similar observation to Ryan (2012) was reiterated more recently by O'Hanlon (2018) who stated that an abundance of military research focused on acquisition and research and development costs while minimal research specifically focused on O&S costs.

This is not to say that there were no studies on O&S results but rather a lack of focus. There are some earlier studies within the DoD which compare the operating costs caused by aging weapon systems. For example, the CBO studied the effects of aging on O&S as early as 2001 and Dixon (2005) also researched the rising costs of aging aircraft. In addition, studies have been performed to exam how to best use O&S dollars in order to increase aircraft availability (Fry, 2010). However, examined as a whole, the DoD did not routinely study O&S costs prior to 2012.

Attention to O&S costs increased with the passage of the Weapon Systems Acquisition Reform Act (WSARA) of 2009. WSARA dictates that within a year from enactment, the Comptroller General is to submit a report on growth in O&S for major weapon systems (Public Law, 2009). Since then, WSARA has served as a catalyst for increased focus on O&S costs in the DoD (Ryan, 2012). Worth noting is that despite this increased focus, there may be no direct measureable linkage between WSARA policies and improvements to the acquisition process (Banford, et al., 2014).

In O&S research many of the studies compare O&S estimates to actuals. This was for good reason since, as of 2012, the DoD had no concept for how O&S cost estimates compared to actual costs (Ryan et al., 2012). A possible reason for this would be that cost reports changed and varied among programs based on metric or time frame (GAO, 2012). That is to say that the earlier studies compared estimates to actual costs instead of focusing on trends within the actual costs themselves, which is the manner of this research.

There has been research related to O&S actual costs and into the many factors that may drive O&S costs. Some cost drivers are more apparent than others, for example O&S costs are theorized to be unique to a particular weapon system; for example, the cost profile and expenditures of a fighter aircraft may be different than that of a cargo aircraft (O'Hanlon et al., 2018). Other research shows that as the US Air Force responds to more threats and increases its Operations Tempo (OPTEMPO), this will lead to the use of more fuel and cause additional wear and tear on the equipment. Both of these factors lead to increases in O&S costs (GAO, 2018). Additionally, as alluded to in Section 2.2, increasing the overall budget will lead to increases in O&S costs. The CBO normalized for increasing budgets in their 2018 study and estimated that the real cost growth associated with aircraft aging generally ranged from 1.5 to 4.1 percent from 1999-2016 (CBO, 2018). Additionally, research has shown that changes to the overall flying hour budget led to changes in O&S expenditures, with the exception of Petroleum, Oil, and Lubricants (POL), which were found to be directly proportional to flying hours, O&S costs have been shown on average to increase by about six percent as flying hours increase ten percent (Unger, 2009).

Other O&S research has had more surprising results; contrary to expectations one finding was that cost O&S cost estimate accuracy should improve as programs mature but in fact, they improve little over the time of a program (Ryan, et al., 2012). Nevertheless, Hewitson et al. (2018) conducted research on the stabilization properties in

O&S costs as a measure of when the variability of costs from year to year and he found that stability results vary by category but generally it is found to occur 80% of the time around five years after the Initial Operating Capability (IOC) phase (Hewitson, 2018).

There have also been studies on O&S cost differences across platforms; for example, in one study a comparison of the O&S costs of 21 platforms with their antecedent showed only seven of them to be cheaper to operate (Harrison, 2013). Since then, studies have also looked at the timing of O&S costs and looked into the bathtub effect where costs are initially high when the system is new, shrink as expertise is acquired and grow again as systems age. Because of this effect, it is also important in cross system comparisons that costs be compared ideally at maturity, meaning when the fleet reaches the maximum size and steady-state in order to have a more homogeneous comparison (Boito, et al., 2015).

A study into newer planes showed a decreasing O&S cost in the maturation phase (CBO, 2018), which is important to take into consideration in cross system comparisons. The importance of good research into O&S cannot be understated as today's acquisitions commit the government to large future obligations in O&S costs (Ferry, 2013). The impact of the magnitude of O&S cost decisions are at their greatest during early design decisions (DoD, 2016). Sustainment strategy decisions originate early in the program lifecycle with significant long-term operational and cost implications (Ritschel and Ritschel, 2016).

2.5 How are O&S Costs are Recorded?

Since WSARA created the requirement for O&S estimates and cost reporting, the DoD has mandated that each military service maintain a historical database of actual

O&S costs for their systems. This led to DoD Directive (DoDD) 5000.4-M, Cost Analysis Guidance and Procedures, which tasked each Component to provide a single authoritative, database for financial and logistics data organized by system or infrastructure. Since then, each military department has developed and maintains their own historical O&S cost data collection system. These data systems were developed in response to an initiative known as Visibility and Management of Operating and Support Costs (VAMOSC). CAPE provides broad policy guidance pertaining to the military department VAMOSC programs, but leaves the details concerning implementation to each department. CAPE took this approach so that each department could make maximum use of its existing unique management information systems (e.g., maintenance data collection or logistics financial management systems) (OSD CAPE, 2014). Though the primary focus of VAMOSC is for future planning and the development of O&S estimates, the nature of the database allows for actual O&S costs to be sorted by weapon system and by year (Ryan, et al. 2012).

In the early stages of the VAMOSC data system, a GAO review showed that the Air Force's and Navy's systems do not collect actual cost data for several cost elements (2010). VAMOSC does not collect actual cost data on some recommended cost elements such as support equipment replacement or modifications. These findings were validated by Boito, et al. when they studied aircraft O&S costs and found challenges with the VAMSOC system specifically, they noted that they did not always capture cost metrics for O&S activities and that metrics should "be formally established and consistently tracked within both organically performed and contracted activities, and periodically reviewed by Air Force leadership in conjunction with corresponding mission performance measures (2016, pg 5)."

Despite early challenges, there is evidence that some improvements have been made. In recent study the GAO determined the information to be sufficiently reliable for the purposes of presenting sustainment metrics, such as aircraft availability and O&S costs, although that study was more concerned with reliability metrics than strictly with costs (2018). This runs contrary to a CBO study that expressed a need for more comprehensive and complete data—specifically, cost and age data for individual aircraft over a longer period so that estimates could be more precise. This level of detail would have allowed the CBO to estimate the effects of aging over the life cycle of aircraft under different budgetary regimes. Those data, however, were not readily available (CBO, 2018).

The Air Force system designed to be compliant with the requirements of VAMOSC is the AFTOC system, or the Air Force Total Ownership Cost system. It provides O&S cost information on all Air Force aircraft, space systems, and missiles. The O&S cost information collected includes unit-level manpower, fuel, depot maintenance overhaul costs, depot-level reparable costs, and other costs of major US Air Force aircraft and engines. AFTOC also maintains data on aircraft quantities and flying hours, numbers of personnel, and other non-cost information (OSD CAPE, 2014). The system provides more than just costs, and, in compliance with the CAPE guide, also provides users with system-level data, as well as lower levels of data (major subsystems and components). VAMSOC data systems, such as AFTOC, should provide O&S-related non-cost data, such as system quantities, manning levels, and operating tempos. [Note: Further information about data fields and AFTOC reporting is available in AFTOC manuals.] AFTOC data presentation is generally well suited for analysis in statistical programs or common software programs within the force.

2.6 Contractor Logistics Support

Contractor Logistics Support (CLS) is another complication to the analysis of O&S costs. CLS is when the contractor performs the maintenance on a weapons system instead of the DoD organically performing maintenance. The popularity of CLS has been rising in recent years and may be beneficial. Ritschel and Ritschel (2016) found that CLS average performance outperforms organic by over three percent for the standard ratio, meaning that the availability rate of aircraft is higher. However, CLS comes as a trade-off since it was found to be more expensive than organic aircraft maintenance. Specifically, they found that the asset specificity phenomenon (propriety advantages) outweighs the benefits of competition such that the contractor's intimate knowledge of complex platforms made up for the monopoly of servicing the aircraft.

The reason CLS can be a challenge for analysis is because VAMOSC systems may collect CLS costs in aggregate but without providing any details by cost elements such as depot maintenance (OSD CAPE, 2014). Within reported CLS costs it is difficult to determine what preciously is being paid for other than the overall category of maintenance. The guidebook states that CLS and Depot cost categories are difficult to categorize since they are likely to include costs for manpower and parts as well as other things such as overhead and facilities (DoD, 2016).

2.7 Reasons for Engine Upgrades

Saving money is a job of Program Managers (PM) who must manage O&S costs to realize more affordable programs, and DoD leadership expects the PM to report progress toward meeting affordability requirements at program reviews. Because of this, it is important that O&S data be collected so that the PM or Component can evaluate the success of the O&S cost management efforts (DoD, 2016).

Aging aircraft is itself a driver of cost increases. The Heritage Foundation reported that, as of 2019, the average age of our aircraft is over 29 years, yet the Air Force has no plans to raise acquisition rates for the F-35 or KC-46 to buy down that average (Heritage Foundation, 2019). Another alternative to replacing a fleet is to replace an engine, a major driver of O&S costs. This is the tactic employed by the B-52 program office to extend the life of that fleet while capturing reductions in fuel costs (Air Force, 2017).

The Air Force has commissioned studies to investigate the savings potential from installing more fuel efficient or more reliable engines. One such example was a 2016 RAND study discussing potential C-130 improvements such as engine-out taxiing, optimum flying levels and speeds, weight reductions, load-balancing improvements, reducing auxiliary power units, and installing microvanes. RAND suggested that full implementation of these options would save about 16 million gallons of fuel annually (Boito, et al., 2016). This can be compared to the savings of a new engine as discussed in Chapters IV and V. These types of modifications are becoming more and more important as AF systems age.

Some other reasons for engine upgrades are unrelated, or tangentially related, to costs savings, they may entail adding capabilities or improving readiness. Either of these types of modifications could increase or decrease costs and are trade-offs for the PM and higher leadership to decide, but their decision depends on quality analysis of what those trade-offs will cost.

2.8 Chapter Conclusion

O&S costs are expensive and increasing. Many legacy systems are experiencing growth in O&S costs that will require mitigation. In the past, the DoD neglected proper analysis of the behavior of O&S costs, which has led to a recent increase in O&S studies. The reason for these studies is highlighted in Appendix C of the OSD CAPE Cost Estimating guide which provides an example of how O&S cost estimates can be an important input to a decision that is often faced by DoD, namely to replace a fleet now, or to upgrade the current fleet and defer replacement until later. One alternative, is to retire the legacy systems and replace with new; another alternative is to upgrade the legacy systems to extend the system service life. For the first alternative, it is assumed that the procurement cost will be lower for a system upgrade than for a new replacement system. This assumption relies on a second level assumption that the new replacement system will have lower O&S costs due to improved reliability, performance or maintainability. In order to properly perform such an analysis, the quantifiable effects of a proposed modifications would need to be estimated and the answers to the research questions posed in Chapter I could direct such an analysis.

III: Data Collection and Methodology

3.1 Chapter Overview

This chapter documents the method of data collection and the required analysis to address the research questions from Chapter I. We first discuss the process of data collection, screening, and standardization as well as the limitations and assumptions related to Air Force data collection methods. We then discuss the methods used to compute and to compare cost and performance metrics. Both descriptive and inferential analysis are used, with an emphasis on the descriptive analysis due to the small sample size. Consequently, the proposed methods are more exploratory than confirmatory as discussed near the end of the chapter.

3.2 Data Limitations

The optimal approach to compare engine performance or cost would be by aircraft tail number in order to compare and to contrast specific aircraft before and after a new engine installation, which would minimize any other external factors. Unfortunately, this ideal approach is impractical Air Force data collection systems. Fuel consumption and flying hours are available by tail number based on the Fuel Automated System (FAS) and is available within AFTOC, but not engines. Neither program offices nor AF data systems track modifications or engine upgrades by tail number. Aside from programmatic information, such as fuel consumption and flying hours, sustainment costs are not available by engine at all. Air Force Lines of Accounting do not isolate a particular tail number or engine. The lowest level of direct data allocation is at the aircraft, or Mission Designation Series (MDS), level as captured by a combination of the data elements, namely the Program Element Code (PEC), Operating Agency Code (OAC) or Resource Center/Cost Center (RC/CC).

AFTOC compiles data into various “data cubes,” sometimes called “universes,” which encapsulates a category of costs. In this research, the three principle data cubes are the CAPE 14 data cube, which contains the aggregate costs from financial systems, the Engine Programmatic data cube which reports fuel usage, flying hours etc. and the CAPE14 Engine Data Cube, hereafter just Engine data cube which attempts to match costs reported in the CAPE14 data cube to aircraft engines using a variety of business rules. There is no Line of Accounting element tied to engines, so the reported Engine data is approximated by using ratios from the REMIS (Resources Management Information Systems) flying hours and comparing them to CEMS (Consolidated Engine Management System) Engine Actuarial data (AFTOC fact sheet, 2017). The engine cost information used in this research is are therefore approximations.

Because of these limitations in how the Air Force collects source data, it is not possible to isolate the effects of new and old engines unless they belong to a separate MDS. One example where this is the case, as highlighted in Chapter I, is with the C-5. The C-5A, B and C all use the TF39-GE-1 engine exclusively. The new F138-GE-100 engine was given its own MDS, the C-5M. Only because of the creation of a new MDS, which is distinguished by the new engine, is it possible to compare the costs of the old engine with the new engine. In the event that a new engine is not isolated to its own MDS, costs are estimated on a proportionate basis as reported by AFTOC Engine data cube. This second approach introduces variation into the computation since it relies on the assumption that the percentage of aircraft with newer engines equates to the same percentage of the flying hours for any particular MDS.

3.3 Engine Inventory Analysis

A first step for comparative analysis is to isolate aircraft platforms with more than one engine, in other words to generate a listing of MDS categories with more than one engine type/model/series (TMS). For the purpose of this analysis, a MDS category is a shared airframe within a larger parent MDS, for example, the various aircraft sharing the C-130 airframe (i.e. AC-130, EC-130, etc.) would count as one MDS category under a parent MDS of C-130. AFTOC did not have an available report field to extract an inventory number of engines, but this information is available from CEMS, which is incorporated into AFTOC. Therefore, the AFTOC helpdesk was able to compile a database of engine inventory by TMS, base, aircraft platform, and serial number. The available information covered 1996 to 2019. This is all the information required to determine which engines aligned to which MDS and if the inventory was increasing or decreasing over the timeframe.

The resulting database contains inventory data by quarter and has over a million rows of data. The initial database had 166 different MDSs and 65 distinct engines as designated by TMS. Approximately 250 rows had no associated aircraft and were deleted. Much of the remaining database was not usable for the purposes of this analysis and therefore needed to be reduced to only the relevant aircraft as we discuss next. Four of the MDSs were Air Cruise Missiles engines that are outside the scope of analysis and were excluded.

Helicopters have a lower O&S profile compared to fixed wing aircraft. Using AFTOC total O&S numbers, helicopter O&S costs on average 18% of what fixed wing aircraft cost. Helicopter engines also operate in a fundamentally different manner than turbojet, turbofan, and turboprop engines as they generate lift through shaft power rather than thrust (MacIsaac & Langton, 2011). Using the metric of gallons per flying hour (see Section 3.4 for the discussion of metrics used), Figure 3 shows that in flying hour terms, helicopters operate a full order of magnitude more efficiently than the fixed wing categories (the MC-12 was removed because of AFSOC reporting abnormality not relevant to the rest of this thesis).

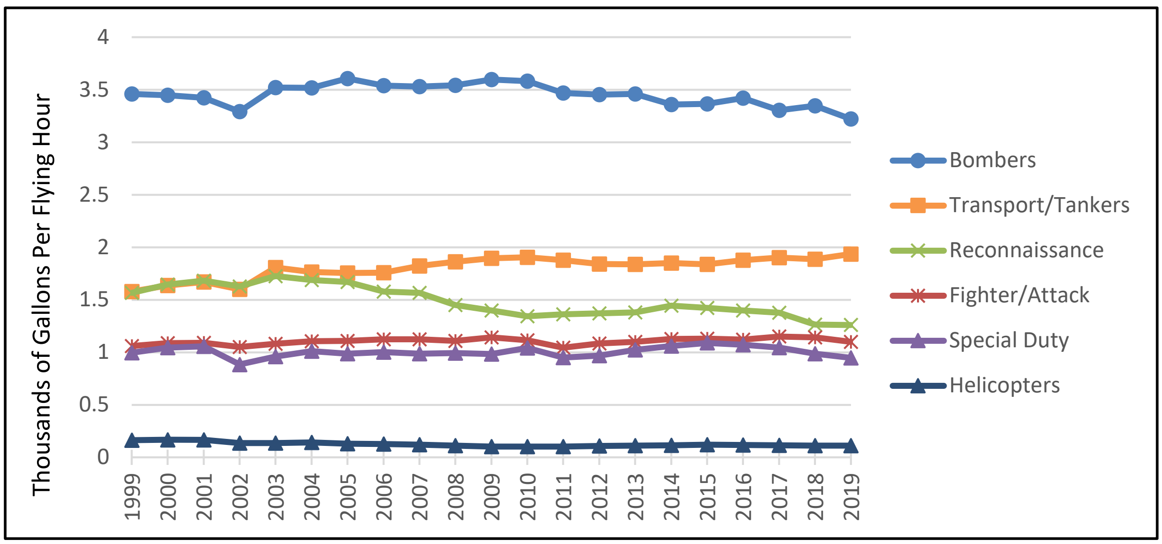


Figure 3: Gallons per Flying Hour by Aircraft Category

Helicopters consist of 15 different MDSs and nine different Engines. Only two engine systems experienced an increasing inventory over the time period, the CV-22B and the TH-1H. The CV-22B entered into the service in 2006 and has no basis for comparison with other MDSs in AFTOC and this eliminates it from analysis. The other new engine is the T53-L-703 associated with the UH-1H and the TH-1H, which is comparable to the T400-CP-400 on the UH-1H. The analysis between these models is complicated by the fact that the TH-1H models are used in training where the usage profile could be expected to deviate from operational use. For these reasons, helicopters are analyzed separately from fixed wing aircraft in this analysis. Within this research, aircraft refers to fixed wing aircraft and helicopters will be referred to as helicopters.

Drones also have a distinct O&S profile from manned aircraft as they have no pilots and operate on a distinct system software. Drones include 11 MDSs, which share ten engines. They were examined separately from the rest of the database, however within the drone data there are no reengine modifications available for analysis and therefore drones were excluded from any further analysis.

The data was then examined for a one-to-one relationship with a weapon system and an engine. If a particular MDS category exclusively matched with only TMS, then those data points were excluded for not having two engines to compare performance. This removal represented almost a third of the total database representing 39 MDS variants and 18 associated TMSs. The list of excluded engines and MDS are in Table 2.

Table 2: Aircraft Excluded from Analysis for Lack of Comparison

MDS Category	TMS	MDS Category	TMS
A-10	TF34GE100	F-117	F404GEF1D2
B-1	F101GE102	F-22	F119PW100
B-2	F118GE100	KC-10	F103GE101
C-141	TF33PW7	T-1	JT15DPW5
C-17	F117PW100	T-37	J69TCO25
E-3	TF33PW100	T-38	J85GE5
E-4	F103GE100	T-39	J60PW3
EC-18	TF33PW102	T-6	PT6APW68
F-111	TF30PW109	U-2	F118GE101

Despite initially passing the criteria of having more than one TMS engine within a MDS category, other aircraft (AC) were excluded from analysis. The NC-130 variants were removed since they were a prototype, were too small in inventory with a maximum of two aircraft, and were modified in such ways that the fuel efficiency would not be comparable with the other 130 variants. Additionally, the EC-18 and E-8 category of aircraft were excluded from analysis despite the fact that they shared the TF33-PW-102 engines with the C-135 models. The EC-18 aircraft has a sufficiently modified mission as well as an airframe design that would have separate effects on fuel efficiency; the nose of the aircraft has a different aerodynamic shape and holds distinct equipment. The KC-135A and the C-137B and C were excluded since there were no active aircraft of these types during the period of analysis.

Upon first glance, the B-52H appears to have two engines, the TF33-103 and the TF33-PW-3. The later engine is not mentioned within the Engine Handbook. Upon request, AFLCMC researched the engines for analysis and revealed identical specifications between the two engines. This led to a request to the System Program Office (SPO) which confirmed that the two engines are the same (C. Honious, personal communication, Dec 10, 2019). With this information, the B-52H was removed from analysis.

Problems in the source data led to the exclusion of the F-4 categories of Aircraft. The Fuel Automated System (FAS) underreported the F-4 fuel consumption and this is a known deficiency documented by AFTOC in a 30 August 2019 factsheet. This error leads to an unreliable measure of fuel consumption, even going into negative amount of fuel per flying hour in 2004. Because of this deficiency in the source data, the F-4 and its variants were altogether eliminated from further analysis.

After all these exclusions, only five MDS categories remain, the various C-130s, C-135s, F-15s, F-16s, and the C-5s. One of the C-130 engines, TF33-PW-105, is a very low inventory engine, reaching six engines at its peak, which means it would correspond to at most one aircraft. Because of this small effect size, it was excluded. The remaining categories include 17 engines and 80 MDSs. The MDS breakout includes two fighter aircraft, the F-15 and F-16, and three categories of cargo aircraft/refuelers, the various C-5, C-130 and C-135 variants such as the KC-135. Of the 17 engines, only three are new engines that the Air Force introduced into the Air Force inventory since 1996, the F138-GE-100 on the C-5M (in FY2010), the AE2100 on various C-130"J" models (in FY2016), and the F108-GE-201 on various C-135 models (in FY2001). Seven of the 17 Engines fully phased out or retired.

Summarizing this section, Table 3 is the inclusion/exclusion table that shows the criteria used to find the MDS to engine pairings used in the subsequent AFTOC data pulls described in Section 3.4. Appendix A contains a table listing the aircraft and engines considered in the analysis, including the last 42 exclusions. The Total Inventory column in Appendix A is not a count of the engines but is an inventory over time. That is, if a particular engine serial number was in use from 1996-2018, then it would have been counted each year and would account for 23 in the Total Inventory column.

For helicopters, the only pairing that could be found among helicopters with four or more PAA with more than one engine is the T53-L-703 and T53-L-13 on the UH-1H and the TH-1H, which is comparable UH-1N which operates on the older, but still in service, T400-CP-400 TMS.

Table 3: Inclusion/Exclusion Table from Engine Analysis

Criteria	Rows	MDSs	MDSs Excluded	Justification
Starting with	1,048,575	166		
Blank MDS	252	--	--	No MDS assigned
Cruise Missles	102,179	4	AGM-86B ALCM, AGM-129A ACM, AGM-86C CALCM, AGM-86D CALCM	Cruise Misses outside scope of analysis
Helicopters	28,434	15	CV-22B, GHH-1H, HH-1H, HH-3E, HH-60G, HH-60U, MH-53J, MH-53M, MH-60G, TH-1H, TH-53A, UH-1H, UH-1N, UH-1V, UH-60L	Analyzed Separately
Drones	10,007	10	MQ-9A, QF-106A, QF-106B, QF-16A, QF-16C, QF-4E, QF-4G, QRF-4C, RQ-4A, RQ-4B	Analyzed Separately
No Pairs	310,421	39	A-10A, A-10C, AT-38B, B-1B, B-2A, C-141B, C-141C, C-17A, C-20B, CT-39A, E-3B, E-3C, E-3G, E-4B, EC-18B, EC-18D, EF-111A, F-111E, F-111F, F-117A, F-22A, GA-10A, GA-10C, GC-141B, KC-10A, KC-46A, NC-141A, NT-39A, OA-10A, RC-26B, T-1A, T-37B, T-38A, T-38C, T-39B, T-6A, TC-18E, TU-2S, U-2S	Not able to isolate the effects of an engine if there is a one-to-one relationship between MDS and engine
E-8s	3,897	3	E-8A, E-8C, TE-8A	Shared Engine with some C-135 models but too dissimilar in function
NC-130s	246	3	NC-130A, NC-130E, NC-130H	Shared Engine with some C-130 models but too dissimilar in function
KC-135A	30	2	KC-135A, NKC-135A	No Active Aircraft 1999-2019
C-137B/C	11	2	C-137B, C-137C	Only one Active Aircraft 1999-2019
B-52	48,761	2	B-52H, GB-52H	Only one Engine despite the appearance of two
F-4	2,695	6	F-4C, F-4D, F-4E, F-4F, F-4C, RF-4C	Problem in Source data
Fewer than 5 PAA	535,995	42	AC-130A, C-130A, C-130B, C-135A, C-135B, C-135C, C-135E, C-5C, EC-135C, EC-135E, EC-135H, EC-135J, EC-135K, EC-135N, EC-135Y, GC-130E, GC-130H, GF-15A, GF-15B, GF-15C, GF-16A, GF-16B, GF-16C, GKC-135E, KC-135D, NC-135W, NF-16A, NF-16D, NKC-135B, NKC-135E, OC-135B, RC-135S, RC-135U, TC-130H, TC-135S, TC-135W, WC-135B, WC-135C, WC-135W, YF-15A, YF-15B, YF-16A	Limit analysis only to aircraft common force, and reduce noise caused by special purpose Aircraft
Ending With	5,647	38	(See Table 6 for List)	

Table 4 contains a listing of the specifications of the engines used in the analysis. Engine specifications are available from the 2014 Engine Handbook as prepared by the Director of Propulsion from the AFLCMC. In some cases, such as the max thrust for the T56-A-7B, the data was not available in the Engine Handbook. Table 5 is a similar listing for the Helicopter engines, where the T53-L-13 is not in the Engine Handbook.

Table 4: Aircraft Engine Specifications from Engine Handbook

TMS	AC	Status	Type	Manufactor	Max Thrust	Normal Thrust	SFC	Starting	Retired
T56-A-7B	C-130	Retired	Turboprop	Allison & Rolls Royce	--	3,443	0.541	--	2013
T56-A-15	C-130		Turboprop	Allion & Rolls Royce	4,591	4,061	0.560	--	--
AE-2100D3	**C-130J**	**New**	**Turboprop**	**Allion & Rolls Royce**	**4,637**	--	--	**2016**	--
TF33-P-9	C-135	Retired	Turbofan	Pratt & Whitney	18,000	14,760	0.505	--	2004
TF33-P-5	C-135	Retired	Turbofan	Pratt & Whitney	18,000	16,400	0.515	--	2006
TF33-PW-105	C-135	Retired	Turbofan	Pratt & Whitney					2004
TF33-PW-102	C-135	Retired	Turbofan	Pratt & Whitney	18,000	14,800	0.505	--	2009
F100-PW-100	F-15	Retired	Turbofan	Pratt & Whitney	23,480	12,410	0.690	--	2010
F100-PW-220	F-15/6		Turbofan	Pratt & Whitney	23,770	12,410	0.710	--	--
F100-PW-229	F-15/6		Turbofan	Pratt & Whitney	28,500	15,130	0.700	--	--
F100-PW-200	F-16	Retired	Turbofan	Pratt & Whitney	25,000	12,410	0.690	--	2003
F110-GE-100C	F-15		Turbofan	General Electric	28,000	14,870	0.673	--	--
F110-GE-129B	F-16	Active	Turbofan	General Electric	28,737	15,440	0.670	--	--
F108-CF-100	C-135		Turbofan	CFM International	21,634	21,194	0.361	--	--
F108-CF-201	**C-135**	**New**	**Turbofan**	**CFM International**	**21,634**	**21,194.000**	**0.361**	**2002**	--
TF39-GE-1C	C-5		Turbofan	General Electric	40,805	35,790	0.310	--	2017
F138-GE-100	**C-5M**	**New**	**Turbofan**	**General Electric**	**51,250**	**38,684.000**	**0.372**	**2010**	--

Table 5: Helicopter Engine Specifications from Engine Handbook

TMS	MDS	Status	Type	Manufactor	Max Thurst	Normal Thurst	SFC	Starting
T400-CP-400	UH-1N	Active	Turborshaft	Pratt & Whitney	1800	1530	0.606	--
T53-L-703	TH-1H	New	Turboshaft	Lycoming		1025	0.568	2006
T53-L-13	UH-1H	New	Turboshaft	Lycoming				2006

3.4 AFTOC Data pulls

The query for engine costs required three pulls from separate databases within AFTOC. In the first, programmatic information was pulled in order to find the PAA of the MDSs listed in Appendix B. The purpose of this was to investigate for aircraft with a PAA of less than five in order to exclude them, as already seen in Table 3. In other words, if the Air Force did not operate at least five of a particular MDS in any of the years under consideration, then that MDS platform was excluded. Aircraft with a small PAA may have an overly influential effect in the database as errors will have a larger effect and any fixed effects within the figures will have a greater impact. Using this exclusion criteria, the analysis was able to eliminate 24 of the C-135 variants reducing the analysis to five, while keeping approximately 95% of the C-135 aircraft (mostly KC-135s) in consideration. From here the analysis centers on the 38 remaining MDSs as shown in Table 6.

Table 6: Aircraft MDSs with 5 or more PAA

C130			C-5	C-135	F-15	F-16
AC-130H	EC-130E	MC-130E	C-5A	KC-135E	F-15A	F-16A
AC-130J	EC-130H	MC-130H	C-5B	KC-135R	F-15B	F-16B
AC-130U	EC-130J	MC-130J	C-5M	KC-135T	F-15C	F-16C
AC-130W	HC-130J	MC-130P		RC-135V	F-15D	F-16D
C-130E	HC-130N	MC-130W		RC-135W	F-15E	
C-130H	HC-130P	WC-130H				
C-130J	LC-130H	WC-130J				

The second AFTOC data pull was from the Engine Programmatic data cube. This data cube contains the fuel costs, flying hours from REMIS, and fuel usage from the Fuel Automated System (FAS) and pulled only for those MDSs in Table 3. There are no costs in this data cube; so it will be used to compute and to compare performance metrics only as discussed in Chapter IV, sections two through seven. In the analysis in Chapter IV, outliers from this metric can be removed. While it is possible an aircraft has a fuel leak or some other reason for wild changes in performance, large outliers are not expected and are likely traced to errors in the source data.

AFTOC created the Engine data cube in response to field requests to track O&S costs by engines. Those costs which are directly attributable to an engine should appear here. However, it is important to realize that not all engine costs can be tied directly to an engine and are therefore not captured within this cube. Of significant note is that CLS costs are not reported in the engine data cube, which will serve to severely underestimate the costs and therefore any savings that are analyzed in Chapter IV.

3.5 How Metrics are Considered

It would be unfair to compare fuel costs without normalizing for usage. If operations tempo increases over time, then costs will vary in accordance with that usage instead of the engine. In order to isolate the effects of the engine costs the most efficient metric available within the database is the number of gallons used divided by the number of flying hours. Using the metric of Gallons / Flying Hour (fuel consumption) should have the effect of creating a homogeneous comparison as long as the comparison is within similar aircraft in the same MDS category. If all else could be held equal, changes in Gallons / Flying Hour would be reasonably well isolated to the new engine.

Unfortunately, the comparison cannot be perfect since there will be errors in the data and measuring inefficiencies. Even if these did not exist, all else cannot be held constant since fuel efficiency varies by altitude, atmosphere conditions, and cruise speed (Rolls Royce, 2005 pg 75), none of which are captured within AFTOC. Aircraft with few flying hours may have a distorted Gallon / Flying Hour metric caused by the fuel used in take-off and landings and taxiing, especially since flying hours are in the denominator of the metric. Since this analysis attempts to quantify the effects of average usage, aircraft with fewer than 20 flying hours by fiscal year were removed. This removal represented 1063 flying hours out of 18 million. In addition, four data points also showed zero or no fuel usage and were removed.

Maintenance costs are normalized to base year 2019 in order to remove the effects of inflation. While maintenance costs do vary by flying hour in the same way that mileage affects automotive maintenance, the number of aircraft is even more important for cost normalization. In accordance with a RAND 2015 study, PAI is inherently more stable than flying hours and is the preferred metric by subject matter experts. This thesis uses PAI to normalize maintenance costs within MD categories (Boito, et al. 2015). In summary, the metrics used are Gallon / Flying Hour for performance metrics, and for maintenance costs it will be BY2019 Maintenance costs / PAI excluding CLS.

3.6 Statistical Method Employed

In all cases the data is first visually observed in order to remove outliers where appropriate and to gauge the sense of the differences in the engines. Graphs and statistical tests are generated using the statistical software program JMP 13 Pro. The most common test for comparing differences in means is a student t-test, however this method is inappropriate when the underlying distributions are non-normal. Therefore, we follow visual examinations of the data with the Wilcoxon Rank Sum test, also called the Rank Sums test. This non-parametric method does not require normality and provides more robust comparisons in addition to being less susceptible to outliers. The chosen α of 0.10 as stated in Chapter I is applied to all Rank Sum tests.

3.7 Chapter Conclusion

In order to quantify costs, we must first determine comparable MDSs that share a similar aircraft frame but that operate on two or more engines. Only five categories of MDSs met this requirement, with only three of them having new engines since 1999, all three on cargo aircraft. Seven engines retired over this time frame, which introduces the two fighter aircraft into the analysis. Lastly, among helicopters, only one engine is present creating another pairing. The data analysis is limited to these engines.

This chapter started with a discussion of the limitations in how the AFTOC system collects O&S data. The lowest level of data available is at the MDS level, which does not allow for pinpoint accuracy on the effects of modifications or engines; that data is simply not available. The engine data cube does approximate engine costs based on time on wing ratios, but it excludes some major expenses, most significantly CLS.

In contrast to those limitations on cost, performance metrics are discernable at the engine level since data is collected this way. Here the performance in fuel efficiency can be calculated and gallons saved per flying hours along with cost savings can be calculated from that. In Chapter IV we present the findings from the data cubes created for analysis in this chapter.

IV: Analysis and Results

4.1 Chapter Overview

This chapter discusses the results of the analysis. Except where noted, descriptive patterns for engines are grouped into three broad color-coded categories: red for new engines, green for retired engines, and blue for engines that are active over the whole study period. For the performance metrics, the data is first examined for outliers, which will be removed. Then, by MD category we visually show the graphs of the data for fuel performance metrics (Gallon / Flying Hour) to observe the effects of new engines. Following that is a discussion of the results of the Wilcoxon Rank Sum statistical tests. After examining fuel performance metrics, we investigate the MD categories by maintenance costs associated with their engines and limitations. The Wilcoxon Rank Sum test is used again to statistically test and quantity the differences between the engine categories.

4.2 Fuel Performance Characteristics of C-130 Models

In Figure 4 we can see the outliers removed from the C-130s. Only the figures showing MD category are shown within this analysis. Outliers for each MD category are further examined within the specific TMS and MDS to ensure that they are outliers. Outliers are determined by visual examination on the relative effect they have on the trend line within their category. While engine fuel performance does vary, large outliers are more likely the result of faulty data collection, such as an underreporting of flying hours, instead of actual fuel performance of the engine and as such are excluded.

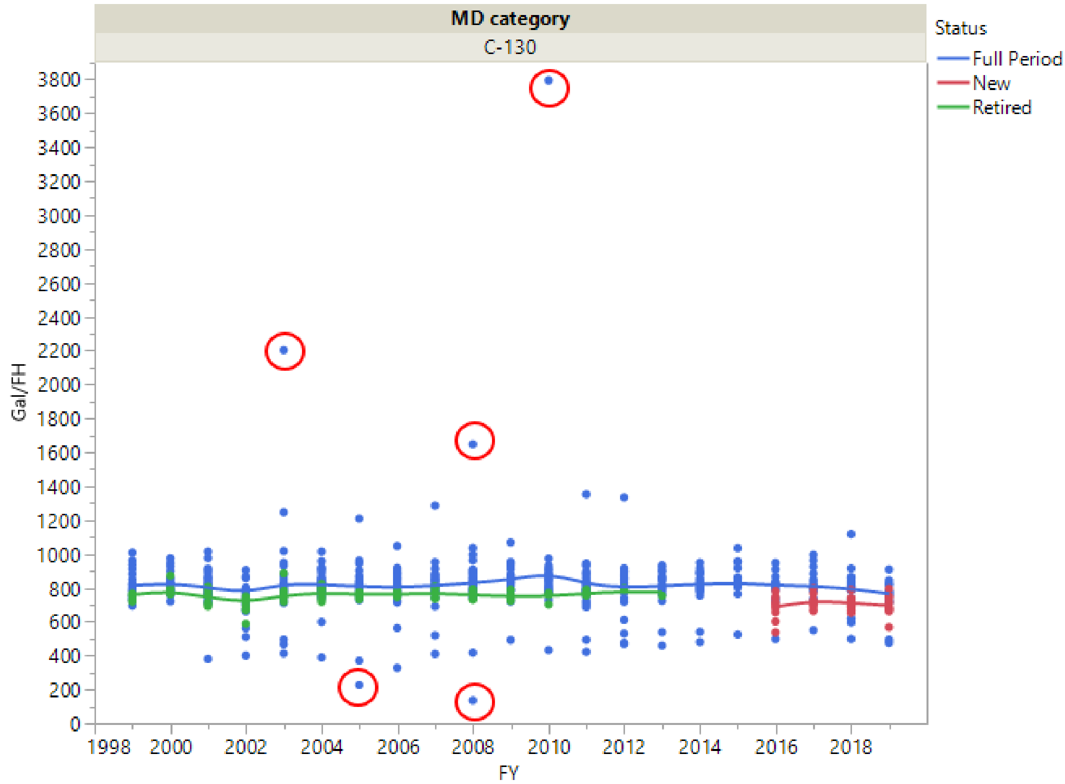


Figure 4: C-130 Outliers Removed

Figure 5 highlights the LC-130 models whose performance is atypical. The LC-130H operates in the Antarctic and has skis instead of landing gear, which explains why its fuel efficiency metrics appear to be different. In order to capture the mean performance of the T56-A-15 engine, which is on multiple C-130 variants, the LC-130 was removed from the analysis.

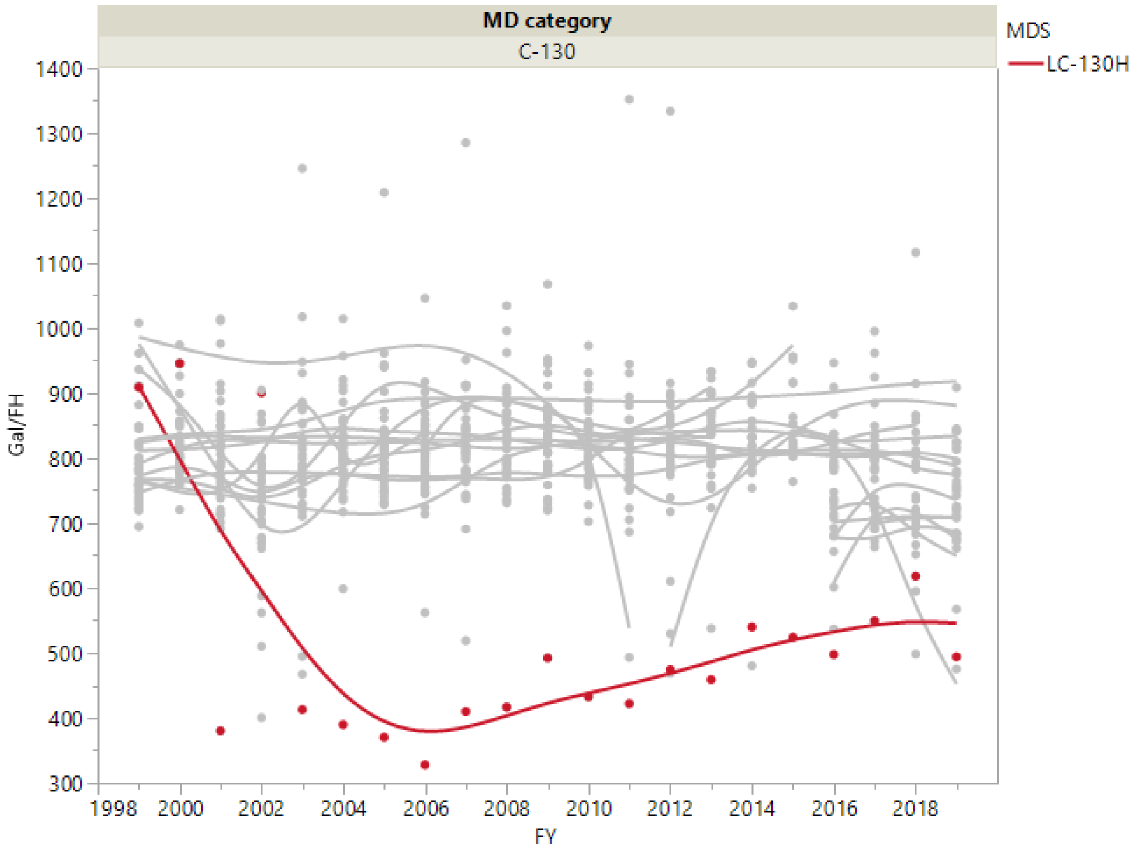


Figure 5: Atypical Fuel Performance of the LC-130

Figure 6 shows the final chart of C-130 performance with the outliers from Figure 4, and the LC-130 from Figure 5 removed. The new engines, (belonging to the –J models) are in red and appear to have a lower gallon per flying hour than the other C-130 models. The Wilcoxon Rank Sum Test results are shown in Table 7.

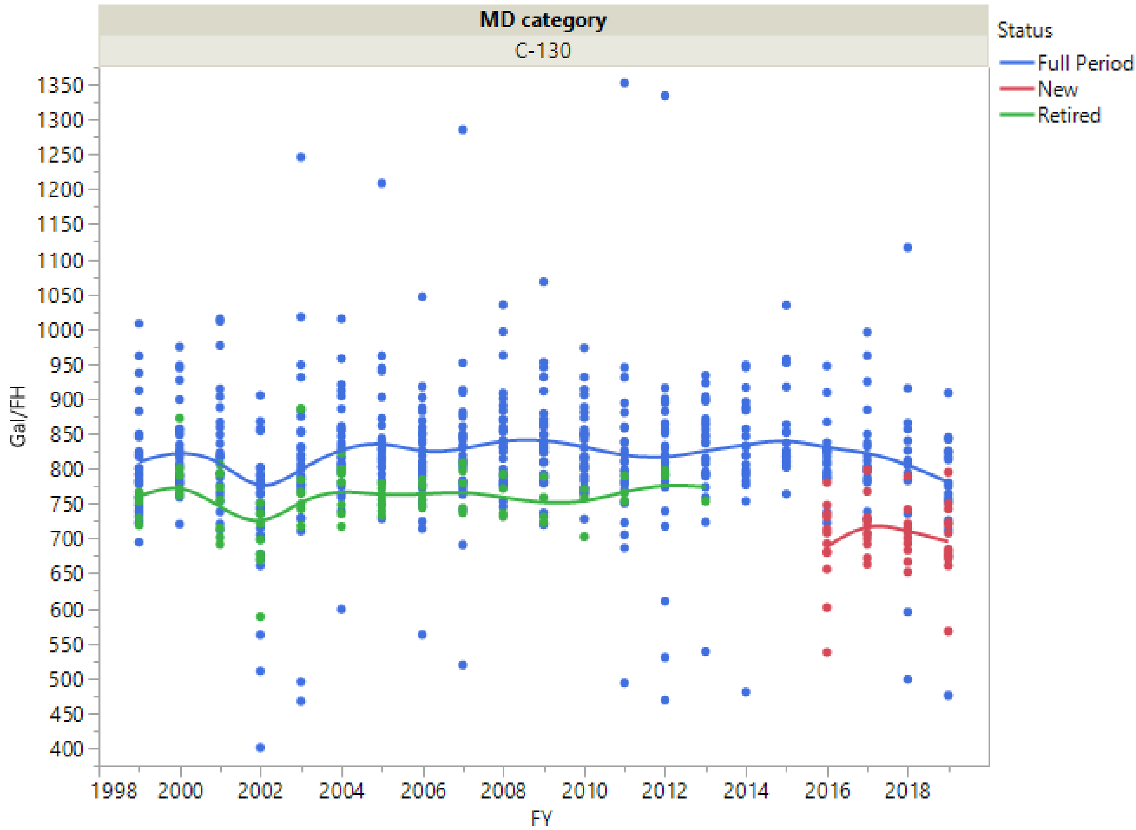


Figure 6: C-130 Models Fuel Performance Metrics

Table 7: Wilcoxon Rank Sum Test Results of C-130 Fuel Performance

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.64485	0.1

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
Retired	New	12.876	3.71176	3.46907	0.0005*	42.401	28.843	60.6427
Retired	Full Period	-84.458	18.61405	-4.53734	<.0001*	-70.008	-93.009	-51.1680
New	Full Period	-108.581	16.18356	-6.70937	<.0001*	-114.773	-135.316	-94.1525

Each test is statistically significant suggesting that there is a difference between each of the categories of engines at the α of 0.10. The score mean difference between the retired and the new is 12.9, which means that the retired engine's performance is higher on average. Since it has a higher Gallon / Flying Hour ratio the new engine is more fuel efficient. The Hodges-Lehmann column is the estimated median performance difference. In this case the new engine is performing more fuel effiecnetly on average by 42.4 gallons per flying hour, with a 90% confidence that we captured the real performance improvement between 28.8 to 60.6 fewer gallons per flying hour. The interpretation for the other two lines is the same with the exception that the sign is negative. Focusing on the last row, the new engine scored a negative 108 when compared to an engine encompassing the full period. This lower Wilcoxon Rank Sum score reflects better fuel performance measured by fewer gallons used per flying hour. Using the Hodges-Lehmann value in the last row of Table 7, each flying hour on the full period engine (T56-A-15) is burning an additional 115 gallons of fuel when compared to the new engine (AE-2100) in median fuel performance.

4.3 Fuel Performance Characteristics of C-135 Models

Three data points on the C-135s were deleted as shown in Figure 7. There are a cluster of data points below one of the removed outliers belonging to the new engine. Since there are five data points in the same general region they were not be removed using the justification of an error in data collection/reporting and further investigation is warranted. The cluster belongs to the RC-135V/W models and when overlaid by using command (and not engine status) as can be seen in Figure 8, it is observed that Air Force Material Command (AFMC) appears to have a distinctive fuel performance profile compared to Air Combat Command (ACC). This may be explained by how AFMC is using the engines in a testing environment. In order to isolate the effect of the fuel performance in operational use of the engines the data points in the AFMC cluster were also excluded for Figure 9. A further discussion of fuel usage by Command is in Chapter V and Appendix C.

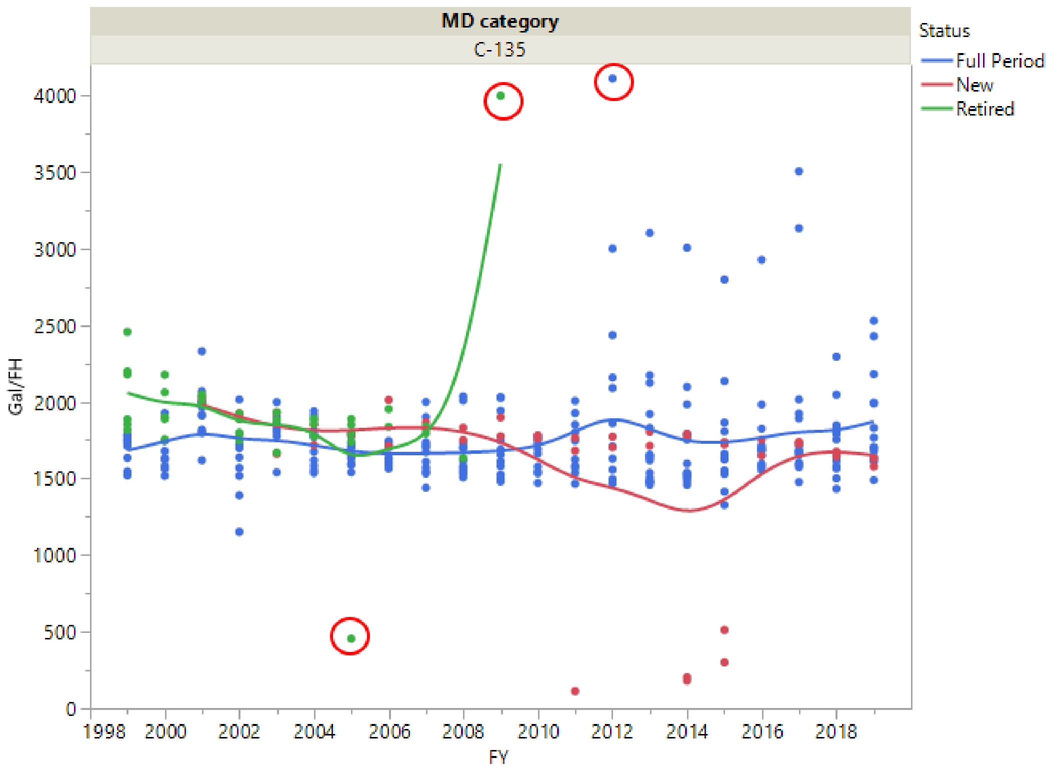


Figure 7: C-135 Outliers Removed

Figure 9 shows the performance of the various C-135 models. Of note, there are three engines comprising the retired category. The performance of all three are still within a relatively small range with the two outliers removed. The fuel performance is not clearly lower than full period engine from the figure.

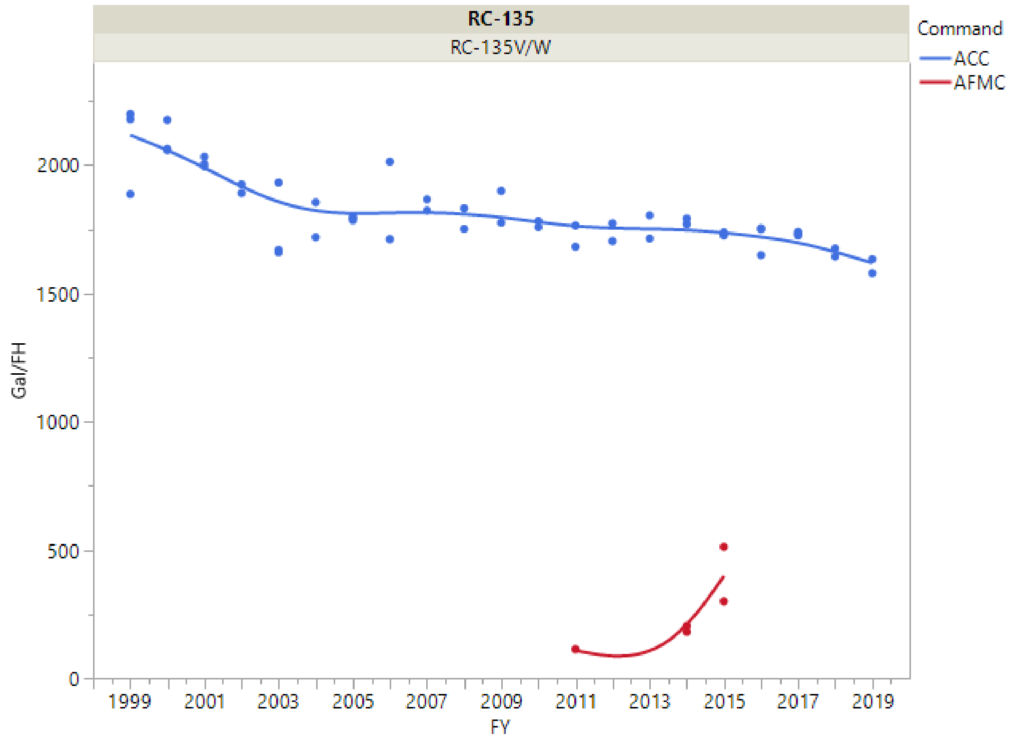


Figure 8: C-135 Fuel Performance by Command

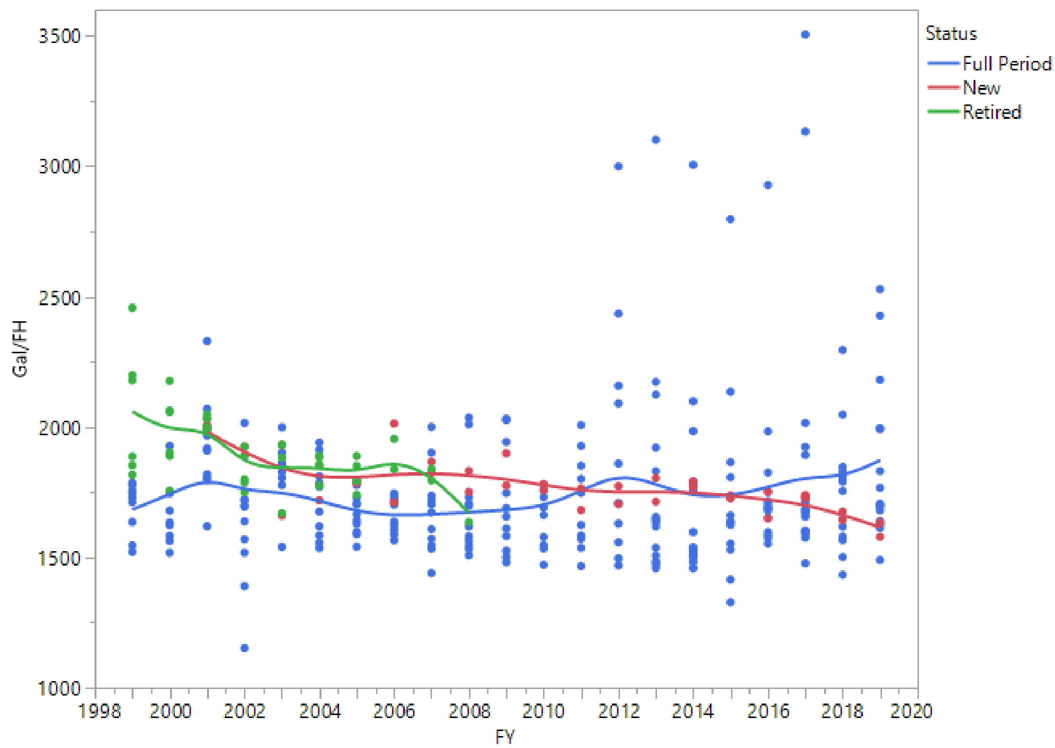


Figure 9: C-135 Models Fuel Performance Metrics

Since the missions of C-135 models are distinct (refueling versus reconnaissance) it makes more sense to compare them by sub-MDS categories as seen in Figures 10 and 11. Figure 10 is for the KC-135E (using the retired engine) compared with the KC-135R/T. Figure 11 is of the RC-135V/W, in Figure 11 the overlay is by engine instead of since they transition from three engines to one. Once broken down in sub categories the fuel efficiency performance is clearly distinguishable as compared to Figure 9.

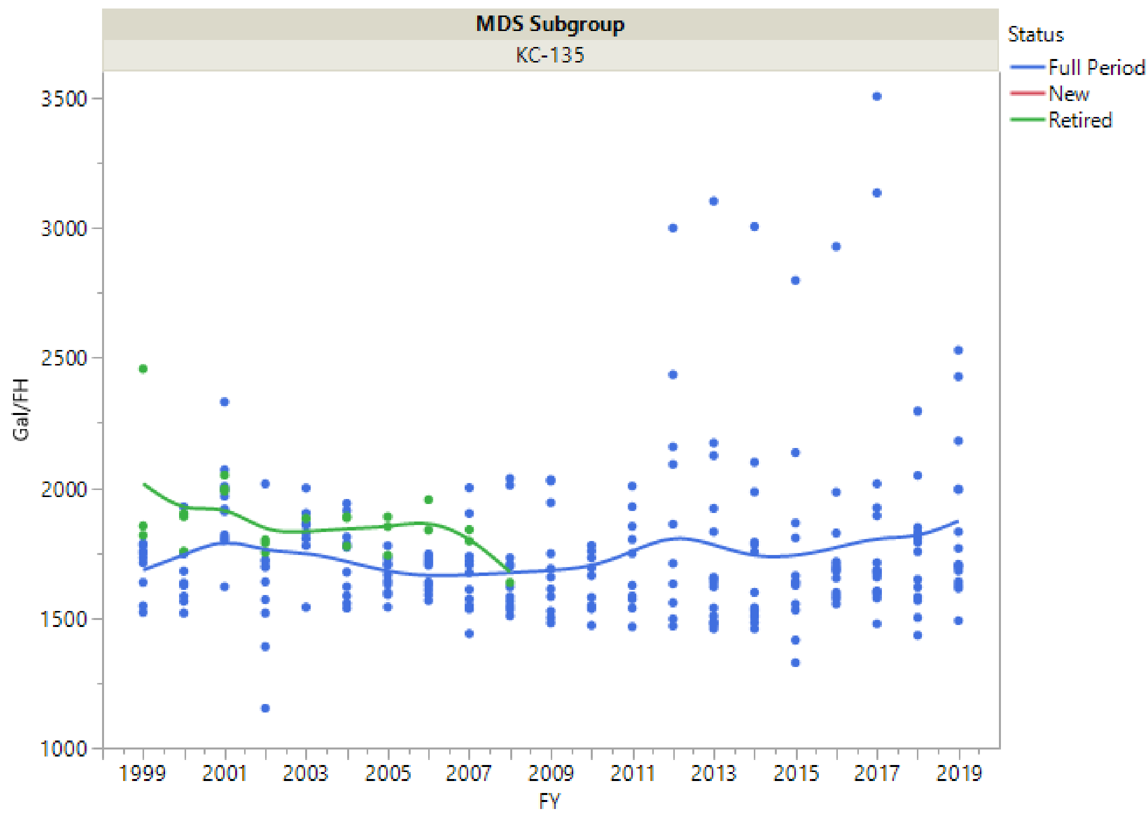


Figure 10: KC-135E and KC-135R/T Fuel Performance Metrics

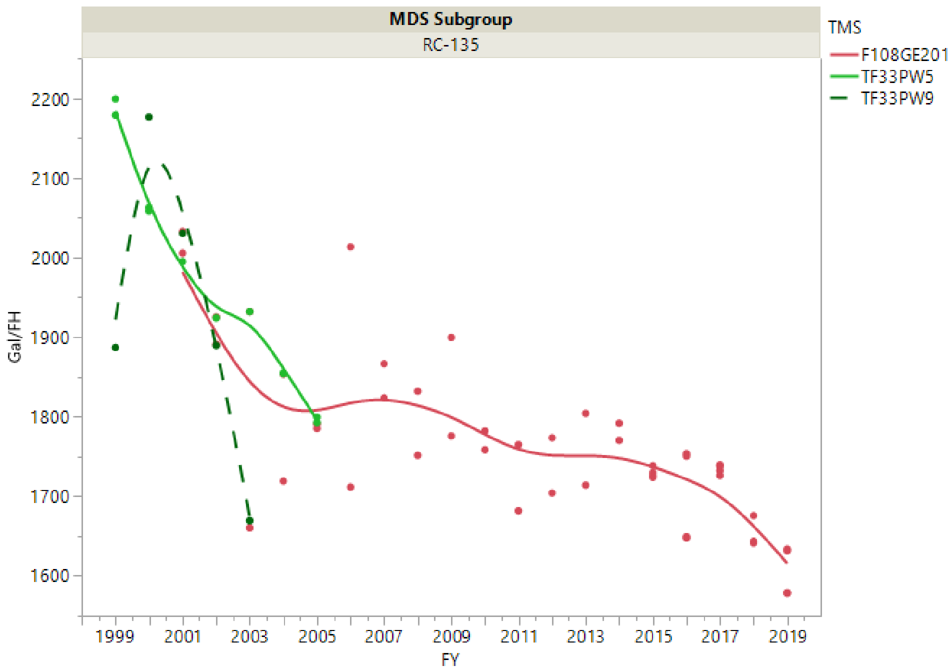


Figure 11: RC-135V/W Fuel Performance Metrics

We can see in the fuel performance metrics that for each pair, the retired engines appear to be acheving a poorer Gallon / Flying Hour than the full period or new engine since the green line is on top of the red line. Table 8 shows the results of statistical tests by MDS pairs and confirms the visual with the statistically significant conlcusion that the Air Force is using a more fuel efficient engine. The interpretation follows the same as the C-130s discussed in Section 4.2. Here, the full period engine on the KC-135s are, in estimated median performance, using 110.9 to 217.6 fewer gallons per flying hour than the retured engine and the results are statisitically significant.

Table 8: Wilcoxon Rank Sum Test Results of C-135 Fuel Performance

KC-135s

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.64485	0.1

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
Retired	Full Period	78.39718	18.63722	4.206485	<.0001*	167.9991	110.9970	217.5879

RC-135s

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.64485	0.1

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
Retired	New	24.94134	5.281305	4.722571	<.0001*	194.0671	141.6072	253.7074

4.4 Fuel Performance Characteristics of C-5 Models

The C-5 is the clearest comparison since there are only three MDSs and one MDS (C-5M) corresponding to only one engine. Figure 12 shows the outliers removed from analysis. The outliers are especially large and are likely related to errors in data collection at the source.

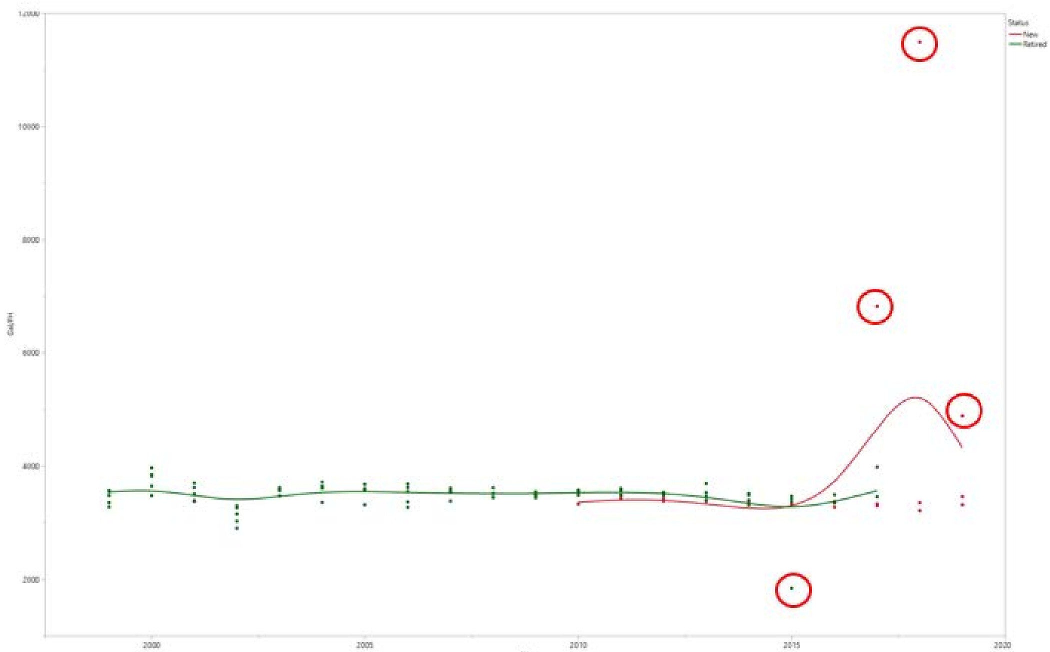


Figure 12: C-5 Model Outliers Removed

Figure 13 shows the performance of the C-5 models. It can be observed that the new C-5 engine is performing better than the retired engine. There is an interesting dip in FY 2002, which shows better performance in that year. The reason for this is unclear, but an observation of the other performance figures shows a similar pattern. Possible explanations could be over reporting in flying hours or underreporting in fuel. This could be further researched.

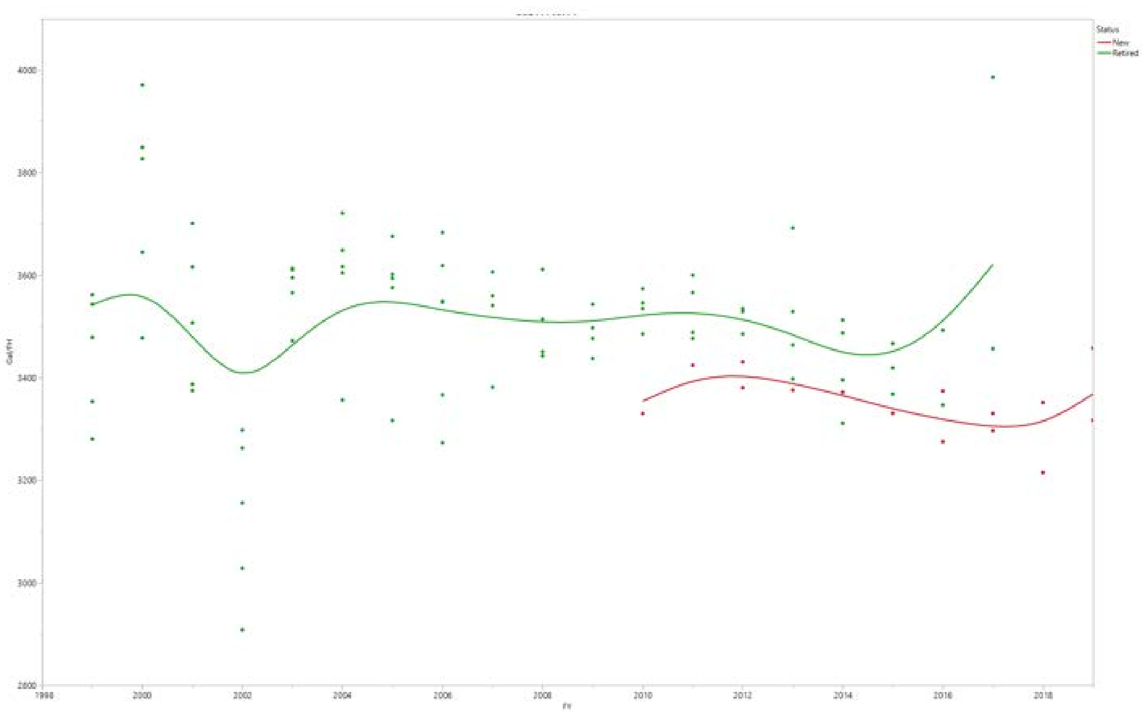


Figure 13: C-5 Model Fuel Performance Metrics

Wilcoxon Rank Sum statistics can be seen in Table 9. When the retired engine is compared with the new, the positive score mean difference implies that the retired engine consumed more fuel than the new one. The result is statistically significant with the estimated fuel savings being between 116.7 to 216.7 gallons per flying hour.

Table 9: Wilcoxon Rank Sum Test Results of C-5 Performance

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.64485	0.1

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
Retired	New	34.32753	8.055556	4.261348	<.0001*	167.0847	116.8693	216.7174

4.5 Fuel Performance Characteristics of F-15 Models

Three outliers identifed in Figure 14 were removed from analysis. In the analysis of the F-15s, and later in the F-16s, there are no new engines, just retired engines.

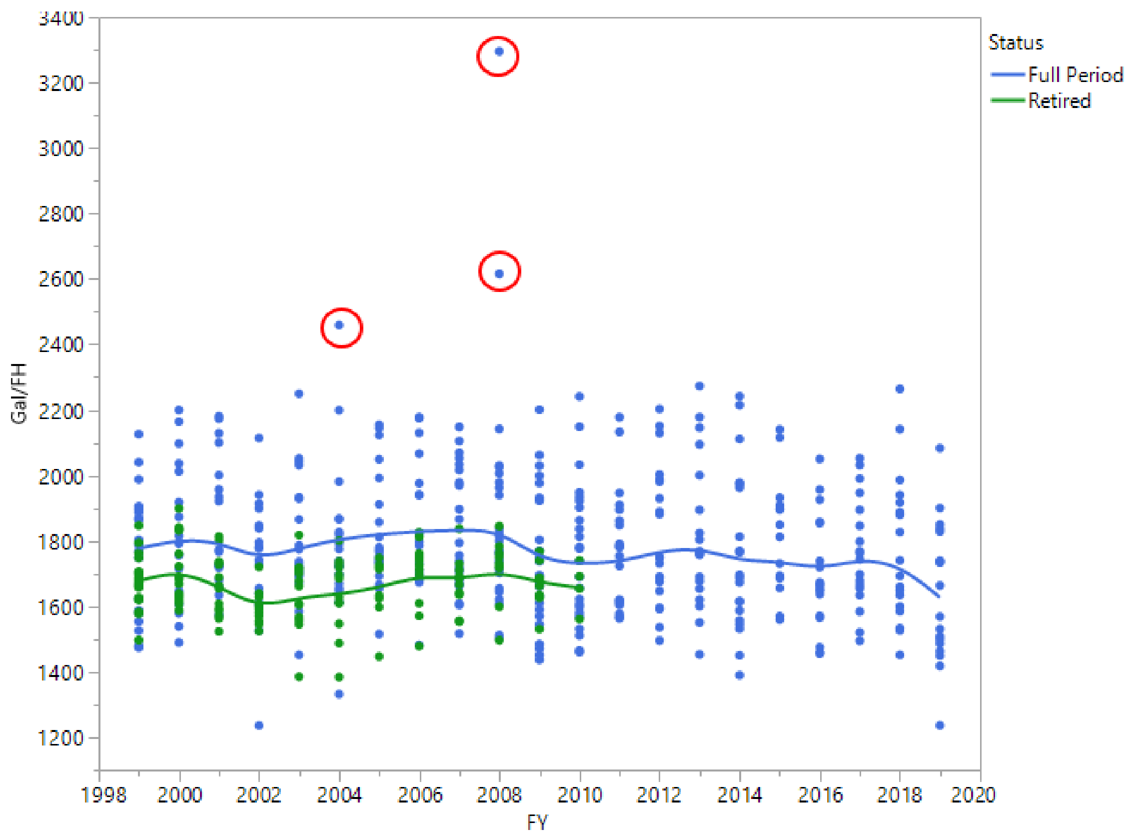


Figure 14: F-15 Model Outliers Removed

The performance metrics for the F-15 models can be seen in Figure 15. In a reversal from the observations of the Cargo/Tanker aircraft, here the green line is below the blue, suggesting that the retired engine was more fuel efficient than the engines being used currently.

Figure 15: F-15 Model Fuel Performance Metrics

The F-15 category also contains the F-15E, which has neither a new engine nor a retired engine. It does have two engines for the whole period from 1999-2019, which allows for a comparasion between them to be made and for completeness it is included the analysis. Figure 16 shows the F-15E on the right along side the F-15C and D in order to show the different fuel efficience of the F-15E. The A and B models were left off the chart for presentation but the performance of those engines are comparable with the C and D. In Figure 16 it appears that, in terms of fuel efficiency, the F100-PW-220 outperforms the F100-PW-229.

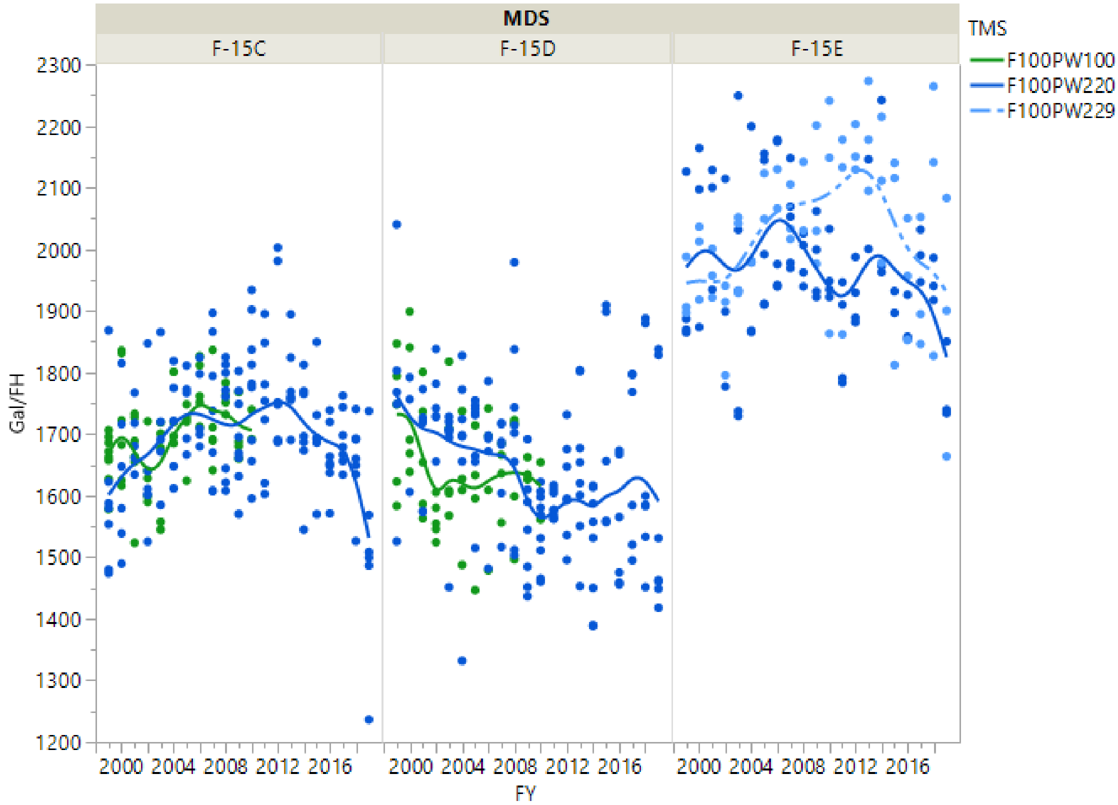


Figure 16: F-15E Fuel Performance Metrics Compared to F-15C/D

Table 10 confirms the visual patterns that the F100-PW-229 performs less fuel efficiently. It has an estimated difference of 53 more gallons per flying hour.

Table 10: Wilcoxon Rank Sum Test Results of F-15E Performance

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.64485	0.1

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
F100PW229	F100PW220	16.03272	6.988487	2.294162	0.0218*	52.97389	15.08740	90.73954

The results of the Wilcoxon Rank Sum test for the remaining F-15 models are shown in Table 11 and show that the retired engines may have a lower score mean, meaning better fuel efficiency but the results are not statistically signficant with a P value of .46 making it unable to reach a conclusion with a 90% confidence.

Table 11: Wilcoxon Rank Sum Test Reults of F-15A-D Performance

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.64485	0.1

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
Retired	Full Period	-10.8732	14.76205	-0.736562	0.4614	-7.52319	-25.2835	10.11255

4.6 Fuel Performance Characteristics of F-16 Models

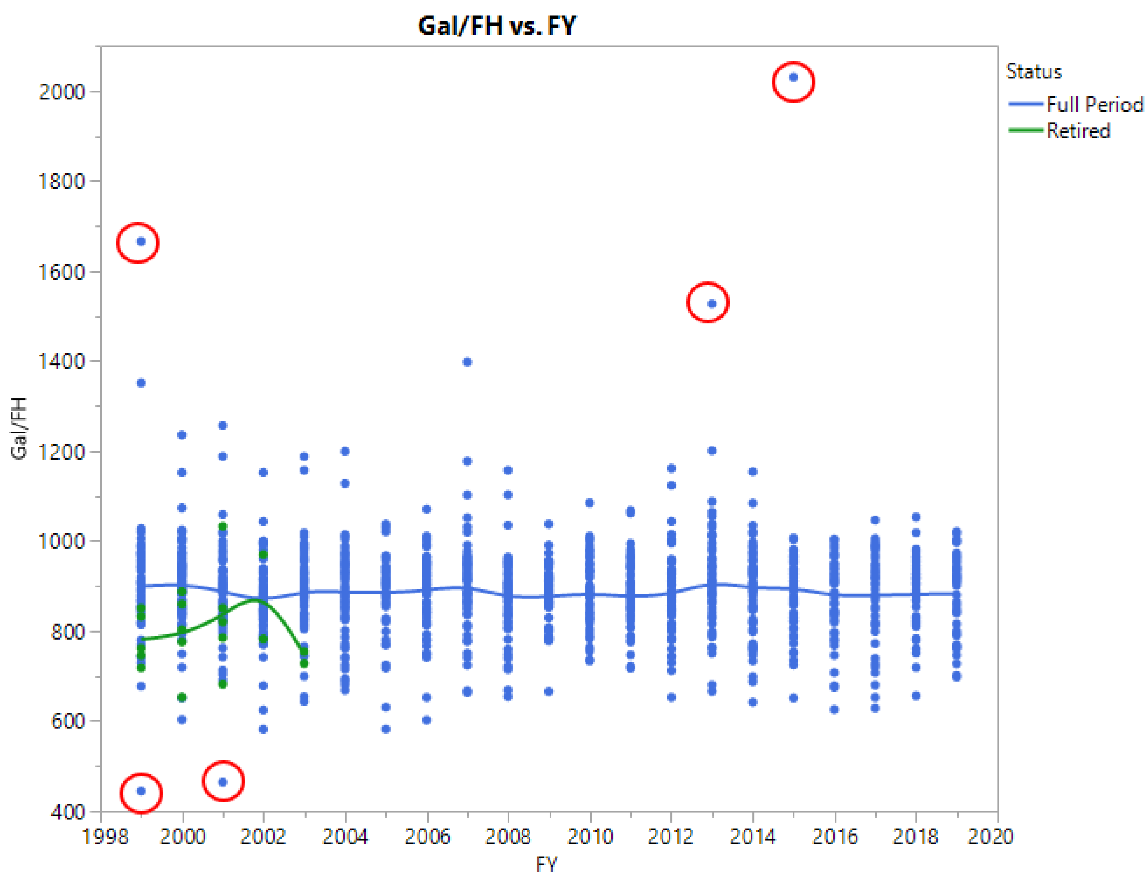


Figure 17: F-16 Model Outliers Removed

Five outliers were removed from the F-16 performance metrics as can be seen in Figure 17. Within the F-16s, only the A/B models have a retired engine, while the C/D models share four engines that all operate over the entire time period, but can still be tested in the same way that the F-15E is tested. Figures 18 and 19 show the relevant model pairings side by side. In the A/B models the retired engine appears to be more fuel efficient, but no patterns are evident in the C/D pairing.

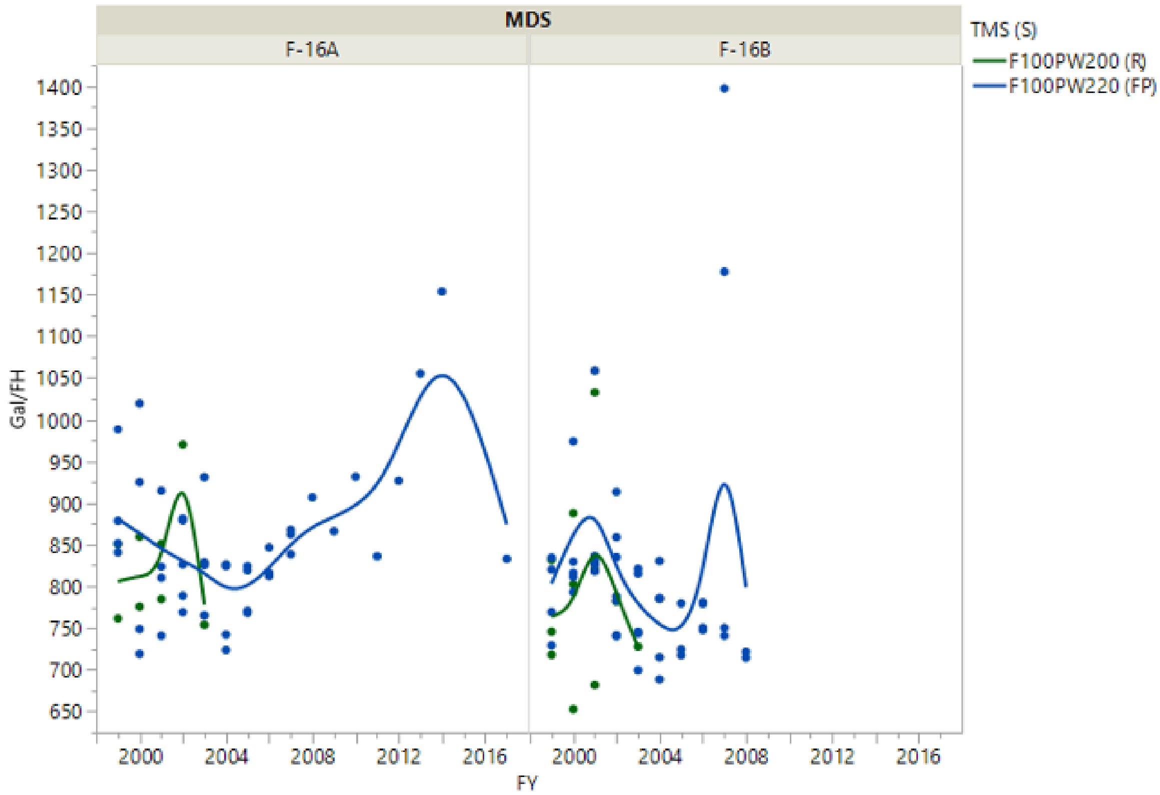


Figure 18: F-16A/B Fuel Performance Metrics

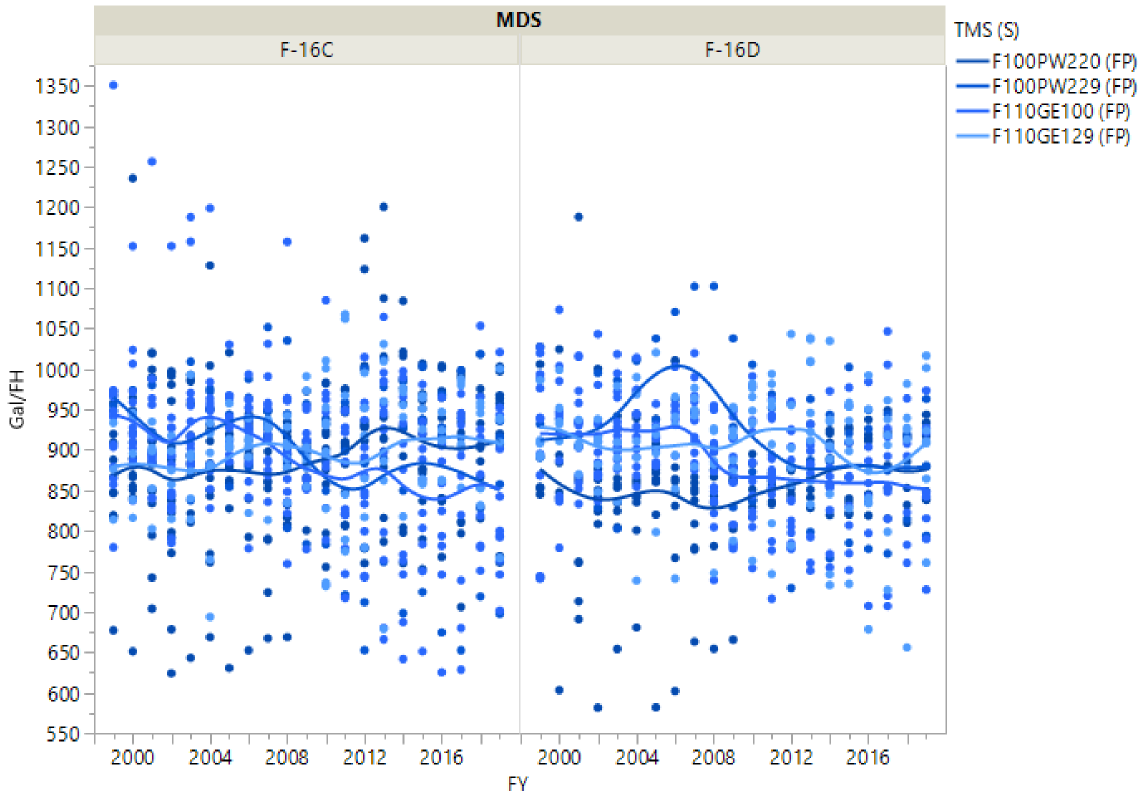


Figure 19: F-16C/D Fuel Performance Metrics

The Wilcoxon Rank Sum tests for the F-16s are shown in Table 12. The F-16A/B model engines are in the first row, with a black line separating the F-16C/D models. While some of the test results on the C/D models are significant, the magnitude is not that large with the best performing engine consumes 33 fewer gallons per flying hour.

Table 12: Wilcoxon Rank Sum Test Reults of F-16A-D Performnace

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.64485	0.1

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
F100PW220 (FP)	F100PW200 (R)	10.17763	8.633167	1.178899	0.2384	26.50494	-10.3020	60.51282
F110GE129 (FP)	F100PW220 (FP)	99.4671	18.47471	5.38396	<.0001*	27.2856	19.3650	35.4228
F100PW229 (FP)	F100PW220 (FP)	84.1243	20.78470	4.04741	<.0001*	33.0848	19.9467	45.7295
F110GE100 (FP)	F100PW220 (FP)	70.8360	19.92826	3.55455	0.0004*	15.5730	8.2635	22.4568
F110GE129 (FP)	F110GE100 (FP)	41.7718	18.13542	2.30333	0.0213*	11.5261	3.2698	19.8898
F110GE129 (FP)	F100PW229 (FP)	-10.2814	12.98503	-0.79179	0.4285	-6.4204	-19.6553	7.2943
F110GE100 (FP)	F100PW229 (FP)	-44.1865	20.22314	-2.18495	0.0289*	-17.2875	-30.4520	-4.3733

4.7 Fuel Performance Metrics for Helicopters

Within the helicopter performance, the UH-1H from 2010-2014 was excluded from analysis due to having only 2 PAA, low levels of flying hours, and minimal levels of maintenance. Figure 20 shows the performance with a clear difference of a lower gallon per flying hour for the new aircraft showing it is significant. The Wilcoxon Rank Sum test is significant and confirms that the new engine performs better as can be seen in Table 13. However, these results are complicated as new engines are predominantly on trainers.

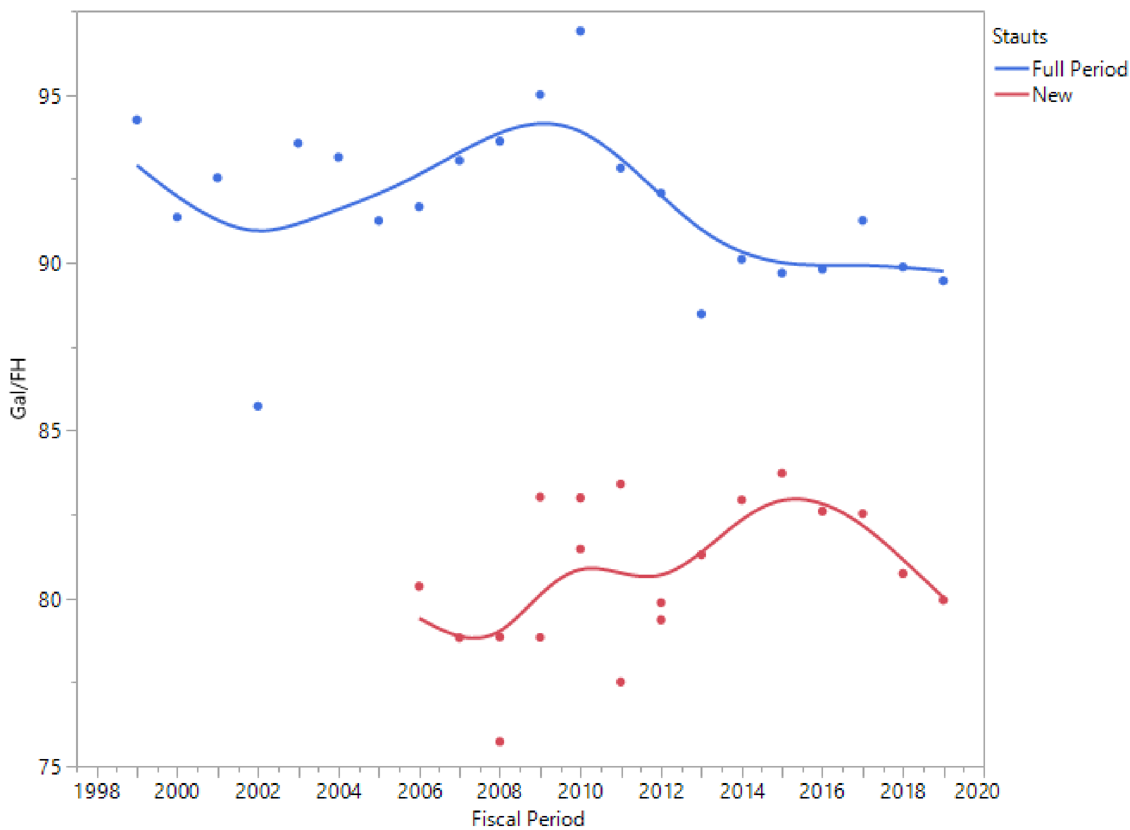


Figure 20: Fuel Performance Metrics for Helicopters

Table 13: Wilcoxon Rank Sum Test Results for Helicopter Fuel Performance

Nonparametric Comparisons For Each Pair Using Wilcoxon Method								
q*	Alpha							
1.64485	0.1							
Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
New	Full Period	-19.9499	3.701475	-5.38971	<.0001*	-10.8663	-12.3025	-9.74101

4.8 Summary of Fuel Performance Metrics

Within the cargo aircraft, new engines appear to be more fuel efficient than old engines. With each engine comparison of the cargo aircraft, the tests were statistically significant and represented better efficiency of the aircraft. With a 90% confidence interval of the estimated location of performance, the gallons of fuel per flying hour saved ranges from a low of 28 (C-130s), to a high of 280 (RC-135s). For the fighter aircraft not all results were statistically significant. For those that were, the range of the estimated confidence intervals from 3 to 90 gallons per flying hour. No new engines were in this later group though.

Table 14 shows the descriptive statistics (mean, median, range, etc.) of the MD category and the engine, as well as the total flying hours since 1999. Using Table 14 the average of the T56A15 engine on the C-130 category is 821, which is compared to the average of the AE2100 new engine of 703. This represents a point estimate of 107 fewer gallons per flying hour. Using that average and multiplying by the 352K flying hours represents 41.6M gallons of fuel saved. Similar calculation for the C-5 results in 15.7M gallons saved. For the new C-135 engine, the comparison is made against the average of the three engines it replaced (the TF33-PW models). The three new engines represent

$279M in savings using 2019 fuel prices. Table 15 is a similar to Table 14 but for helicopters.

Table 14: Descriptive Statistics of Aircraft Fuel Performance Metrics

			Gallon / Flying Hour						Total 1999-2019		Calculated
MD Category	Engine Status	TMS	Mean	Median	Std Dev	Min	Max	Range	Flying Hours	Gallons	Gallons Saved
C-130	**New**	**AE2100**	**703**	**708**	**48**	**537**	**798**	**261**	**352,450**	**255,075,279**	**41,589,100**
	Full Period	T56A15	821	817	94	401	1,352	952	3,238,642	2,591,433,122	Comparison
	Retired	T56A7	757	759	42	588	886	298	905,422	677,248,643	
C-135	**New**	**F108GE201**	**1,761**	**1,745**	**106**	**1,578**	**2,033**	**455**	**193,003**	**341,286,405**	**37,056,576**
	Full Period	F108GE100	1,753	1,693	296	1,153	3,505	2,352	3,707,658	6,212,052,517	
	Retired	TF33PW102	1,876	1,852	154	1,635	2,457	822	275,392	512,773,397	
	Retired	TF33PW105	1,967	1,932	134	1,799	2,199	400	3,760	7,276,579	Comparion
	Retired	TF33PW5	1,962	1,932	129	1,793	2,179	386	14,571	28,872,090	Comparion
	Retired	TF33PW9	1,930	1,889	189	1,669	2,176	507	17,211	34,318,480	Comparion
C-5	**New**	**F138GE100**	**3,345**	**3,341**	**61**	**3,215**	**3,458**	**243**	**97,157**	**324,283,323**	**15,739,434**
	Full Period	TF39GE1	3,507	3,522	167	2,908	3,987	1,078	674,526	2,358,627,896	Comparison
F-15	Full Period	F100PW220	1,724	1,707	175	1,236	2,249	1,014	1,648,931	2,918,591,702	
	Full Period	F100PW229	2,024	2,032	129	1,664	2,273	609	527,955	1,040,301,325	
	Retired	F100PW100	1,664	1,666	93	1,384	1,899	515	727,397	1,217,918,767	
F-16	Full Period	F100PW220	871	870	90	582	1,397	816	1,576,358	1,381,219,482	
	Full Period	F100PW229	903	921	93	653	1,102	450	353,380	315,876,824	
	Full Period	F110GE100	893	897	83	625	1,351	725	2,472,734	2,207,174,889	
	Full Period	F110GE129	902	911	72	656	1,068	412	1,106,583	982,343,532	
	Retired	F100PW200	805	785	93	653	1,033	380	21,683	16,842,687	

Total Gallons Saved: 94,385,110

$'s saved using DLA JP-8 2019 rate (2.96): $279,379,926

Table 15: Descriptive Statistics of Helicopter Fuel Performance Metrics

			Gal/FH							Flying Hours
MDS	**TSM**	**Stauts**	**N**	**Mean**	**Median**	**Std Dev**	**Min**	**Max**	**Range**	**Sum**
TH-1H	T53L703	New	12	81.1	81.9	2.46	75.7	83.7	8.00	89629
UH-1H	T53L13	New	7	80.2	79.4	1.74	78.8	83.4	4.58	31374
UH-1N	T400CP400	Full Period	21	91.7	91.7	2.48	85.7	96.9	11.18	403948

4.9 Maintenance Costs Limitations

Maintenance costs are significantly more difficult to normalize than fuel performance metrics. Maintenance costs are more variable with higher coefficients of variation and larger outliers. This makes it difficult to detect any outliers that should be removed and consequently none were. The AFTOC engine cost cube does not include CLS costs, which serve to underestimate total costs, an acknowledged limitation in the data. This is complicated by the fact that CLS costs generally are growing as a percentage of maintenance costs (Ritschel and Ritschel, 2016). Figure 21 provides a visual representation of the scale of this limitation but needs to be interpreted with caution as it is not taken from the same source data as the remainder of the charts. Figure 21 comes from AFTOC's Weapon System data cube converted to Base Year 2019. It includes the maintenance costs of the 38 MDSs in this study taken as an aggregate and is only used here to show the growth of CLS both in dollar amounts and as a percentage of maintenance. These costs correspond to all maintenance costs on the weapon systems and not just engines since the Weapon System data cube does not have a breakout for engine costs. CLS is in red. Table 16 provides further evidence that CLS is more prevalent on new engines; Table 16 shows the average amount of CLS as a percentage of maintenance for each MD category by engine status if the engine corresponded to a new MDS (C-5M and C-130"J" models). Since the F-15 and F-16s contain no new engines the F-22 and F-35 are included in Table 16 to provide an indication of how much CLS is being used to support the newer platforms.

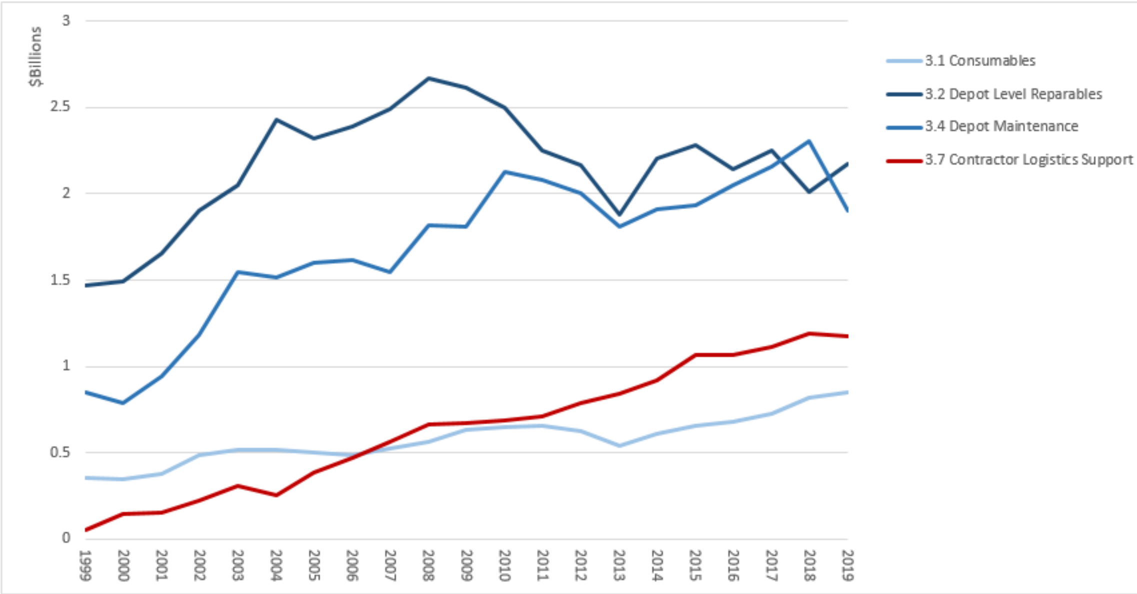


Figure 21: Maintenance and CLS Costs of the 28 Aircraft MDSs

Table 16: Average Percentage of Maintenance that is Performed via CLS

Engine:	New	Old	Mixture
C-130s	55.0%	13.3%	
KC-135s		2.4%	3.0%
RC-135s			89.7%
C-5s	23.2%	4.8%	
F-15s			5.1%
F-16s			3.8%
F-22/F-35	>95%		

When analyzing for fuel performance, a standard metric of Gallons / Flying Hour is homogenous. In analyzing maintenance costs, there is not an obvious way to normalize the data. Costs in maintenance could vary by flying hour but could also vary based on the number of planes in inventory in the same way that the maintenance on a fleet of cars varies both in how much they are driven and how many cars are in the fleet. The number of planes is an appropriate measure to use when comparing across aircraft systems since the inventory is more stable over time than flying hours (Boito et al., 2015). However since this research is looking at costs within the same weapon system we have chosen to use BY 2019 costs divided by PAA divided by Flying Hours to capture both usage and quantity.

Another aspect that complicates the analysis of maintenance is the effect of aging. Over time engines will likely cost more to maintain through the accumulation of wear and tear as well as obsolete parts and supply chains. Engines maintenance costs are theorized to follow a bathtub effect where costs are higher in the beginning due to initial learning or defects, reach a lower steady state and then the ending with higher costs due to the aging effect. (Kiley, G. T., & Skeen, J., 2001). The best comparison of engine costs would be to compare base year costs from steady-state of one engine to the steady-state the other. Unfortunately, this comparison is not possible using AFTOC as the data source. Referring back to Table 4, there are only three new engines with 10, 9 or 5 years from when they initially entered inventory and fewer years from when they become widely used. Only one engine, the F108-GE-201, has 20 or more flying hours before 2010. Given how long the Air Force keeps engines in inventory, AFTOC's 21 years of data does not capture a large enough time frame to compare steady operations. And what is available is understated because CLS is not reported as an engine cost.

A final note for the limitations with the Engine Data Cube is that the F-15A/B, F-15C/D, F-16A/B and F-16C/D MDS model pairs are grouped together and the individual costs for each aircraft is not known. There are additionally some TMS costs for the F100-PW-100 mapped to the F-15 without the model destination. This analysis adds these costs to the C/D models, which is the predominate user of the engine.

4.10 Maintenance Costs of New, Retired and Full Period Engines

Figures 22 and 23 are not colored by engine status but instead are colored by MD category. The three sections represent the retired engines on the left, those operating over the full period in the middle, and the new engines on the right. Figure 22 shows the manpower maintenance costs (CAPE 1.2) and Figure 23 shows the 3.0 maintenance costs, which are repair parts, depot level maintenance and engine overhauls. These figures have no data points excluded, however the scale was adjusted to show the patterns that would otherwise be obscured by large outliers. Figure 22 is cut off at $100 per Flying Hour per PAA, and Figure 23 is cut off at $300 per Flying Hour per PAA.

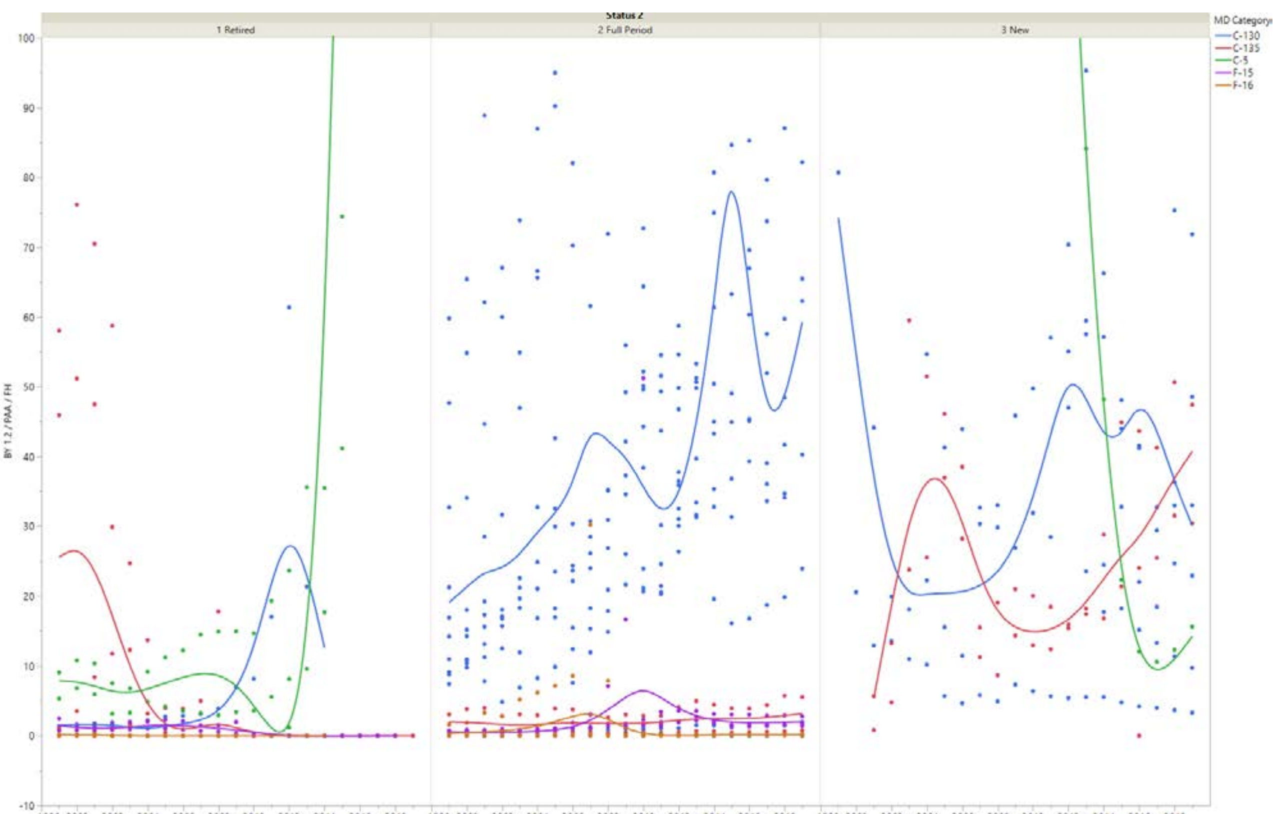


Figure 22: CAPE 1.2 Engine Maintenance Costs by MD Category

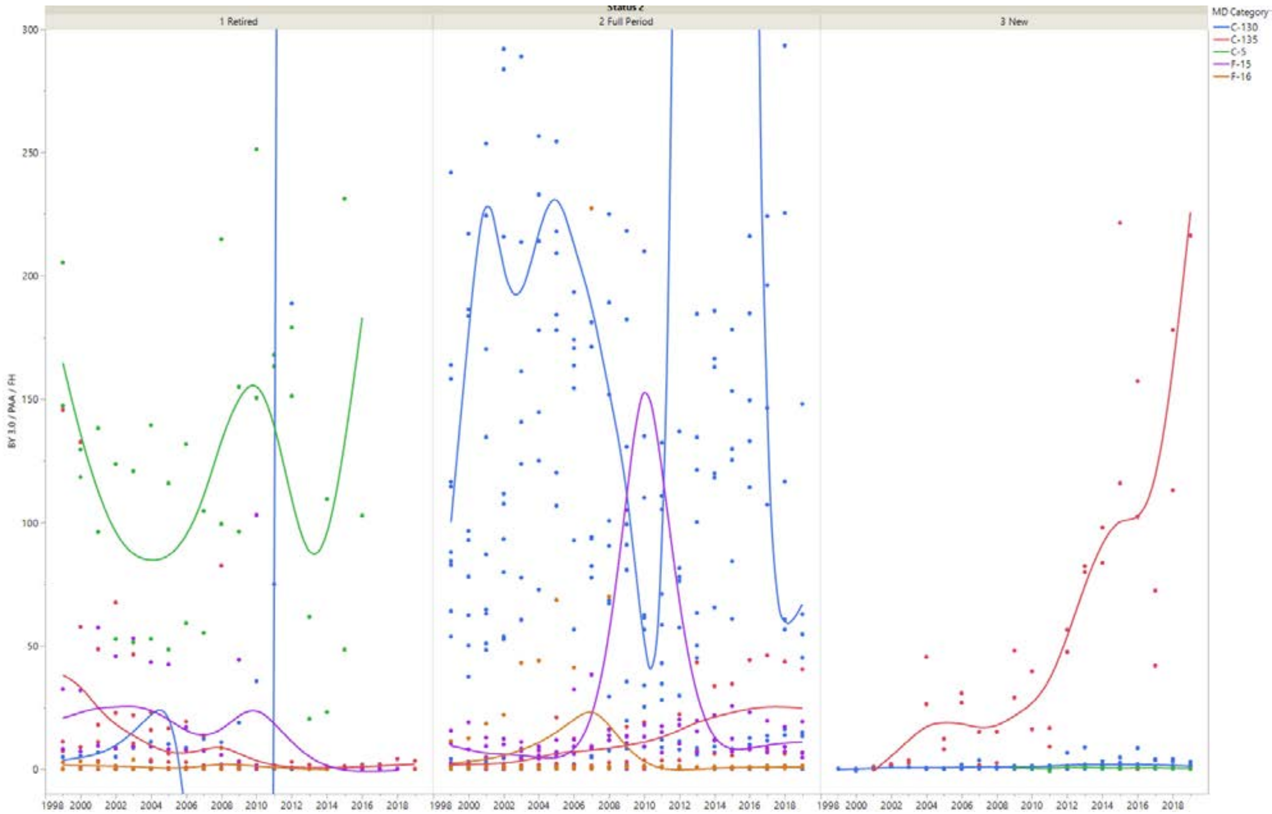


Figure 23: CAPE 3.1-3.4 Engine Maintenance Costs by MD Category

The intention of these two figures is to show the scale and variability of the maintenance costs, and that the maintenance cost on the new engines is significantly lower compared to the other engines. This is likely a result of the aging factor and the incomplete ramp up of the new engines. In both figures many of the costs appear to be around zero as a result of the scale of some of the other MD categories.

Another observation from Figures 22 and 23 is that maintenance costs, especially manpower, precede and succeed usage. Engines not in use incur costs, while retired engines continue to accrue costs well beyond usage. In an attempt to remove this effect engines costs in the year of retirement onward, and prior to the year of inception were removed in subsequent maintenance charts. Of particular note, the C-130J models have a discrepancy between the usage reported in the Engine Programmatic cube, which shows usage only from 2016 onwards and the Weapon System Cost cube which shows usage from 1999 onwards; in this analysis we opted to use the Engine Programmatic data. An investigation into the discrepancy is ongoing with the AFTOC helpdesk.

4.11 Maintenance Cost Results by MD category

Once the exclusions are made for engine maintenance costs, which occurred outside of their usage, we are left with 645 data points. Since the presentation of this data is primarily visual, graphs with large outliers distort the visual to such an extent that it obscures patterns. For that reason, outliers more than three standard deviations from the mean (within their respective MDS and TMS) are excluded in Figures 24-28. This represented 12 data points; a further discussion of these data points and some graphs and data statistics and are included in Appendix C. With these last data points removed we now examine Figures 24-28, which are the normalized maintenance costs by MD categories. These costs are for total maintenance costs, so both 1.2 and the 3.0 categories.

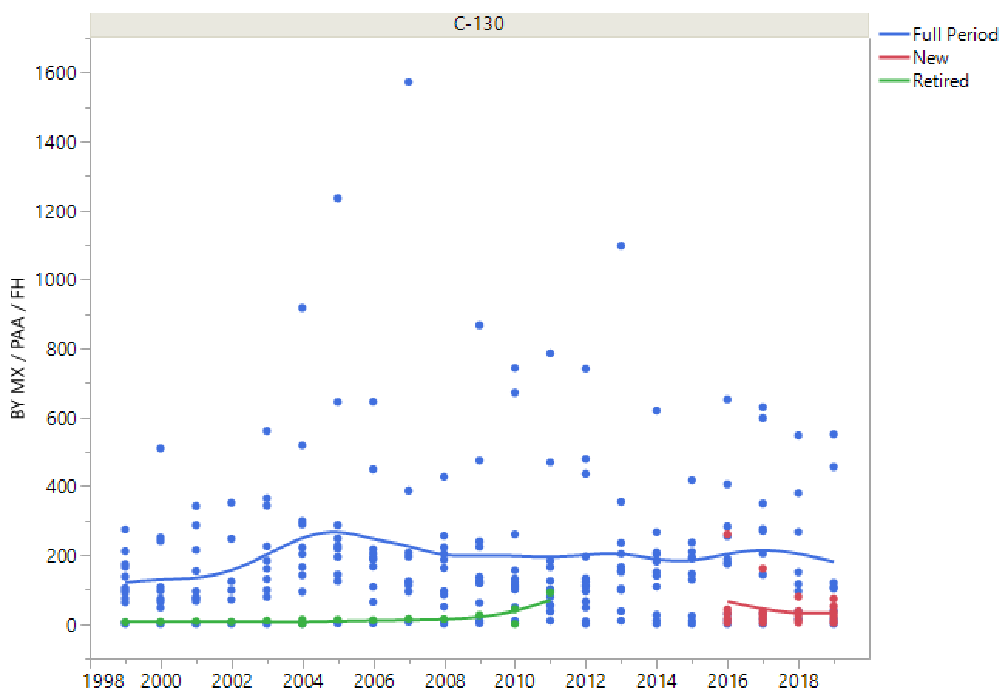


Figure 24: Maintenance Costs of the C-130 Models

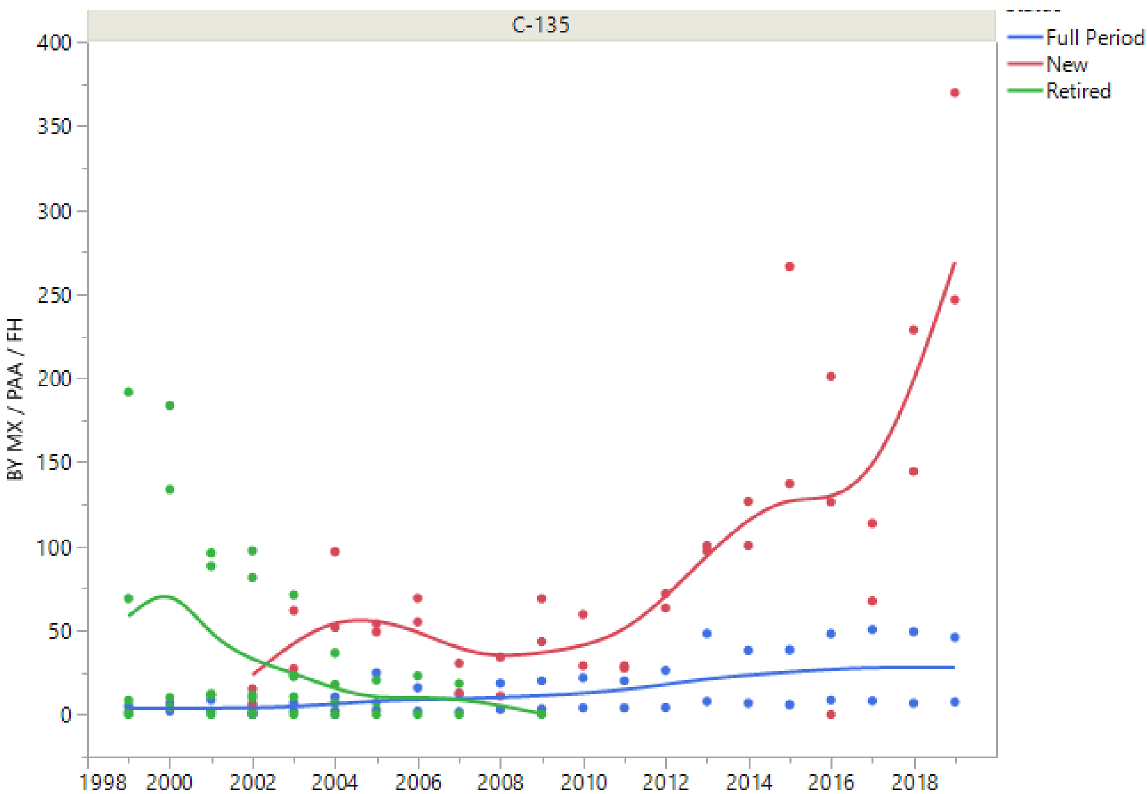


Figure 25: Maintenance Costs of the C-135 Models

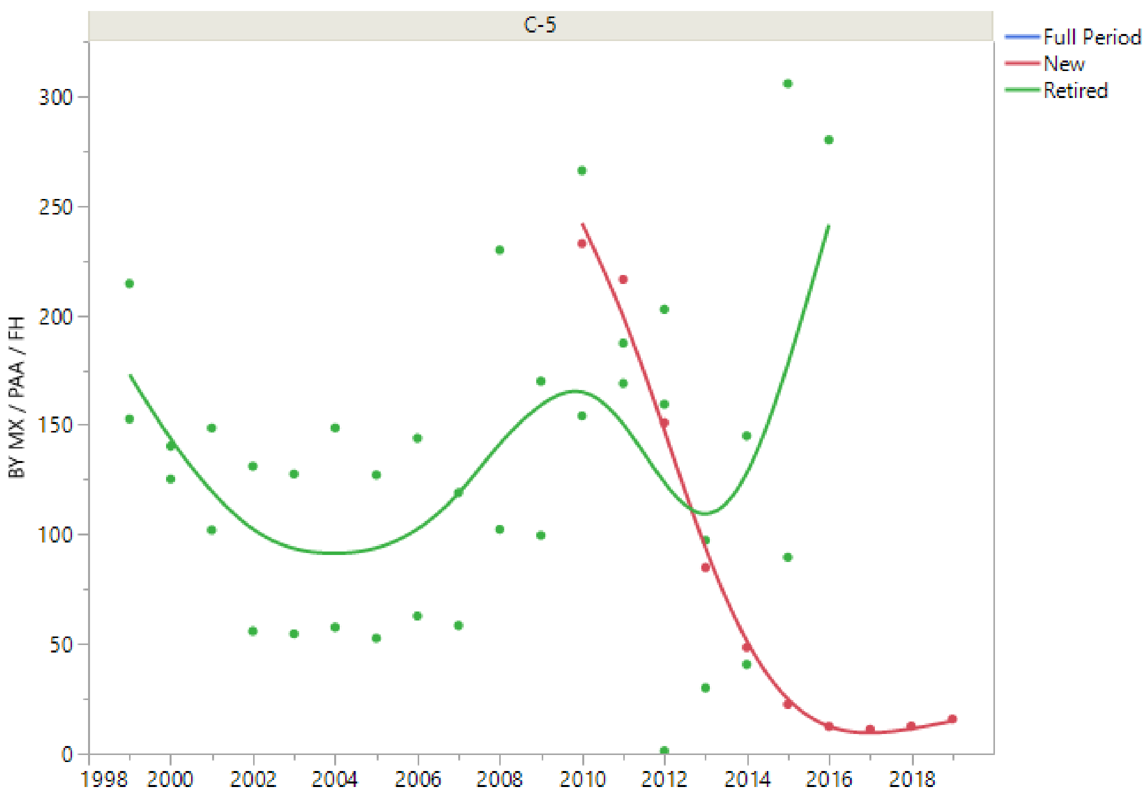


Figure 26: Maintenance Costs of the C-5 Models

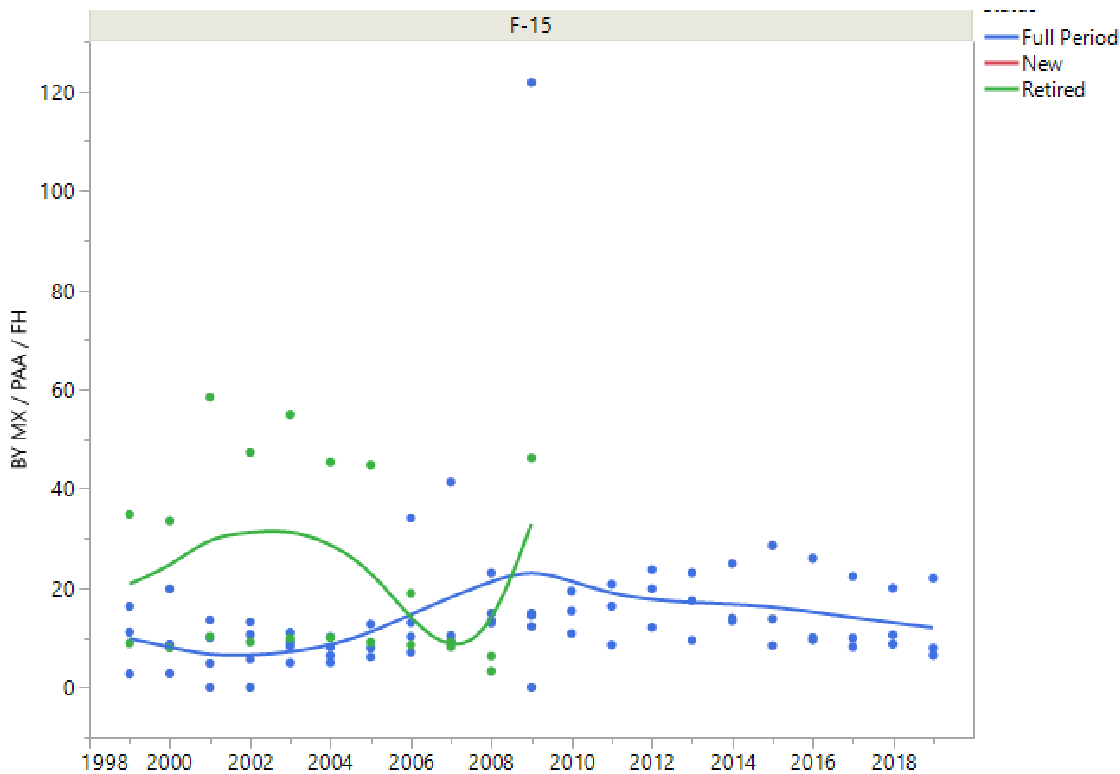


Figure 27: Maintenance Costs of the F-15 Models

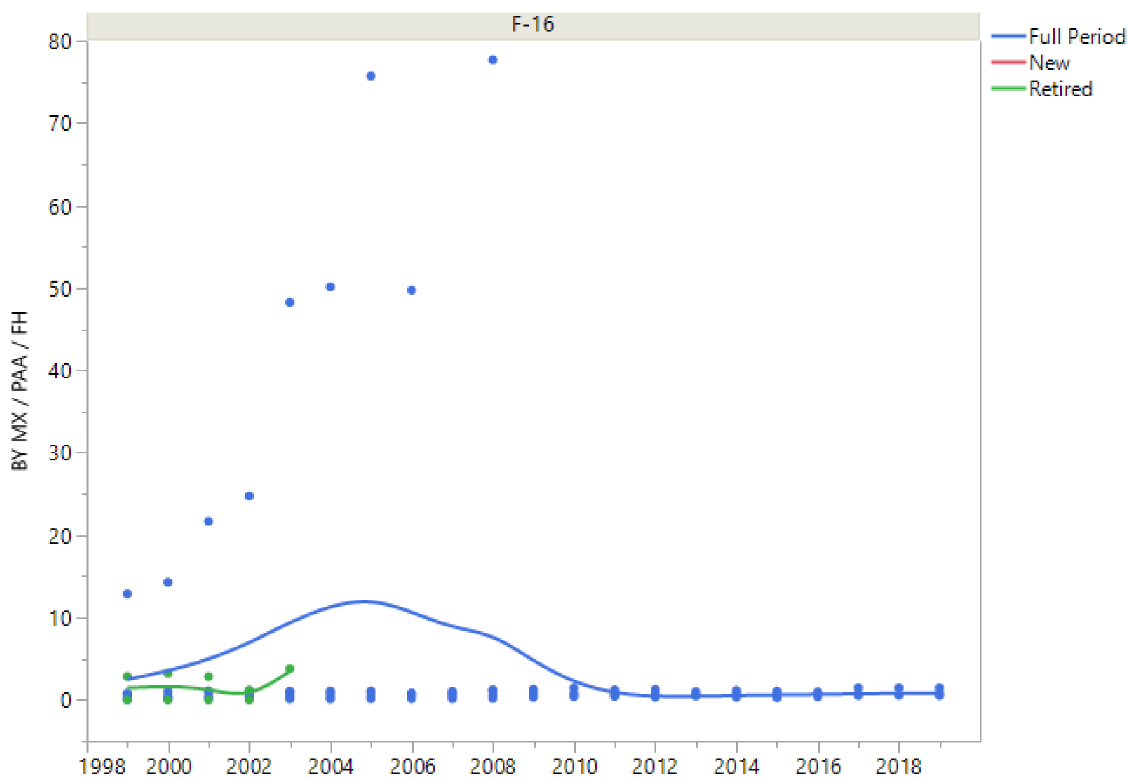


Figure 28: Maintenance Costs of the F-16 Models

The results are mixed. Within the C-130 models both the retired and the new engines appear cheaper to operate. Within the C-5s, the new engines were initially more expensive, but the costs quickly fell to lower levels (consistent with the bathtub concept). With the F-15s the retired engines appear somewhat higher but it is inconclusive from the diagram. For the F-16 models the retired engine appears to have been less expensive to operate, although that may be the result of some unusual outliers. The most interesting results are from the C-135 models; here the new engine appears much more expensive. Similar to the fuel performance section, the C-135s are further investigated by breaking them into their MDS. Figures 29 and 30 shows the results by MDS which reveals the potential source of the higher engine maintenance costs.

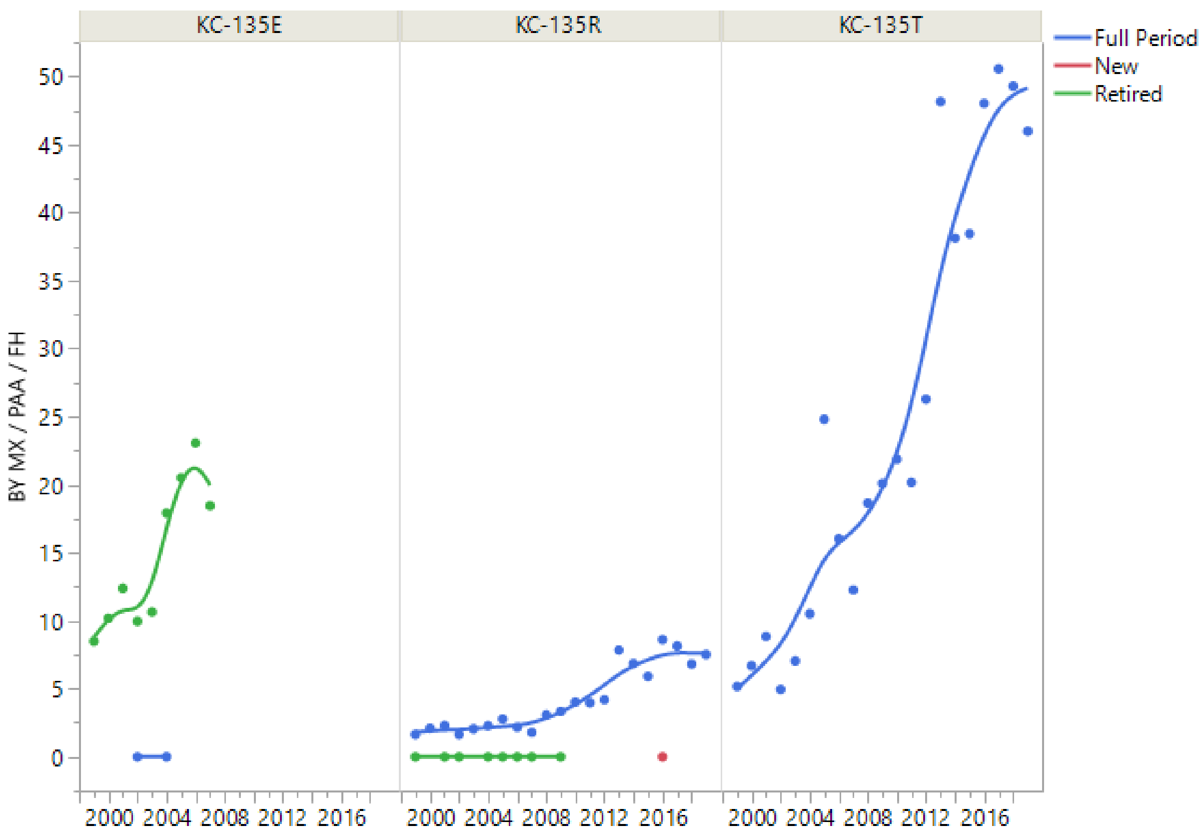


Figure 29: KC-135 Model Maintenance Costs

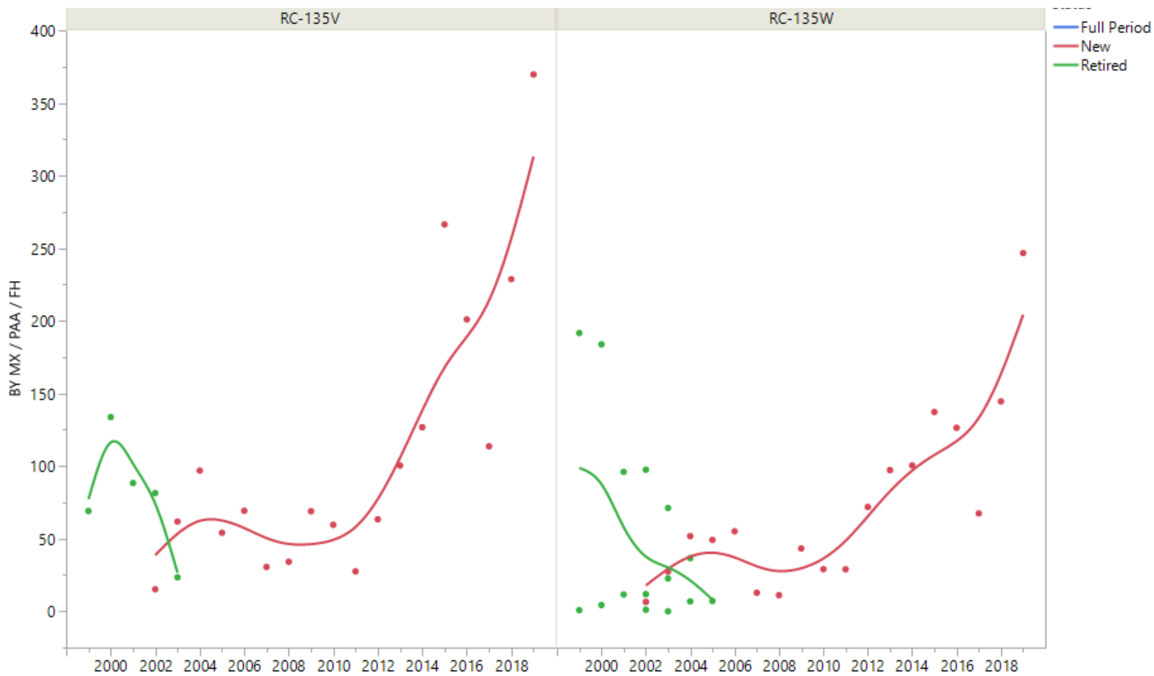


Figure 30: RC-135 Model Maintenance Costs

From these two figures, the differences in costs are not as pronounced as what is observed in Figure 25. Despite being normalized by base year, the costs show upward trends; Figure 29 shows the KC-135s, and interesting there appear to be some maintenance costs, especially on the KC-135R, that were assigned to the wrong engine. The dollar figures were very small and were excluded; similar analysis was performed on all MDSs and 27 more data points were excluded, for a total of 39. The retired engines on the KC-135E are more expensive than the KC-135R, but because of the variability in the KC-135T the results are inconclusive. For Figure 30, the engines appear to be around the same maintenance costs, and then the new engines experience increases in costs in the later years.

Each engine within the MD category was tested using the Wilcoxon Rank Sum test. Table 17 contains the listing of comparisons that were not significant at the 0.10 level. None of the F-15 tests were significant. Table 18, contains the results of the

Wilcoxon Rank Sum test that were significant at the 0.10 level. Where a new engine is compared to an engine it replaced the line is bolded. For the fighter jets, the estimated saving are very small, the highest median difference as computed by the Hodges-Lehmann is $2.67 per flying hour per aircraft. Table 19 shows only the new engines compared against the engine they replace with the exception of the F108GE201 and TF33PW9 since it was statistically insignificant. Where available, Table 19 is supplemented with the average amount of support that the aircraft receive as a percentage of CLS computed by taking the average from 1999-2019 reported in AFTOC. This was possible for the C-5 and C-130 since the new engines correspond to MDSs. However, it is not known how much CLS is spent on engines or on other aircraft maintenance activities. Since the new and retired engines on the RC-135 models do not have distinct MDSs the percentage of CLS is estimated based on averages from 2000-2003 (predominately retired engines) and 2004 to 2019 (predominately new engines).

Table 17: Statistically Insignificant Test Results of Maintenance Costs

MD	Level	- Level	Z	p- Value
C-130	AE2100 (N)	T56A7 (R)	1.638	0.101
C-135	F108GE201 (N)	TF33PW9 (R)	0.938	0.349
C-135	TF33PW9 (R)	TF33PW102 (R)	1.376	0.169
C-135	TF33PW9 (R)	TF33PW105 (R)	1.357	0.175
C-135	F108GE100 (FP)	TF33PW105 (R)	0.171	0.864
C-135	F108GE201 (N)	TF33PW5 (R)	-0.444	0.657
C-135	TF33PW9 (R)	TF33PW5 (R)	-1.278	0.201
C-135	TF33PW105 (R)	TF33PW102 (R)	-1.237	0.216
C-135	F108GE100 (FP)	TF33PW102 (R)	-1.594	0.111
C-135	F108GE100 (FP)	TF33PW9 (R)	-1.529	0.126
F-15	F100PW229 (FP)	F100PW220 (FP)	-0.301	0.763
F-15	F100PW229 (FP)	F100PW100 (R)	-0.990	0.322
F-15	F100PW220 (FP)	F100PW100 (R)	-0.991	0.322
F-16	F100PW220 (FP)	F100PW200 (R)	-1.391	0.164

Table 18: Wilcoxon Rank Sum Test Results for Aircraft Maintenance Costs

MD	Level	- Level	Score Mean Dif	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
C-130	T56A15 (FP)	T56A7 (R)	85.48	19.48	4.388	<.0001	$117.59	$86.13	$175.46
C-130	**AE2100 (N)**	**T56A15 (FP)**	**-75.39**	**15.35**	**-4.912**	**<.0001**	**($102.59)**	**($141.75)**	**($74.81)**
C-135	F108GE201 (N)	F108GE100 (FP)	32.94	5.15	6.400	<.0001	$53.14	$41.73	$66.18
C-135	F108GE201 (N)	TF33PW102 (R)	19.38	4.89	3.958	<.0001	$50.67	$32.06	$87.31
C-135	**F108GE201 (N)**	**TF33PW105 (R)**	**19.15**	**5.41**	**3.541**	**0.0004**	**$56.15**	**$29.75**	**$99.61**
C-135	TF33PW5 (R)	TF33PW102 (R)	5.59	2.40	2.329	0.0199	$77.60	$26.02	$165.90
C-135	TF33PW5 (R)	TF33PW105 (R)	5.42	2.17	2.500	0.0124	$84.28	$24.79	$176.97
C-135	**F108GE100 (FP)**	**TF33PW5 (R)**	**-19.75**	**5.83**	**-3.386**	**0.0007**	**($75.91)**	**($95.46)**	**($34.60)**
C-5	**F138GE100 (N)**	**TF39GE1 (R)**	**-10.09**	**4.71**	**-2.143**	**0.0321**	**($65.44)**	**($114.14)**	**($17.44)**
F-16	F110GE100 (FP)	F100PW229 (FP)	20.95	3.79	5.534	<.0001	$0.86	$0.74	$0.94
F-16	F110GE129 (FP)	F100PW229 (FP)	14.29	3.79	3.773	0.0002	$0.23	$0.13	$0.30
F-16	F110GE100 (FP)	F100PW220 (FP)	8.22	4.23	1.943	0.0521	$0.24	$0.06	$0.36
F-16	F110GE100 (FP)	F100PW200 (R)	-10.90	3.81	-2.863	0.0042	($1.79)	($2.23)	($1.39)
F-16	F100PW229 (FP)	F100PW200 (R)	-12.88	3.81	-3.383	0.0007	($2.67)	($3.08)	($2.34)
F-16	F110GE129 (FP)	F100PW200 (R)	-12.88	3.81	-3.383	0.0007	($2.44)	($2.84)	($2.07)
F-16	F110GE129 (FP)	F100PW220 (FP)	-20.36	4.23	-4.813	<.0001	($0.38)	($0.53)	($0.27)
F-16	F110GE129 (FP)	F110GE100 (FP)	-20.76	3.79	-5.484	<.0001	($0.63)	($0.70)	($0.53)
F-16	F100PW229 (FP)	F100PW220 (FP)	-25.14	4.23	-5.943	<.0001	($0.60)	($0.74)	($0.48)

Table 19: New Engines Compared to Replaced Engine Maintenance Costs

MD	New Engine	% of AC maintenance from CLS	Compared to	% of AC maintenance from CLS	Low Est Savings	High Est Savings	Interpretation, given Quality of the Data
C-130	AE2100 (N)	55.0%	T56A15 (FP)	13.3%	$74.81	$141.75	The new engine is $75-$142 **less** expensive to maintain per PAA/FH
C-135	F108GE201 (N)	~90.8%	TF33PW105 (R)	~92.2%	($99.61)	($29.75)	The new engine is $30-$100 **MORE** expensive to maintain per PAA/FH
C-135	F108GE201 (N)	~90.8%	TF33PW5 (R)	~92.2%	$34.60	$95.46	The new engine is $35-$95 **less** expensive to maintain per PAA/FH
C-5	F138GE100 (N)	23.2%	TF39GE1 (R)	4.8%	$17	$114	The new engine is $17-$114 **less** expensive to maintain per PAA/FH

As discussed in Section 4.8 the limitations in the data impact the results. Generally, the data available reveals that a new engine is less expensive to maintain, with the exception that the F108GE201 tested as more expensive than the TF33PW105, but not the TF33PW5, all of which belong to the RC-135V/W. When computing for fuel performance these models required the removal of AFMC. For both the C-130 and the C-5 more maintenance was performed by CLS on the aircraft with new engines than on the old engines.

Table 20 contains the descriptive statistics of the data with mean, median, standard deviation and coefficient of variation of each engine by MD category. Table 20 is computed without the 39 exclusions discussed earlier in this section, and in Appendix C. The maintenance costs are inclusive of CAPE 1.2 as well the 3.0 categories recorded in AFTOC (CAPE 3.1 through 3.4). The new engines, along with the engines they are meant replace, are displayed next to each other and are in bold print. The costs are normalized by Base Year 2019 and PAA / FH. Of note is the high coefficient of variations that remain even with the removal of the 12 data points that were over three standard deviations from the mean.

Table 20: Descriptive Statistics of Aircraft Maintenance Costs

MD	Status	TMS	N	Mean	Median	Std Dev	CV
C-130	**New**	**AE2100**	**24**	**$43.82**	**$30.21**	**57.1**	**1.30**
	Retired	**T56A7**	**13**	**$20.62**	**$12.84**	**23.7**	**1.15**
	Full Period	T56A15	223	$201.07	$137.72	220.1	1.09
C-135	**New**	**F108GE201**	**36**	**$91.54**	**$65.40**	**81.5**	**0.89**
	Retired	**TF33PW105**	**6**	**$9.69**	**$9.25**	**7.6**	**0.79**
	Retired	**TF33PW5**	**7**	**$97.72**	**$96.04**	**69.4**	**0.71**
	Retired	**TF33PW9**	**7**	**$56.74**	**$69.08**	**50.2**	**0.88**
	Full Period	F108GE100	42	$14.55	$7.28	15.6	1.07
	Retired	TF33PW102	9	$14.62	$12.38	5.4	0.37
C-5	**New**	**F138GE100**	**10**	**$80.77**	**$35.43**	**87.7**	**1.09**
	Retired	**TF39GE1**	**35**	**$135.75**	**$131.14**	**68.2**	**0.50**
F-15	Full Period	F100PW220	51	$15.24	$10.87	17.4	1.14
	Full Period	F100PW229	24	$11.28	$11.76	5.9	0.52
	Retired	F100PW100	21	$23.11	$10.06	19.0	0.82
F-16	Full Period	F100PW220	30	$13.04	$0.84	23.1	1.77
	Full Period	F100PW229	21	$0.30	$0.29	0.1	0.49
	Full Period	F110GE100	21	$1.15	$1.09	0.2	0.17
	Full Period	F110GE129	21	$0.52	$0.47	0.2	0.32
	Retired	F100PW200	5	$2.78	$2.86	1.0	0.35

4.12 Maintenance Cost Results for Helicopters

The maintence costs of helicopters are displayed in Figure 29 and shows that the newer aircraft appear significantly cheaper. Unlike fixed wing Aircraft, Figure 29 only shows the results of the CAPE category 3 costs and not unit level maintenacne (CAPE 1.2). The reasons for the ommision is because unit level maintenance for training aircraft is not available in AFTOC, and this can be seen in the descriptive statitics provided in Table 21. Lastly, the Wilcoxon Rank Sum Test is available in Table 22 and the results are significant at the α level of 0.10.

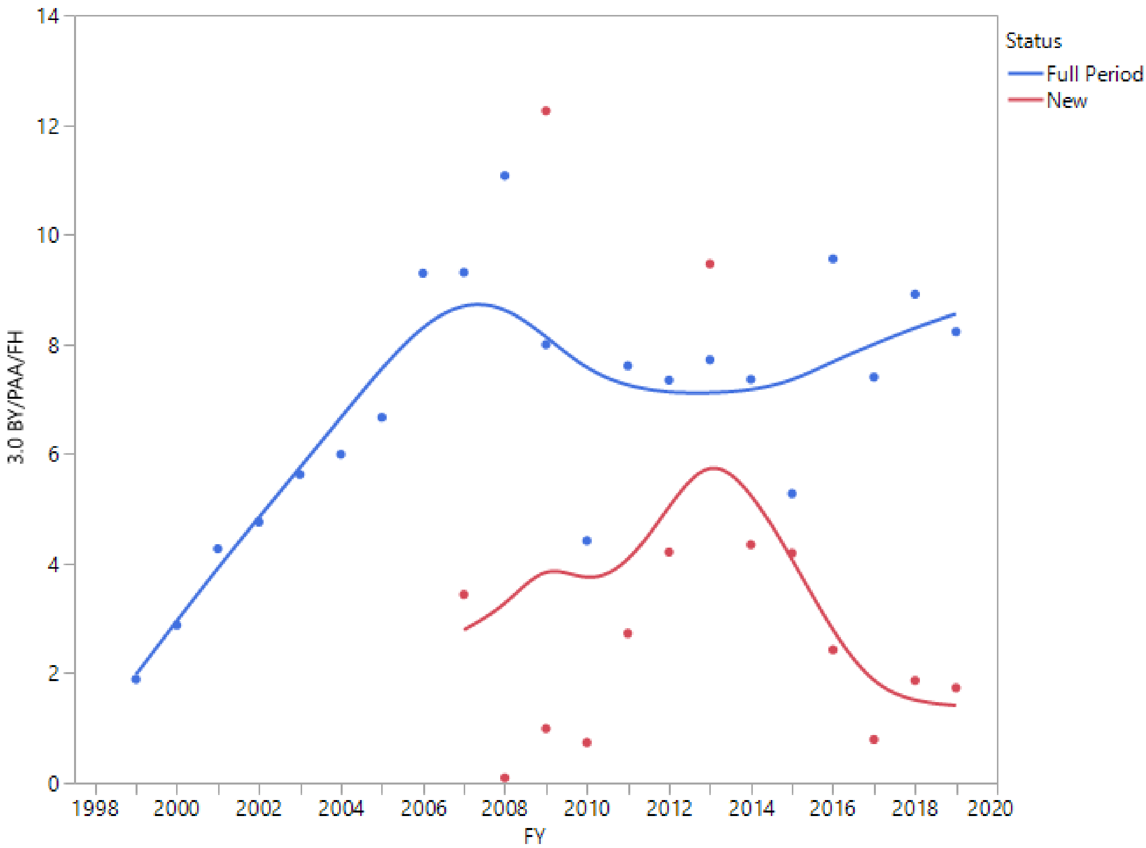


Figure 31: CAPE 3.0 Maintenance Costs for Helicopters

Table 21: Descriptive Statistics of Helicopter Maintenance Costs

		1.2 Maintenance		BY 2019 Maintenance Costs (CAPE 3.1,3.2 and 3.4)								
				3.0 costs / PAA					3.0 costs / Flying Hours			
MDS	TMS Status	N	Mean	N	Mean	Median	Std Dev	CV	Mean	Median	Std Dev	CV
TH-1H	New	0	--	11	$25,580	$17,882	$23,017	90.0%	$70	$55	$59	84.3%
UH-1H	New	1	$752,371	3	$29,041	$23,743	$31,383	108.1%	$42	$49	$38	90.5%
UH-1N	Full Period	21	$1,182,248	21	$131,307	$137,817	$44,766	34.1%	$394	$428	$160	40.6%

Table 22: Wilcoxon Rank Sum Test Results for Helicopter Maintenance Costs

Nonparametric Comparisons For Each Pair Using Wilcoxon Method

q*	Alpha
1.64485	0.1

Level	- Level	Score Mean Difference	Std Err Dif	Z	p-Value	Hodges-Lehmann	Lower CL	Upper CL
New	Full Period	-11.3690	3.535534	-3.21565	0.0013*	-3.99150	-5.48936	-2.45255

4.13 Chapter Summary

In this chapter each MD category and helicopters available are graphically and descriptively examined for fuel efficiency performance and maintenance costs. The comparison for fuel efficiencies generally show improvement in fuel performance with statistically significant results when compared to older engines. The same is true for maintenance costs within the available data.

We addressed some of the limitations that complicate the analysis, especially within the maintenance costs. In the course of this analysis, we found statistically significant results at the 0.10 confidence level that are visible in the graphs of the engine performance. In Chapter V we conclude the thesis with a discussion of the research questions, some lessons learned and a discussion of the implications of the research.

V. Conclusions and Recommendations

5.1 Chapter Overview

In this chapter we answer the research questions posed in Chapter I. After that we discuss the significance of the research and conclusions. In addition to broader implications of the research, we use a case study for the performance cost savings that could be materialized using the recent reengine efforts from the E-8 (JSTARS) aircraft. We conclude with recommendations for future action and research.

5.2 Investigative Questions Answered

1). *What are the quantifiable effects of an engine upgrade to the ongoing O&S costs of a weapon system?* Only three new engines were able to be analyzed on aircraft, AE-2100 on the C-130"J" models, the F138-GE-100 on the C-5M, and the F108-CF-201 on the RC135 models. One new engine was available in the data for helicopters, the T53-L-703. Seven engines were retired on various MDSs including fighter and cargo aircraft as seen in Table 4. Engine fuel performance is measurable with the available data and is capable of being normalized. The difference in fuel performance is statistically significant in almost all cases with the exception of the retired F100-PW-100 compared to the newer F100-PW-220. Fuel performance is rated better in the estimated range of 28 to 280 fewer gallons per flying hour on cargo aircraft. Maintenance costs are difficult to quantify as costs available by engine are approximated and do not include CLS, and using AFTOC data steady-state to steady-state comparisons are not available. From the data that is available, maintenance costs on new engines are significantly lower than the engines they are replacing.

2). *How do these effects vary across different weapon systems?* Only cargo, refuelers and fighter aircraft could be analyzed. Compared to the retired fighter jet engine, fuel efficiencies are either not statistically different or are more costly for fighter aircraft, suggesting that other characteristics of the engine, such as thrust, power or reliability were determined to be more important. Helicopters followed the same fuel performance pattern as cargo aircraft, where the increase to other engine performance characteristics still resulted with improved to fuel efficiency.

3). *To what extent do historical data have predictive capacity for future O&S cost estimates?* In most cases, the p-values from the various Wilcoxon Rank Sum tests are usually less than 0.0001, suggesting a high statistical significance. This suggests that the observed differences seen in the graphs are predictive of what fuel savings are attainable. Point estimates for fuel savings on aircraft can be computed by comparing the average of one engine with another is possible by examining Tables 4 and 14. Tests regarding engine maintenance costs also had low p-values which normally suggest predictive ability, but the limitations in how the data are collected raise doubts to their reliability and interpretation, namely the inability of tracing CLS costs to engines and the inability of comparing engines at steady-state since there are only four new engines. More studies will be required as new engines reach steady-state. The early indications are that maintenance costs are lower for replaced engines and the savings are potentially significant.

5.3 Significance of Research

Within the cargo aircraft, we observed large improvements in fuel efficiencies. This happened despite an increase in the power of the engines as captured in Table 4. In terms of maintenance, they appear to be cheaper to operate, although this will take time to fully capture the extent of these savings. In essence, the Air Force has perhaps enjoyed the best of both worlds, higher quality performance for a lower price. How did this happen? The answer could be in the advancement of technology compared to the age of our engines. Our aircraft are old (Heritage, 2019) with some aircraft, such as the B-52, already in their mid to late sixties. While the engines are not always as old as the aircraft, we can infer that with only three new TMS engines in over 20 years, the engines are too old to compete in performance and cost with modern technology both in terms of maintenance costs and fuel consumption.

In financial terms, the cost of a new engine should be compared to the present value of the potential savings. This thesis has only looked at one side of that equation, how much can we expect in potential savings. Recently, because of the state of the B-52H, a new engine was necessary in order to keep the aircraft operational, but the evidence suggests that the decision to purchase new engines may save significant sums in fuel and maintenance.

The JSTARS were in the process of acquiring new engines, with $160M in then year dollars on RDT&E from 2007 to 2011 based on the President's Budget in those years. However, the acquisition of the engines has not yet materialized. The JSTARS operate on the TF33-P-102C with similar characteristics to the TF33-PW-102 which was analyzed in this study. If the JSTARS had new engines with similar fuel consumption as the F108-GE-201, then (from Table 4) a point estimate for the average fuel savings would be 348 gallons per flying hour. Using AFTOC data over the last six years the JSTARS have averaged 8,100 flying hours per year, which equates to 2.8 million gallons of fuel a year. Using the 2020 DLA standard rate for JP-8 of $2.96 per gallon, this represents $8.3M of savings per year. Using a conservative 2% inflation rate, the savings in fuel has a present value of $136M over 20 years. Given how long engines stay in inventory, 20 years may also prove to be conservative. Additionally, the maintenance savings would add to this figure. The increased reliability and performance upgrades would be a bonus.

5.4 Recommendations for Action and Future Research

Acquisition cost research is well studied, and cost analysts create estimates for each new ACAT program. The O&S side of the estimate is less researched and more uncertain. This research helps to fill in that gap for some aircraft engines. For those engines that the Air Force is considering replacing, decision makers need reliable information in order to understand the trade-offs. Part of that trade-off comes in the form of more capabilities, but maintenance and fuel performance are measurable and also need to be taken into account.

Research like this is hampered by the availability of data. Originally, the scope of this thesis was on modifications generally. However, that data is not available. Costs are not tracked at a low enough level to compare the performance of tail numbers. The lowest level that costs can be tied to is by MDS or engine, which is where this research was forced to focus. It is not known (in an accessible manner) when any particular aircraft has been modified or is awaiting modification. Program offices do not track modifications with this level of granularity and neither do Air Force data entry systems. Since the past is the best predictor of the future, it would behoove the Air Force to track costs at lower levels.

Our engines are old and have reached the point where the trade-off in performance on cargo aircraft comes at a reduction in costs instead of an addition to costs. Future research should be able to further bear this out. A more exact estimate of savings could be accomplished if an analyst were able to exam the costs per aircraft and normalize by metrics other than flying hours, such as cargo load or distance of sortie. A root cause analysis for the lower fuel performance deviations that were noted in FY 2002 (as mentioned in Section 4.5) could be further examined. Additionally, further examination of the variation in command or type of usage (refueling, training etc.) may be of value to analysists at those commands. Appendix D contains charts of the fuel performance by each MD category broken out by the Major Commands. The colors used in Appendix D are consistent with the majority of the thesis, red for new engines, green for retired, and blue for engines in use over the full time period. In each case, AFMC shows higher variation in fuel performance, likely as a result of how AFMC uses aircraft.

Lastly, a normalization for the amount of cargo, or alternately the weight of the aircraft, would also improve the results of this research. Much of the variation in fuel performance is likely explainable by the weight of the aircraft. A limitation for this research though is that would entail significant resources in order to collect in order to compile the necessary database. Research could also be performed on Navy systems.

5.5 Chapter and Thesis Summary

In this chapter concluded the thesis by restating and answering the research questions from Chapter I. Fuel efficiency can be calculated from data that is already captured by AFTOC, but maintenance costs caused by modification or tied directly to an engine is not available the way the AF currently collects data. The costs allocated to engines is estimated by ratios and, significantly, does not include CLS at all since CLS is generally not traceable to components. If the AF desires to track the costs of engines it will require some amount of restricting of the line of accounting or contract reporting requirements. Further complicating engines maintenance analysis is the inability to compare steady-state engines when starting with the AFTOC stand up date of 1996.

We also used the JSTARS re-engine effort as a case study for potential savings. While we are left with a significant shortfall for estimating the costs of maintenance, the saving potential in fuel could be approximated to a present value of $136M. Different assumptions as far as inflation, usage and the range of actual fuel savings will provide different point estimates

This research could be improved if costs could be more narrowly pinned down, but regardless the results are overwhelming for the cargo aircraft. There are significant savings available for the reduction of O&S costs in the future, both in maintenance and fuel as the AF modernizes its inventory of engines. Further areas of research are available to exam performance metrics that can be analyzed or normalized by command or usage.

Appendix A – Acronym Listing

ACAT	Acquisition Category
AFLCMC	Air Force Life-Cycle Management Center
AFTOC	Air Force Total Ownership Costs
BY	Base Year
CAPE	Cost Assessment and Program Evaluation
CBO	Congressional Budget Office
CEMS	Consolidated Engine Management System
CER	Cost Estimating Relationship
CLS	Contractor Logistics Support
DLR	Depot Level Maintenance
DoD	Department of Defense
FAS	Fuel Automated System
FFRDC	Federally Funded Research and Development Centers
FH	Flying Hours
FY	Fiscal Year
GAO	Government Accountability Office
LCC	Life Cycle Costs
MDAP	Major Defense Acquisition Program
MDS	Mission Designation Series
O&S	Operations and Support
OAC	Operating Agency Code
OPTEMPO	Operations Tempo
PAA	Primary Aircraft Assigned
PAI	Primary Aircraft Inventory
PEC	Program Element Code
PM	Program Manager
RC/CC	Resource Center
RDT&E	Research, Development, Test and Evaluation
REMIS	Resources Management Information Systems
RERP	Reliability Enhancement and Re-engining
SLEP	Service Life Extension Programs
SPO	System Program Office
TAI	Total Aircraft Inventory
TMS	Type Series Modification
VAMOSC	Visibility and Management of Operating and Support Costs
WSARA	Weapon Systems Acquisition Reform Act

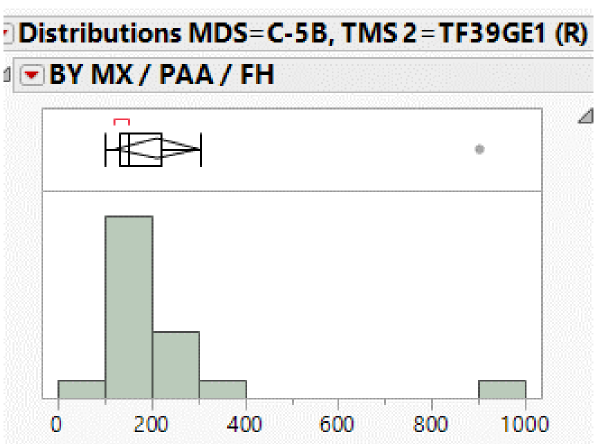
Appendix B – Listing of Included MDS Categories and Engines

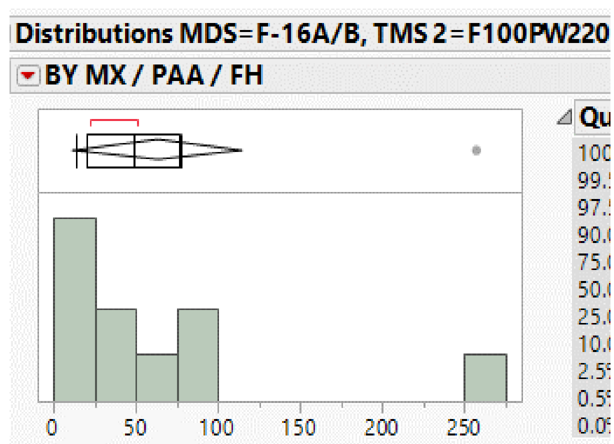
MDS Category	Engine TMS	MDS	Total Inventory (over time)	MDS Category	Engine TMS	MDS	Total Inventory (over time)
C-5	F138GE100	C-5M	577.5	**C-135**	F108GE100	KC-135R	21784.75
	TF39GE1	C-5A	3499.25			KC-135T	3287.25
		C-5B	2818		F108GE201	RC-135S	86.25
		C-5C	125.5			RC-135U	68.75
C-130	AE2100	AC-130J	43.75			RC-135V	292.25
		C-130J	675.5			RC-135W	291.5
		EC-130J	48.5			TC-135S	10.5
		HC-130J	128.75			TC-135W	96.25
		MC-130J	243.25		TF33PW102	C-135E	49.75
		WC-130J	42.25			EC-135E	33
	T56A15	AC-130H	478			EC-135K	23.5
		AC-130U	1073			EC-135N	22.25
		AC-130W	261.5			EC-135Y	11
		C-130E	309.75			KC-135D	106
		C-130H	19337.25			KC-135E	4220
		EC-130E	380.75			KC-135R	5.75
		EC-130H	951.5			NKC-135E	51.75
		GC-130H	3.75		TF33PW5	C-135B	34.25
		HC-130N	663.5			C-135C	36.75
		HC-130P	1338.5			OC-135B	74.25
		LC-130H	601.75			RC-135S	53.25
		MC-130E	568			RC-135W	125.5
		MC-130H	1601.5			TC-135S	25
		MC-130P	1669.25			TC-135W	16.25
		MC-130W	128			WC-135W	42.75
		TC-130H	44.75		TF33PW9	EC-135C	76.5
		WC-130H	594.75			NKC-135B	25.5
	T56A7	C-130E	8535.75			RC-135U	43.75
		GC-130E	16.5			RC-135V	133.5
						WC-135C	52.5
F-15	F100PW100	F-15A	2184.5	**F-16**	F100PW200	F-16A	321.75
		F-15B	465.75			F-16B	162.25
		F-15C	5599		F100PW220	F-16A	720
		F-15D	1212.75			F-16B	331.75
		GF-15C	4.5			F-16C	6049.75
		YF-15A	5.25			F-16D	1525.75
	F100PW220	F-15A	378		F100PW229	F-16C	1451
		F-15B	32.5			F-16D	260.25
		F-15C	7009.75		F110GE100	F-16C	10207
		F-15D	821.5			F-16D	1340.25
		F-15E	4977.25		F110GE129	F-16C	3410.75
	F100PW229	F-15E	3997.75			F-16D	531

Appendix C, Maintenance Cost Statistics with Outliers Included

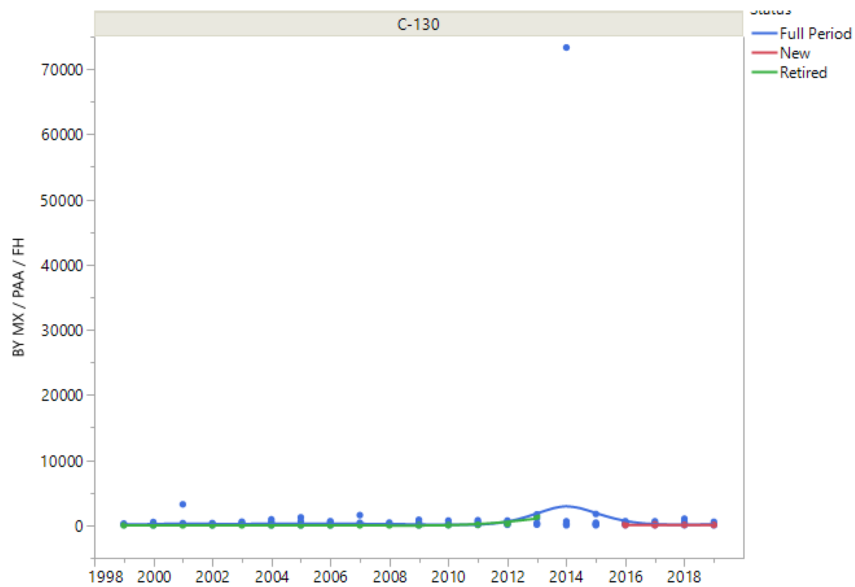
As discussed 12 outliers were removed from the Section 4.11 of Chapter IV. Unlike with fuel performance, large outliers are possible based on how maintenance costs are performed. While unusual, it is not surprising if maintenance in one year is three or four times higher the next year, which would be unusual in fuel performance.

Since this thesis is based on typical operation, outliers more than 3.5 standard deviations from the mean were removed. In total, 12 outliers were removed, seven on full period engines and five on retired engines. Due to the nature of the data all 12 were 3.5 or more standard deviations above the mean, and none below. Seven were from the C-130 models, two from F-15s and one each from F-16, C-135s, and C-5s. Outliers were identified using histograms by MDS and TMS, two examples are shown below: as shown below (C-5B and F-16A/B):





Since Section 4.11 is based on charts, removing outliers like the one above create meaningful figures. With removing outliers, Figure 24 (and others) would not be very meaningful and look like this:

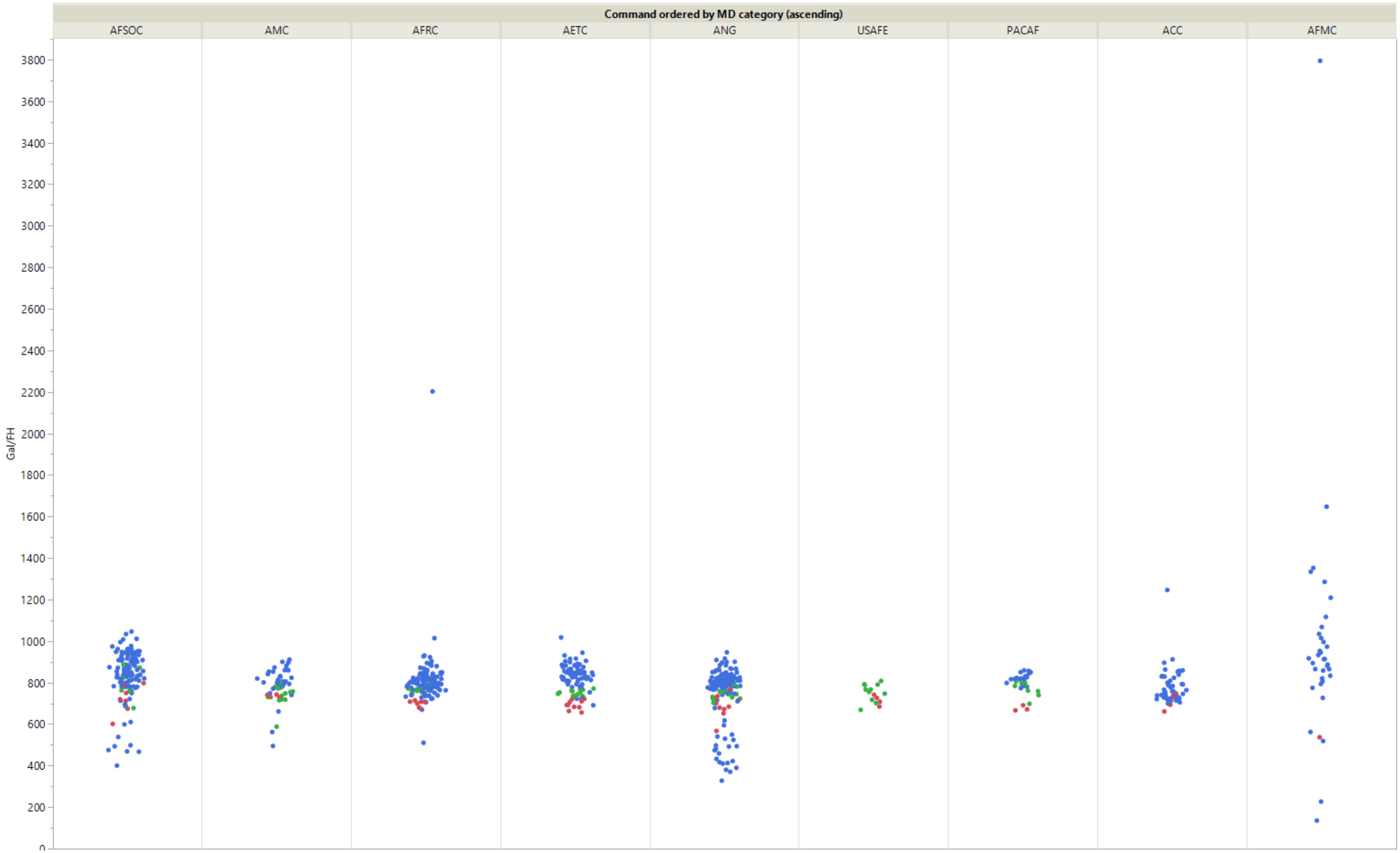


For completion Table 20 is replicated below and includes all data points.

MD	Status	TMS	N	Mean	Median	Std Dev	CV
C-130	**New**	**AE2100**	**24**	**$43.82**	**$30.21**	**57.1**	**1.30**
	Retired	**T56A7**	**19**	**$99.20**	**$11.40**	**311.6**	**3.14**
	Full Period	T56A15	235	$535.50	$136.33	4780.2	8.93
C-135	**New**	**F108GE201**	**37**	**$89.07**	**$63.36**	**81.8**	**0.92**
	Retired	**TF33PW105**	**6**	**$9.69**	**$9.25**	**7.6**	**0.79**
	Retired	**TF33PW5**	**7**	**$97.72**	**$96.04**	**69.4**	**0.71**
	Retired	**TF33PW9**	**9**	**$44.13**	**$23.41**	**50.2**	**1.14**
	Full Period	F108GE100	44	$13.89	$6.95	15.5	1.12
	Retired	TF33PW102	16	$14.49	$10.07	24.3	1.68
C-5	**New**	**F138GE100**	**10**	**$80.77**	**$35.43**	**87.7**	**1.09**
	Retired	**TF39GE1**	**37**	**$152.88**	**$131.14**	**144.9**	**0.95**
F-15	Full Period	F100PW220	52	$49.69	$10.97	249.0	5.01
	Full Period	F100PW229	24	$11.28	$11.76	5.9	0.52
	Retired	F100PW100	22	$22.18	$9.98	19.1	0.86
F-16	Full Period	F100PW220	31	$20.93	$0.86	49.4	2.36
	Full Period	F100PW229	21	$0.30	$0.29	0.1	0.49
	Full Period	F110GE100	21	$1.15	$1.09	0.2	0.17
	Full Period	F110GE129	21	$0.52	$0.47	0.2	0.32
	Retired	F100PW200	9	$1.55	$1.18	1.6	1.05

Appendix D – Fuel Performance by MD Catergory by Major Command

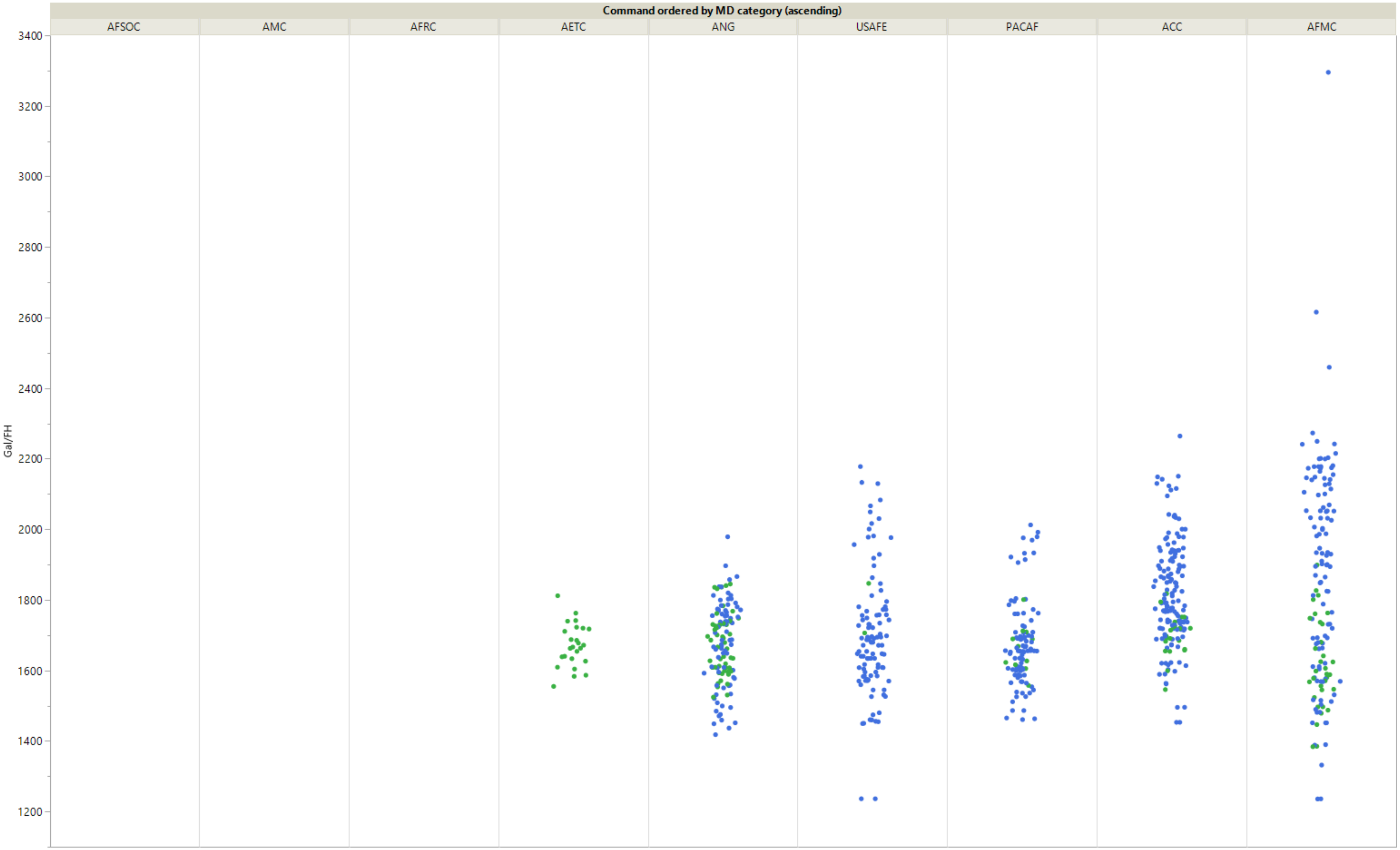
MD Catergory C-130s



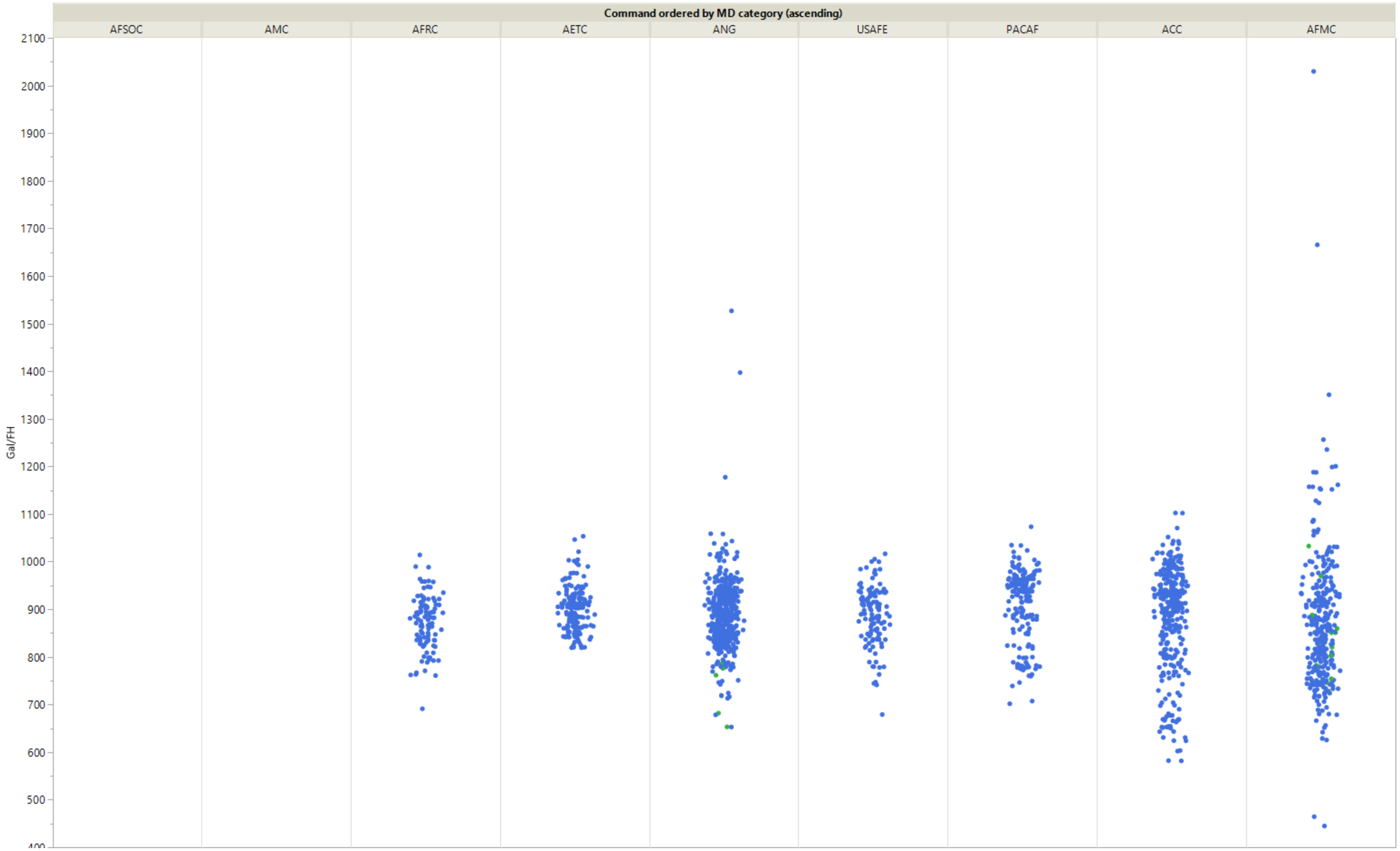
MD Catergory C-135

MD Category C-5

MD Category F-15



MD Category F-16



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14. ABSTRACT
As research into Operating and Support (O&S) costs matures, the focus can narrow. This research represents a first of its kind for the Air Force; it is an empirical study to analyze the effects of new engines on fuel efficiency and maintenance over those engines they replace. Within this research, new engines are those with distinct Type Series Modification (TMS) designators that appear within categories of Mission Designation System (MDS) aircraft. The only new engines appear on C-5s, C-130s, and C-135s. The inclusion of retired engines brings in two fighter aircraft, F-15s and F-16s. The data source is the Air Force Total Ownership Cost (AFTOC) database, which collects flying hours and gallons of fuel and is available by engine. Using this data, the realized fuel efficiencies of the new engines can be effectively graphed, quantified and tested. Maintenance costs are not tracked by engine but are approximated from ratios determined by AFTOC. Of note, these costs do not include Contractor Logistics Support (CLS) which may weaken the analysis for estimating future engine maintenance costs. From the data available, the potential savings that can be realized in fuel and maintenance are significant and do not come at a trade-off in engine performance.

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