2021

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

Bradford A. Myers

Edward D. White
Air Force Institute of Technology

Jonathan D. Ritschel
Air Force Institute of Technology

R. David Fass
Air Force Institute of Technology

Image designed by Nicole Brate

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

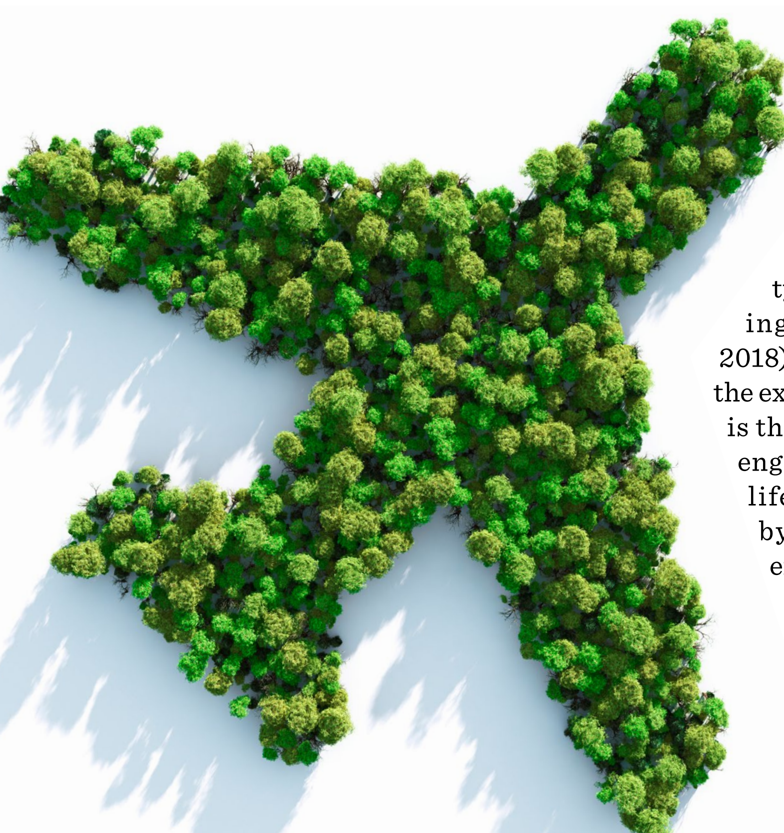
Bradford A. Myers, Edward D. White, Jonathan D. Ritschel, and R. David Fass

For fixed wing aircraft within the U.S. Air Force, Operating and Support (O&S) costs encompass a large portion of total life cycle costs. O&S costs include fuel, maintenance, and engine upgrades. To the authors' knowledge, no study to date has attempted to empirically quantify the realized effects of new aircraft engines on sustainment costs. Utilizing the Air Force Total Ownership Cost database, they focused on new engines appearing on the C-5s, C-130s, and C-135s. Although narrow in scope, results suggest newer engines have lower fuel costs. Maintenance costs for newer engines were not consistently higher or lower than the engines they replaced, although Contractor Logistics Support was not tracked by engine in this study. We found that savings from improved fuel efficiency tended to be greater than a potential increase in maintenance costs.

DOI: https://doi.org/10.22594/dau.20-862.28.03
Keywords: *Engine Upgrades, Operating and Support (O&S) Costs, Contractor Logistics Support (CLS), Life Cycle Costs (LCC)*

For many Department of Defense (DoD) programs, Operating and Support (O&S) costs encompass the largest portion of Life Cycle Costs (LCC), which is a key reason why defense acquisition leadership has expressed a renewed emphasis on O&S affordability and cost management (Office of the Secretary of Defense, Cost Assessment & Program Evaluation [OSD CAPE], 2014). O&S consists of all sustainment costs, including personnel, fuel, supplies, maintenance, upgrades, etc. (OSD CAPE, 2014). For DoD aircraft, engines are expensive components to acquire, maintain, and upgrade. As such, their O&S costs need to account for perhaps the decreasing reliability and increasing maintainability costs of old engines versus the establishment and integration of newer engines. Despite O&S costs accounting for an average of 55% of total LCC (Jones et al., 2014), no study to our knowledge has attempted to empirically quantify the realized effects of new aircraft engines on sustainment costs.

Previous studies (Mouton et al., 2015; National Research Council, 2007) have analytically investigated possible ways to reduce fuel usage and the feasibility of such proposals such as engine-out taxiing strategies, optimal flight level and speed, and reducing aircraft weight. Additionally, Boito et al. (2016) discussed potential C-130 improvements, including the previous measures as well as load-balancing improvements, reduction of auxiliary power units, and installation of microvanes™. Their study suggested that full implementation of these options could save about 16 million gallons of fuel annually. These types of modifications are becoming more and more important as U.S. Air Force (USAF) systems age.



The Heritage Foundation (2020) reported that, as of 2019, the average age of USAF aircraft is over 29 years. This fact is important because the age of an aircraft typically correlates with increasing O&S costs (Hewitson et al., 2018). One way the USAF deals with the expensive issue of replacing a fleet is through modernizations, such as engine upgrades to extend service life. This is the tactic employed by the B-52 program office to extend the life of that fleet while capturing reductions in O&S costs via more fuel-efficient modern engines. On May 19, 2019, the USAF released a formal solicitation for the B-52 Commercial Engine Replacement Program.

In this article, we investigate how engine upgrades influence ongoing O&S costs, specifically fuel performance and total engine maintenance costs less Contractor Logistics Support (CLS), for a small group of USAF fixed-wing aircraft. For purposes of this article, we refer to engine upgrades as either technology insertions (modifications) into existing engines or a "re-engine," which entails replacing engines and a new Mission Designation Series (MDS).

> **"The O&S cost information collected includes unit-level manpower, fuel, depot maintenance overhaul costs, depot-level reparable costs, and other costs of major USAF aircraft and engines.**

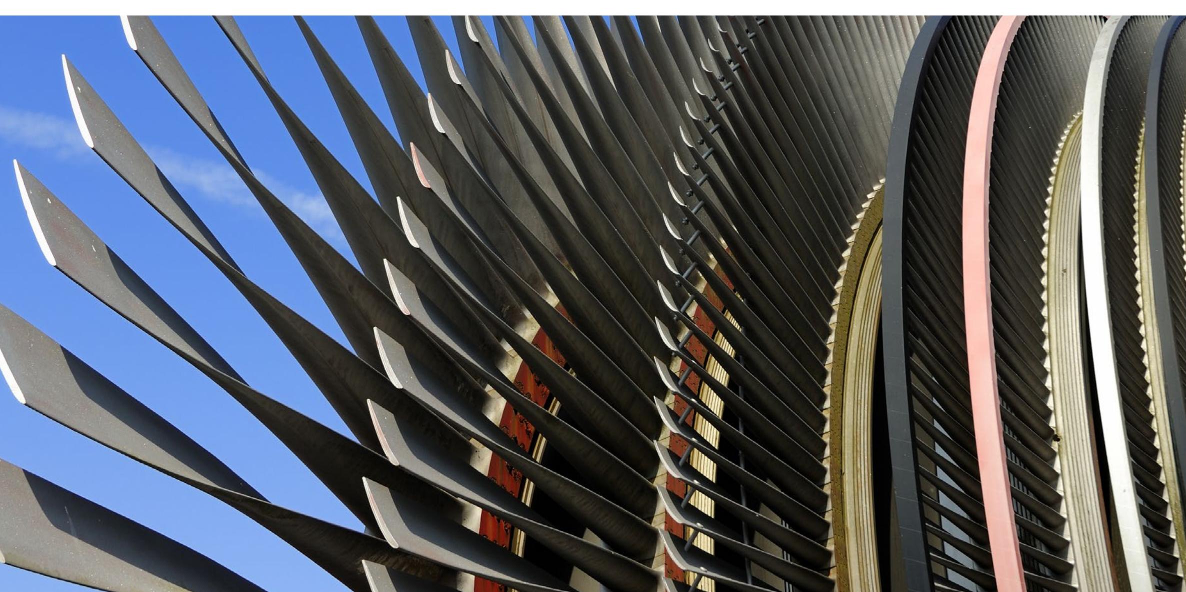
The analysis focuses on a small number of USAF aircraft because our dataset identified only three new aircraft engines introduced into the inventory in the past 20 years: the F138-GE-100 on the C-5M (in Fiscal Year [FY] 2010), the AE2100 on various C-130 "J" models (in FY2016), and the F108-GE-201 on various C-135 models (in FY2001). All three engines are for cargo aircraft. To investigate the effects of upgrading engines, the analysis requires comparable aircraft with O&S data on at least two different engines. A different engine is defined here as those engines with a separate Type Series Modification (TMS) designator.

Background and Data

The passing of the Weapon Systems Acquisition Reform Act (WSARA) in 2009 elevated the importance of O&S estimates and cost reporting. Each military department maintains its 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). OSD CAPE provides broad policy guidance pertaining to the military department VAMOSC programs, but leaves the details concerning implementation to each department. Though the primary focus of VAMOSC is for future planning and the development of O&S estimates, the nature of the database allows actual O&S costs to be sorted by weapon system and by year (Ryan et al., 2012).

The Air Force system designed to be compliant with the requirements of VAMOSC is the Air Force Total Ownership Cost (AFTOC) 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 USAF aircraft and engines. AFTOC also maintains data on aircraft quantities and flying hours, number of personnel, and other noncost information (OSD CAPE, 2014). In compliance with the CAPE guidance, AFTOC also provides users with system-level data, as well as lower levels of data (major subsystems and components).

The optimal approach to compare engine performance or cost would be by aircraft tail number. This would allow accurate comparisons before and after a new engine installation for a specific aircraft, thereby minimizing any other external factors. Unfortunately, this ideal approach is unobtainable with current USAF data collection systems. Fuel consumption and flying hours are available by tail number based on the Fuel Automated System and are available within AFTOC, but not engines. Neither program offices nor USAF data systems track modifications or engine upgrades by tail number. 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 MDS, level as captured by a combination of the data elements, namely the Program Element Code, Operating Agency Code, or Resource Center/ Cost Center.



Further complicating specific costs associated with an individual aircraft tail number is the accounting of CLS. 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). The *DoD O&S Cost Management Guidebook* states that CLS and Depot cost categories are difficult to categorize since they are likely to include costs for personnel and parts as well as other things such as overhead and facilities (DoD, 2016). Because of this, the data we used to compare the effects of replacing an older engine with a newer one do not include CLS costs.

"Overall, only engines that entered service between FY1997 through FY2017 are considered, for a total of 21 years of O&S data.

AFTOC compiles data into various "data cubes," which encapsulate categories of costs. For this study, we used three principal data cubes: the CAPE14 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. No Line of Accounting element is tied to engines, so the reported Engine data are approximated by using ratios from the REMIS (Reliability and Maintainability Information System) flying hours and comparing them to CEMS (Consolidated Engine Management System) Engine Actuarial data. The engine costs information used in this research are therefore approximations—a limitation we recognize.

Because of these limitations in how the Air Force collects source data, isolation of the effects of new and old engines is not possible unless they belong to a separate MDS. One example where this is the case 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 directly compare the costs of the old engine with the new engine. If a new engine is not isolated to its own MDS, costs are estimated on a proportionate basis as reported by AFTOC's 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 given MDS.

The initial step for comparative analysis is to isolate aircraft platforms with more than one engine, generating a listing of MDS categories with more than one engine type/model/series (TMS), one of which must be a newer engine. These MDS categories were rolled up into a parent MDS family (C-5s, C-130s, C-135s) which, for purposes of this analysis, was used to identify whether 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 family of C-130s. The AFTOC helpdesk compiled a database of engine inventory by TMS, base, fixed-wing aircraft platform, and serial number that spanned from 1999 to 2019. Drones and helicopters were not considered in this article due to their distinct operating differences from fixed-wing aircraft.

Actual data for engine inventory on aircraft are used to find engine pairings. Engines put into place after FY2017 do not have at least 2 years of new O&S costs for statistical comparison. By the same logic, only those engines that have been in place since FY1997 allow for at least 2 years of premodification O&S data using AFTOC stand-up-date of FY1996. Overall, only engines that entered service between FY1997 through FY2017 are considered, for a total of 21 years of O&S data.

Aircraft with a small Primary Aircraft Authorization (PAA) (aircraft authorized to a unit for performance of its operational mission) number 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. Therefore, in addition to the requirement that the MDS category has more than one TMS engine, we also restricted the analysis to platforms with a PAA of five or more. After all these exclusions, only three MDS families remained—the various C-130s, C-135s, and C-5s. The MDS breakout includes three categories of cargo aircraft/refuelers—the various C-5, C-130, and C-135 variants such as the KC-135. Table 1 lists the final set of aircraft included for analysis.

TABLE 1. AIRCRAFT MDS CONSIDERED WITH 5 OR MORE PRIMARY AIRCRAFT AUTHORIZATIONS

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

Note. AC = Attack Cargo; C = Cargo; EC = Electronic Cargo; HC = Search and Rescue Cargo; KC = Tanker Cargo; MC = Multi-Mission Cargo; RC = Reconnaissance Cargo; WC = Weather Cargo.

It would be inaccurate to compare fuel consumption, efficiency, and cost without standardizing for operations tempo. If operations tempo increases over time, then costs will vary in accordance with that usage instead of the engine. Using the metric of gallons per flying hour (FH)—fuel consumption— mitigates the issue and creates a homogeneous comparison across aircraft in the same MDS family. Theoretically, changes in gallons/FH will be reasonably well isolated to the effects of the new engine.

While maintenance costs do vary by flying hour in the same way that mileage affects automotive maintenance, the number of aircraft is also important for cost standardization.

Unfortunately, the comparison is not perfect since the data will generate errors and measuring inefficiencies. Even if these did not exist, additional variation is likely since fuel efficiency varies by altitude, atmospheric conditions, and cruise speed (Rolls Royce, 2015), none of which are captured within AFTOC data. Aircraft with few flying hours may have a distorted gallons/FH metric caused by the fuel used in takeoff 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 reported flying hours by FY were removed. This removal represented 0.006% of the total flying hours reported.

Maintenance costs were also standardized prior to comparing the new engines to the older engines. We converted costs to Base Year 2019 dollars 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 also important for cost standardization. Boito et al. (2015) suggested that the Primary Aircraft Inventory (PAI) is inherently more stable than flying hours and is the preferred metric by subject matter experts to standardize maintenance costs. [Note: We used PAA in place

of PAI since PAI is not available in the AFTOC data cubes; this does not meaningfully change the results of the analysis.] We use PAA to standardize maintenance costs within MDS categories. In summary, the metrics we use for comparison between new engines and older engines entail gallons/FH for fuel performance metrics; for maintenance costs we use Base Year 2019 maintenance costs/PAA/FH, excluding CLS.

We used the JMP 13 Pro statistical package for all the graphs and analyses presented in the next section. It should also be noted that our intent for the analysis was not to generate a regression model to predict fuel consumption or maintenance cost; there are simply too many uncontrolled variables for our limited dataset to adequately conduct such an undertaking. Instead, we are simply investigating the realized effects of fuel consumption and maintenance cost (minus CLS).

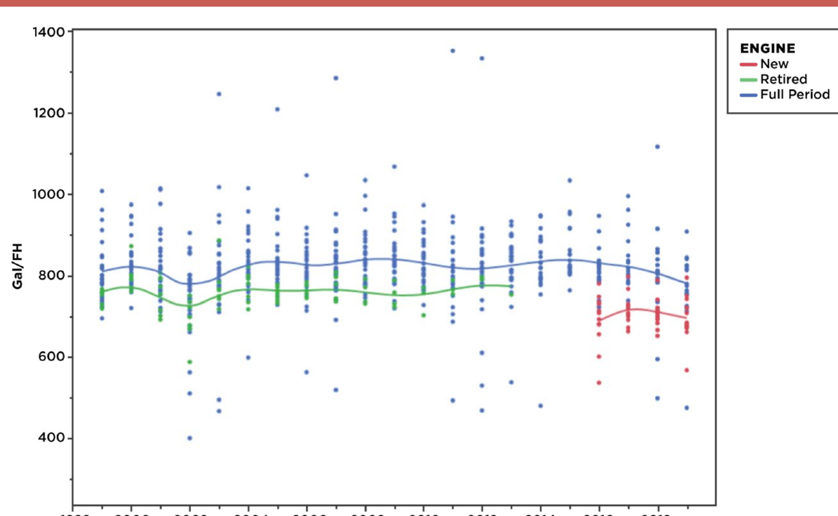
The most common test for comparing differences in means is a student *t*-test; however, this method is inappropriate when the underlying distributions are nonnormal. Therefore, we used the more conservative Wilcoxon Rank Sum test, also called the Rank Sums test, to test for statistical differences between the fuel efficiency and maintenance costs of the new versus retired engines. We also use the Hodges-Lehmann statistic (Hodges & Lehmann, 1963) to estimate the median differences and associated confidence intervals. Neither of these nonparametric methods require normality, and both provide robust comparisons in addition to being less susceptible to outliers. Since this study is exploratory and not confirmatory, we chose to minimize the chance of committing a Type II error, which is a failure to find a relationship where one exists. Therefore, we selected a level of significance of 0.1 to use for all the nonparametric tests conducted.

Analysis and Results

Except where noted, visualization 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 entire recorded study period (1999–2019). We first display graphs for the fuel performance metrics (gallons/FH) by MDS family to observe the effects of new engines. Following those, we present the results of the nonparametric tests with a discussion. After examining fuel performance metrics, we investigate the MDS by maintenance costs associated with their engines and limitations. The Wilcoxon Rank Sum test is used again to test and quantify the differences between the engine categories using the Hodges-Lehmann statistic.

All graphs are presented without outliers more than three standard deviations from the mean (within their respective MDS and TMS). 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. For all presented figures, each dot represents a reported value from a particular command (Air Combat Command, Air Education and Training Command, Air Force Materiel Command, Air Force Reserve Command, Air Force Special Operations Command, Air Mobility Command, Air National Guard, Pacific Air Forces, and U.S. Air Forces in Europe). Since the various C-130 variants are in most of the commands, figures for that MDS have several dots. Additionally, the curves connecting the points from year to year are smoothed splines and played no role in any statistical analysis. They simply display visual trends.

FIGURE 1. MEAN GALLONS/FH CONSUMPTION RATE BY FISCAL YEAR FOR THE C-130 MDS FAMILY



Note. Gal/FH = Gallons Per Flying Hour.

TABLE 2. WILCOXON RANK SUM TEST RESULTS FOR C-130 FUEL PERFORMANCE

Comparison	Test Statistic (Z)	P-value	Hodges-Lehmann Value	Lower 90% Bound	Upper 90% Bound
Retired vs. New	3.47	0.0005	42.4	28.84	60.64
Retired vs. Full Period	-4.54	< 0.0001	-70.01	-93.01	-51.17
New vs. Full Period	-6.71	< 0.0001	-114.77	-135.32	-94.15

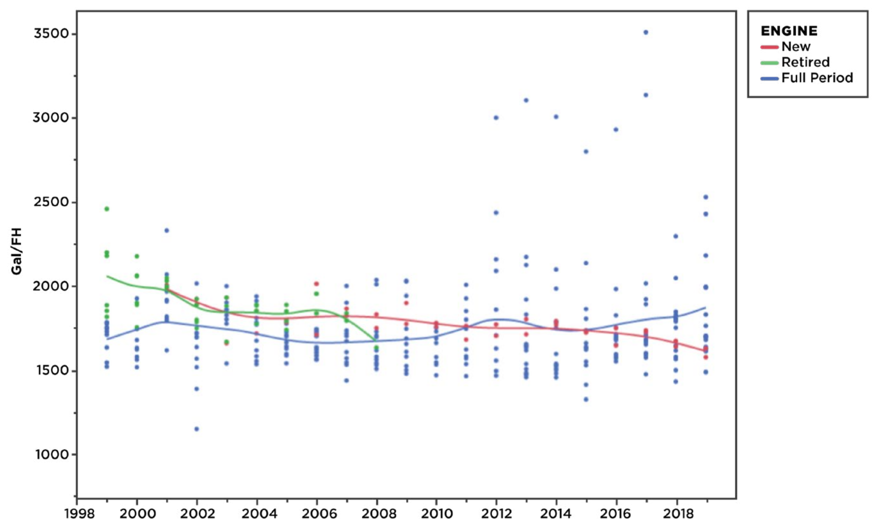
Note. Test statistic based on large sample approximation (Z-score). Values are gallons/FH. Numbers rounded to two digits after decimal place.

We begin with Figure 1, which highlights the C-130 fuel performance metrics. The new engines (belonging to the "J" models) are in red and appear to have a lower gallons/FH consumption rate than the other C-130 models. Table 2 shows the Wilcoxon Rank Sum test results. Each test is statistically significant, suggesting that a difference exists between each of the categories of engines at an α of 0.10. The Hodges-Lehmann column is the estimated median performance difference. In this case, the new engine is performing more fuel efficiently on average by 42 gallons/FH, with an associated 90% confidence interval of between 29 to 61 fewer gallons/FH in comparison to the retired engine.

The interpretation for the other two comparisons (retired or new versus engines utilized over the full study period) is comparable with the exception that the Hodges-Lehmann statistic is negative. As an example, using the Hodges-Lehmann value in the last row of Table 2, each flying hour on the full period engine (T56-A-15) is burning an additional 115 gallons/FH when compared to the new engine (AE-2100) in median fuel performance.

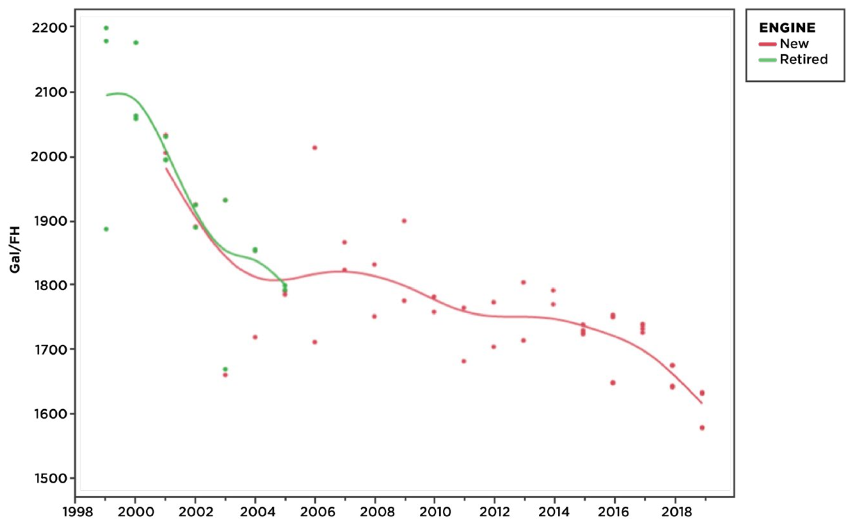
For the C-135 MDS, we chose to investigate subcategories since the missions of C-135 models are distinct (refueling versus reconnaissance) and appeared different from the rest with respect to fuel consumption. In comparison, we did not separate the C-130 models into subcategories, for there appeared to be no discernible differences except for the LC-130, which was excluded from our study due to its fundamental difference. The Lockheed LC-130 is a ski-equipped USAF variant of the C-130 Hercules used in the Arctic and Antarctic regions.

FIGURE 2. MEAN GALLONS/FH CONSUMPTION RATE BY FISCAL YEAR FOR C-135 MDS



Note. Gal/FH = Gallons Per Flying Hour.

FIGURE 3. MEAN GALLONS/FH CONSUMPTION RATE BY FISCAL YEAR FOR RC-135V/W AIRFRAME



Note. Gal/FH = Gallons Per Flying Hour.

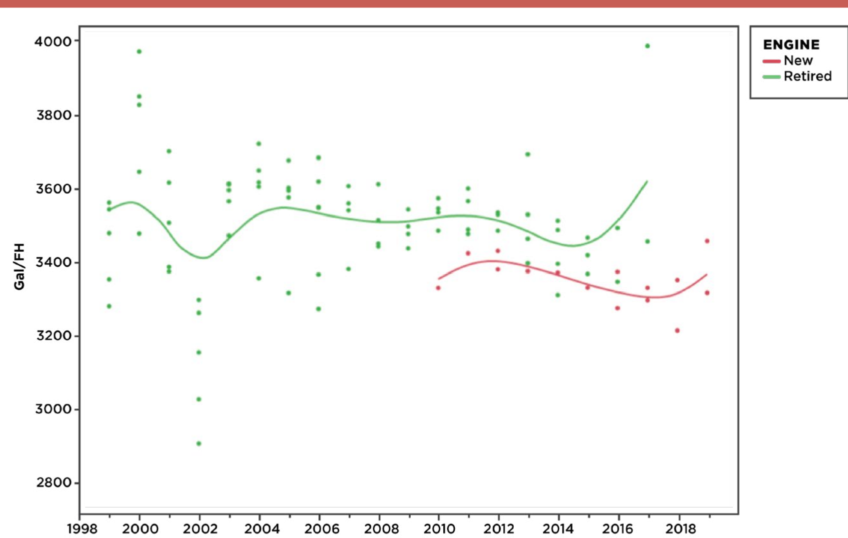
TABLE 3. WILCOXON RANK SUM TEST RESULTS FOR C-135 FUEL PERFORMANCE

Comparison (MDS)	Test Statistic (Z)	P-value	Hodges-Lehmann Value	Lower 90% Bound	Upper 90% Bound
Retired vs. New (RC-135)	4.72	< 0.0001	194.07	141.61	253.71
Retired vs. Full Period (KC-135)	4.21	< 0.0001	168.00	111.00	217.59

Note. Test statistic based on large sample approximation (Z-score). Values are Gallons Per Flying Hour (Gallons/FH). Numbers rounded to two digits after decimal place.

Figure 2 highlights the C-135 fuel performance metrics, while Figure 3 highlights just those RC-135V/W model metrics. For point of reference, only the RC-135V/W involved a new engine. Table 3 reflects the associated Wilcoxon Rank Sum tests and Hodges-Lehmann values. We can see in the fuel performance metrics that for each pair, the retired engines appear to be consuming more gallons/FH in comparison to either the full period or new engines since the green line is on top of the red line. With respect to the new engine, the estimated median performance suggests an improved engine efficiency between 142 and 254 gallons/FH in comparison to the retired engines. These results are statistically significant at the 0.1 level of significance.

FIGURE 4. MEAN GALLONS/FH CONSUMPTION RATE BY FISCAL YEAR FOR C-5 MDS CATEGORY



Note. Gal/FH = Gallons Per Flying Hour.

TABLE 4. WILCOXON RANK SUM TEST RESULTS FOR C-5 FUEL PERFORMANCE					
Comparison (MDS)	Test Statistic (Z)	P-value	Hodges-Lehmann Value	Lower 90% Bound	Upper 90% Bound
Retired vs. New	4.26	< 0.0001	167.08	116.87	216.72

Note. Test statistic based on large sample approximation (Z-score). Values are Gallons Per Flying Hour (Gallons/FH). Numbers rounded to two digits after decimal place.

Lastly, the C-5 provides the clearest comparison since there are only three MDS categories—only one of which (C-5M) corresponds precisely to just the new engine. Figure 4 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. The Wilcoxon Rank Sum statistic presented in Table 4 supports this conclusion statistically at the 0.1 level of significance. 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 117 to 217 gallons/FH.

TABLE 5. DESCRIPTIVE STATISTICS OF AIRCRAFT FUEL PERFORMANCE						
MDS	Status	TMS	Mean	Median	Std Dev	CV
C-130	New	AE2100	703	708	48	0.07
	Retired	T56A7	757	759	42	0.06
	Full Period	T56A15	821	817	94	0.11
C-135	New	F108GE201	1761	1745	106	0.06
	Retired	TF33PW102	1876	1852	154	0.08
	Retired	TF33PW105	1967	1932	134	0.07
	Retired	TF33PW5	1962	1932	129	0.07
	Retired	TF33PW9	1930	1889	189	0.10
	Full Period	F108GE100	1753	1693	296	0.17
C-5	New	F138GE100	3345	3341	61	0.02
	Retired	TF39GE1	3507	3522	167	0.05

Note. Numbers given are in gallons/flying hour from 1999 through 2019. CV = Coefficient of Variation.

TABLE 6. FUEL CONSUMPTION COMPARISONS BETWEEN THE NEW ENGINES AND RETIRED ENGINES

MDS	Status	TMS	% savings (Mean)	% savings (Median)
C-130	New	AE2100		
	Retired	T56A7	7.68%	7.20%
C-135	New	F108GE201		
	Retired	TF33PW102	6.53%	6.13%
	Retired	TF33PW105	11.70%	10.72%
	Retired	TF33PW5	11.41%	10.72%
	Retired	TF33PW9	9.60%	8.25%
C-5	New	F138GE100		
	Retired	TF39GE1	4.84%	5.42%

Note. Positive percentages indicate newer engines burn less Gallons Per Flying Hour (Gallons/FH) comparisons based on both mean and median Gallons/FH.

From this exploratory data analysis, even given the relatively small sample size of new engines introduced into the inventory by the USAF over the past 20 years, the new engines appear to be more fuel-efficient than the older retired engines. With each engine comparison among the cargo aircraft, the nonparametric tests were statistically significant, suggesting better fuel efficiency of the engines. Looking at the 90% confidence intervals in an aggregate, the estimated gallons/FH of fuel saved ranged from a low of 28 (C-130s), to a high of 280 (RC-135s). Given the tens to hundreds of thousands of hours that the fleet of USAF cargo planes fly annually, the potential cost savings could be substantial. Tables 5 and 6 reflect fuel consumption metrics and estimated percentage savings comparing the retired and new engines.

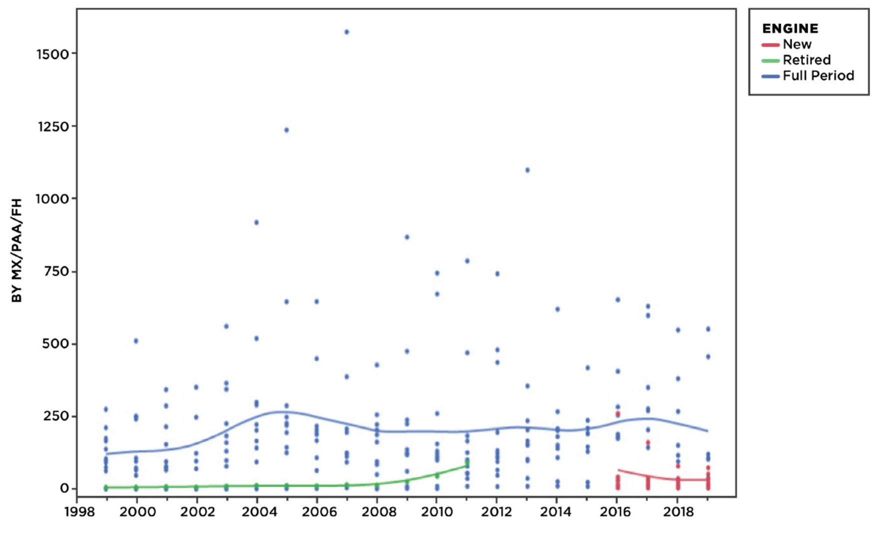
Maintenance costs are more difficult to analyze than fuel performance metrics. First, maintenance costs in general appear to vary more from year to year in comparison to fuel performance costs. Second, the AFTOC engine cost cube does not include CLS costs, thus underestimating total

> **“Engine maintenance costs are theorized to follow a bathtub effect, wherein costs are higher in the beginning due to initial learning or defects, reach a lower steady state, and then rise due to the aging effect.**

costs—an acknowledged limitation in the data. Lastly, this is further complicated by research showing the decision to utilize CLS as a maintenance strategy is found to generally cost more than not using it as such (Ritschel & Ritschel, 2016).

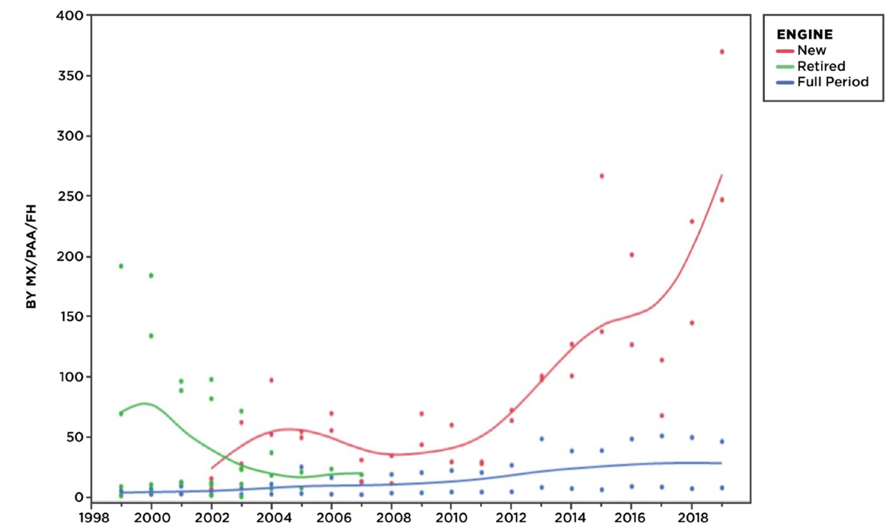
An aspect that further complicates the analysis of maintenance is the effect of aging. Over time, engines will likely cost more to maintain through the accumulation of wear and tear as well as obsolete parts and supply chains. Engine maintenance costs are theorized to follow a bathtub effect, wherein costs are higher in the beginning due to initial learning or defects, reach a lower steady state, and then rise due to the aging effect (Kiley, 2001). The best comparison of engine costs would be to compare Base Year costs from the steady state of one engine to the steady state of the other. Unfortunately, the newer engines have only been in the USAF inventory less than 10 years, decreasing the likelihood that steady state costs have fully materialized.

FIGURE 5. MEAN MAINTENANCE COSTS BY PRIMARY AIRCRAFT AUTHORIZATION BY FLYING HOUR FOR FISCAL YEARS 1999–2019 FOR THE C-130 MDS



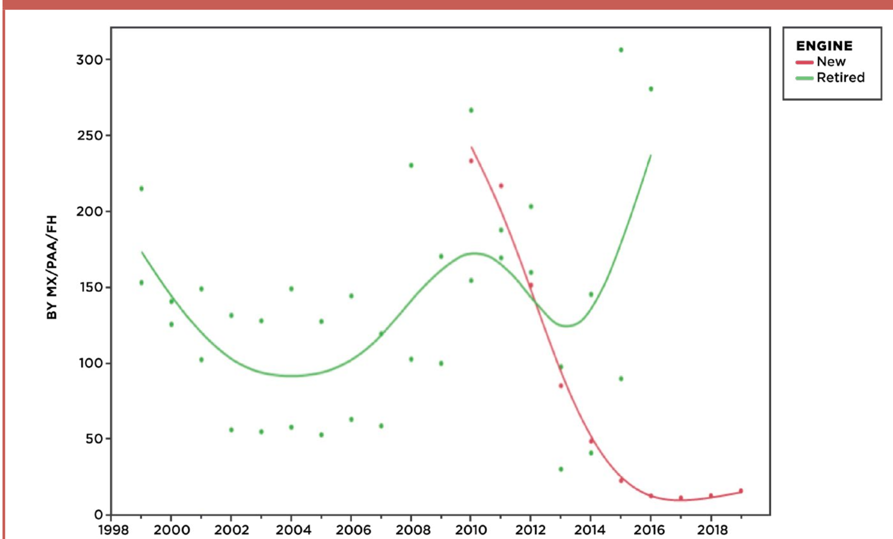
Note. MX/PAA/FH = Maintenance/Primary Aircraft Authorization/Flying Hour.

FIGURE 6. MEAN MAINTENANCE COSTS BY PRIMARY AIRCRAFT AUTHORIZATION BY FLYING HOUR FOR FISCAL YEARS 1999–2019 FOR C-135 MDS



Note. MX/PAA/FH = Maintenance/Primary Aircraft Authorization/Flying Hour.

FIGURE 7. MEAN MAINTENANCE COSTS BY PRIMARY AIRCRAFT AUTHORIZATION BY FLYING HOUR FOR FISCAL YEARS 1999–2019 FOR C-5 MDS



Note. MX/PAA/FH = Maintenance/Primary Aircraft Authorization/Flying Hour.

TABLE 7. COMBINED WILCOXON RANK SUM TEST RESULTS FOR THE C-130, C-135, AND C-5 MDS MAINTENANCE COSTS

Comparison (MDS and engine)	Test Statistic (Z)	P-value	Hodges-Lehmann Value	Lower 90% Bound	Upper 90% Bound
C-130 Full Period (T56A15) vs. Retired (T56A7)	4.39	< 0.0001	117.59	86.13	175.46
C-130 New (AE2100) vs. Full Period (T56A15)	-4.91	< 0.0001	-102.59	-141.75	-74.81
C-135 New (F108GE201) vs. Full Period (F108GE100)	6.40	< 0.0001	53.14	41.73	66.18
C-135 New (F108GE201) vs. Retired (TF33PW102)	3.96	< 0.0001	50.67	32.06	87.31
C-135 New (F108GE201) vs. Retired (TF33PW105)	3.54	0.0004	56.15	29.75	99.61
C-135 Full Period (F108GE100) vs. Retired (TF33PW5)	-3.39	0.0007	-75.91	-95.46	-34.60
C-5 New (F138GE100) vs. Retired (TF39GE1)	-2.14	0.032	-65.44	-114.14	-17.44

Note. Test statistic based on large sample approximation (Z-score). Costs are standardized to Base Year 2019. Values are dollars by Primary Aircraft Authorization by Flying Hour. Numbers rounded to two digits after decimal place.

TABLE 8. DESCRIPTIVE STATISTICS OF AIRCRAFT MAINTENANCE COSTS BY PRIMARY AIRCRAFT AUTHORIZATION BY FLYING HOUR

MDS	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	TF33PW102	9	14.62	12.38	5.4	0.37
	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
C-5	New	F138GE100	10	80.77	35.43	87.7	1.09
	Retired	TF39GE1	35	135.75	131.14	68.2	0.50

Note. Costs are standardized to Base Year 2019.

As when we compared fuel performance, we excluded outliers that were more than three standard deviations from the mean (within their respective MDS and TMS). This resulted in the removal of only nine points across all the MDS. Figures 5 – 7 illustrate the maintenance costs for the C-130, C-135, and C-5 MDS, respectively. The maintenance costs are inclusive of CAPE 1.2 (unit-level maintenance) as well the 3.0 categories recorded in AFTOC (CAPE 3.1 through 3.4; consumable materials and repair parts, depot-level repairables, intermediate maintenance [external to unit-level], and depot maintenance). Note: Figure 7 shows a large decrease in the cost of maintaining the C-5M, which can be partially explained by CLS (~23% of C-5M maintenance) and by the growth in PAA inventory from less than 10 (2011) to almost 50 (2018), which would exaggerate the effects of any fixed costs using the PAA/FH metric. Table 7 reflects the associated Wilcoxon Rank Sum tests and Hodges-Lehmann values for comparing the new engines to the retired ones and engines spanning the entire AFTOC observational window of 1999–2019. Table 8 contains the descriptive statistics of the maintenance cost data for each engine by MDS.

Overall, the maintenance results are mixed. Within the C-130 MDS family, both the retired and the new engines appear cheaper to maintain in comparison to the full period engines. Within the C-5s, the new engines were initially more expensive, but the costs quickly fell to lower levels. Although such a trend is consistent with the bathtub concept of perhaps a steady state occurring, the almost fivefold increase in PAA from 2011 to 2018 certainly contributed to this decreasing trend. The most interesting results are from the C-135 models; here, the new engine appears much more 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. We must caution that these statistical comparisons may need to be tempered given that we excluded CLS maintenance data that could not be gathered to the engine level.

Conclusions

Understanding how new engines may potentially affect costs associated with fuel performance and maintenance should improve program 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 (Government Accountability Office, 2010).

In this article, we investigated three new engines for fixed-wing aircraft introduced into the USAF inventory in the past 20 years: the 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. For these cargo/reconnaissance aircraft, we observed improvements in fuel efficiencies. In all instances observed during the entire study period (1999–2019), statistically significant findings consistently showed the new engines had better fuel efficiency in comparison to retired engines or engines still in service. Fuel performance is rated better in the estimated range of 28 to 280 fewer gallons/FH on cargo aircraft. Maintenance costs are difficult to quantify, because costs available by engine are approximated and do not include CLS. Also, steady state to steady state comparisons are not available using AFTOC data. From the data that are available, it appears that maintenance costs on the new engines are significantly lower than the engines they are replacing for the C-5 and C-130, but higher for the C-135. We recommend that further studies address return-on-investment strategies since there will be expenses in procuring and installing the new engines, including costs associated with spares inventory, training equipment (i.e., simulators), pilot training, or possible specialized maintenance tooling/equipment, etc.

> **While we realize this analysis is more exploratory than confirmatory in nature, we believe the potential saving is considerable when updating fixed aircraft with more modern, fuel-efficient engines.**

To conclude, we now use a case study for the cost savings that could occur using the recent re-engine efforts from the E-8 Joint Surveillance Target Attack Radar System (JSTARS) aircraft. The JSTARS was in the process of acquiring new engines, with $160 million in then-year dollars on research, development, test and evaluation from 2007 to 2011 based on the President's Budget in those years. However, the acquisition of the engines has not yet materialized. JSTARS uses the TF33-P-102C, which has similar characteristics to the TF33-PW-102 (Air Force Life Cycle Management Center, 2014) and was analyzed in this study. From our database, the median consumption rate for this engine was 1,852 gallons/FH.

If the JSTARS had new engines with similar fuel consumption as the F108-GE-201, based on our data, the median consumption rate would drop to 1,745 gallons/FH. This is a net saving of 107 gallons/FH. Using the 2020 Defense Logistics Agency standard rate for JP-8 of $2.96 per gallon, this translates into a saving of approximately $317/FH. If we use the maintenance data from Table 6 that suggests that the newer engines cost more to operate by approximately $53/PAA/FH and subtract that from $317/FH, we get a net saving of $264/PAA/FH. Using AFTOC data over the last 6 years, the JSTARS has averaged 8,100 flying hours per year, which equates to approximately a $2.1 million saved per year. Even using a conservative 2% inflation rate, this saving in present value is slightly over $51 million over 20 years. Given how long engines stay in inventory, 20 years may also prove to be conservative. While we realize this analysis is more exploratory than confirmatory in nature, we believe the potential saving is considerable when updating fixed aircraft with more modern, fuel-efficient engines. Over the lifespan of a fixed-wing aircraft, this has the potential of significantly reducing overall O&S costs.

References

Air Force Life Cycle Management Center. (2014). *The engine handbook*. AFLCMC, Director of Propulsion.

Boito, M., Light, T., Mills, P., & Baldwin, L. (2016). *Managing U.S. Air Force aircraft operating and support costs: Insights from recent RAND analysis and opportunities for the future.* RAND. https://www.rand.org/pubs/research_reports/RR1077.html

Boito, M., Keating, E., Wallace, J., DeBlois, B., & Blum, I. (2015). Metrics to compare aircraft operating and support costs in the Department of Defense. RAND. https://doi.org/10.7249/RR1178

Department of Defense. (2016). *Operating and support cost management guidebook*. https://www.dau.edu/guidebooks/Shared%20Documents/OS%20Cost%20Guide.pdf

Government Accountability Office. (2010). *Defense management: DoD needs better information and guidance to more effectively manage and reduce operating and support costs of major weapon systems* (Report No. GAO-10-717). https://www.gao.gov/products/GAO-10-717

Heritage Foundation. (2020). *An assessment of U.S. military power*. https://www.heritage.org/military-strength/assessment-us-military-power/us-air-force

Hewitson, S. C., Ritschel, J. D., White, E., & Brown, G. (2018). Analyzing operating and support costs for Air Force aircraft. *Journal of Defense Analytics and Logistics, 2*(1), 38–54. https://doi.org/10.1108/JDAL-03-2018-0006

Hodges, Jr., J. L., & Lehmann, E. L. (1963). Estimates of location based on rank tests. *Annals of Mathematical Statistics, 34*(2), 598–611. https://projecteuclid.org/download/pdf_1/euclid.aoms/1177704172

Jones, G., White, E. D., Ryan, E. T., & Ritschel, J. D. (2014). Investigation into the ratio of operating and support costs to life-cycle costs for DoD weapon systems. *Defense Acquisition Research Journal, 21*(1), 442–464. https://apps.dtic.mil/dtic/tr/fulltext/u2/a600495.pdf

Kiley, G. T. (2001). *The effects of aging on the costs of operating and maintaining military equipment*. Congressional Budget Office. https://apps.dtic.mil/dtic/tr/fulltext/u2/a393973.pdf

Mouton, C. A., Powers, J. D., Romano, D. M., Guo, C., Bednarz, S., & O'Connell, C. (2015). *Fuel reduction for the Mobility Air Forces*. RAND. https://www.rand.org/pubs/research_reports/RR757.html

National Research Council. (2007). *Improving the efficiency of engines for large nonfighter aircraft*. The National Academies Press. https://doi.org/10.17226/11837

Office of the Secretary of Defense, Cost Assessment and Program Evaluation. (2014). *Operating and support cost-estimating guide*. https://www.cape.osd.mil/files/os_guide_v9_march_2014.pdf

Ritschel, J. D., & Ritschel T. L (2016). Organic or contract support? Investigating cost and performance in aircraft sustainment. *Journal of Transportation Management, 26*(2), 47–58. https://core.ac.uk/download/pdf/212888423.pdf

Rolls Royce. (2015). *The jet engine*. Wiley.

Ryan, E., Jacques, D., Colombi, J., & Schubert, C. (2012). A proposed methodology to characterize the accuracy of life cycle cost estimates for DoD programs. *Procedia Computer Science, 8*, 361–369. https://doi.org/10.1016/j.procs.2012.01.073

Weapon Systems Acquisition Reform Act of 2009, 10 U.S.C., Pub. L. 111-23 (2009). https://www.govinfo.gov/app/details/PLAW-111publ23

Author Biographies

MSgt Bradford Myers, USAF

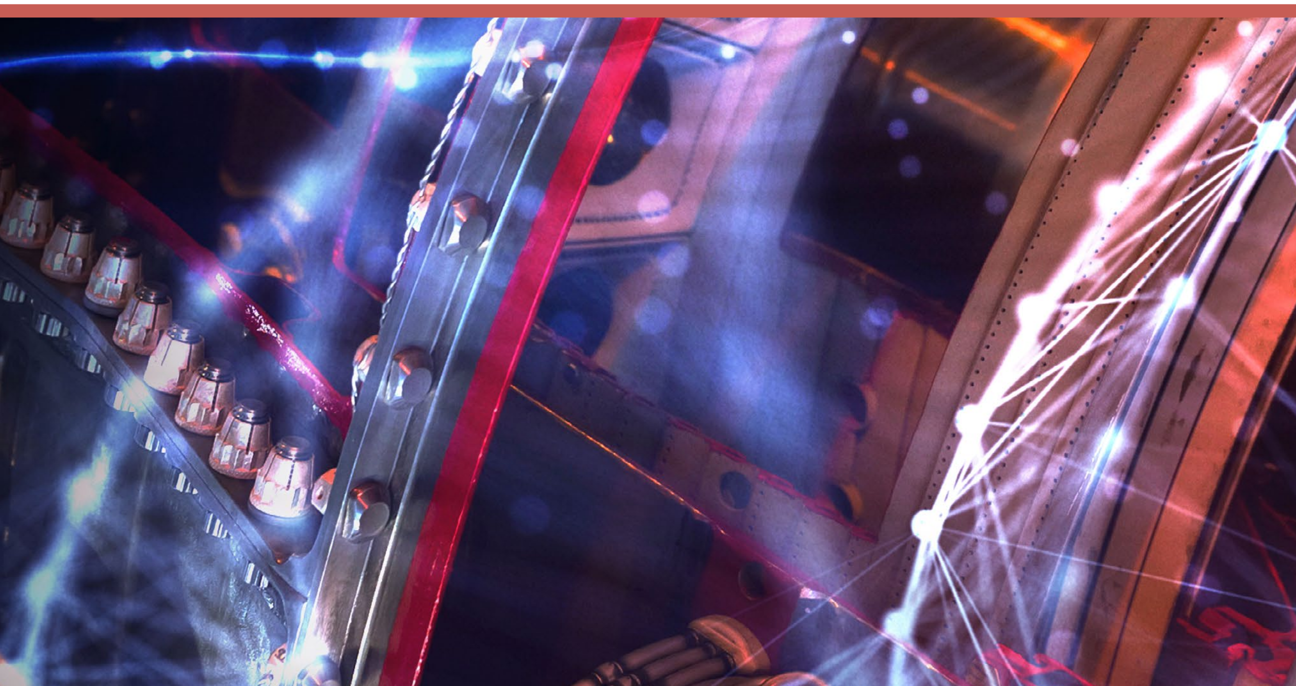
works for the Tyndall Air Force Base Property Management Office as an analyst and branch lead supporting the base reconstruction efforts following the devastation caused by Hurricane Michael in 2018. He is a recent graduate of the Air Force Institute of Technology (AFIT) with a Master's of Science in Cost Analysis. MSgt Myers is also a certified Professional Cost Estimator Analyst (PCEA).

(E-mail address: bradford.myers@us.af.mil)

Dr. Edward D. White

is a Professor of Statistics in the Department of Mathematics and Statistics at AFIT. He received his BS in Mathematics from the University of Tampa, MAS from The Ohio State University, and PhD in Statistics from Texas A&M University. His primary research interests include statistical modeling, simulation, and data analytics.

(E-mail address: Edward.White@afit.edu)



Dr. Jonathan D. Ritschel

is an Assistant Professor of Cost Analysis in the Department of Systems Engineering and Management at AFIT. He received his BBA in Accountancy from the University of Notre Dame, his MS in Cost Analysis from AFIT, and his PhD in Economics from George Mason University. Dr. Ritschel's research interests include public choice, the effects of acquisition reforms on cost growth in DoD weapon systems, and economic institutional analysis.

(E-mail address: Jonathan.Ritschel@afit.edu)

Dr. Robert D. Fass

is an Assistant Professor in the Department of Systems Engineering and Management at AFIT. He holds a BA in Economics, an MBA from the University of New Mexico, and a PhD in Business Administration and Management from New Mexico State University. Dr. Fass's research interests include cost analysis, decision analysis, risk analysis, behavioral economics, organizational behavior, organizational change, and government acquisition policy.

(E-mail address: Robert.Fass@afit.edu)