START, TAXI, AND TAKEOFF FUEL MODELING FOR THE C-17

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Abstract

The purpose of this research is to establish and measure a C-17 Ground Fuel Model that accounts for variance in conditions and locations. Currently, the United States Air Force only uses a single mission design series specific fuel consumption number for the start, taxi, and takeoff phases. The Baseline Model does not account for fuel consumption variations during ground operations due to environmental or location-specific conditions.

The research methodology used the aircraft technical orders and procedures to build a fixed fuel model for the pre-flight, start, and pre-taxi phases of ground operations. The taxi phase model utilized the Haversine Formula with data derived average fuel flows and location-specific delay times. Finally, the takeoff model used regression analysis with location-specific pressure altitudes and temperatures combined with aircraft Gross Weights to model takeoff fuel requirements.

Overall fuel accuracy was increased by 32.6 percent. All models have significantly reduced fuel requirements from the baseline model while only incurring a small risk of under-fueling aircraft.

The real-world impact of applying this new Ground Operations Fuel model can save 8,641,048.92 pounds of fuel. These fuel savings equate to savings of over $2.4 million each year at a minimum when only applied to the C-17.

Acknowledgments

Thank you to my wife and family, who have always supported me through every long day with grace, love, and patience. I am privileged and humbled by the sacrifices you make, and the humility you show each day continues to inspire me. With all of my love.

I would also like to extend my deepest thanks to my advisor, Doctor Adam Reiman, for his patience and support during this year. Sir, you made this project possible, and I will never forget the time and effort you sacrificed to help me across the finish line.

Jeff Schmidt

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START, TAXI, AND TAKEOFF FUEL MODELING FOR THE C-17

Introduction

Cost savings during U.S. Air Force aircraft operations continues to dominate the discussions for both the Air Force and the airline industry. With razor-thin profit margins for both industries, any cost savings in fuel during operations will result in a reduction in total fuel weight carried and less overall costs. Numerous studies seek to quantify the fuel needed for ground operations versus the planning fuel required. However, while there are several C-17 and U.S Air Force fuel efficiency studies for the in-flight stage of operations (Havko, 2018), the Air Force has not addressed the need for a more refined model for ground operations. Therefore, this study aims to create a holistic fuel model for all C-17 ground operations.

Overview

Currently, the Air Force accounts for "just under 50 percent of the total DoD energy consumption and costs, with the vast majority, 86 percent, spent on aviation fuel" (Energy, 2017). An estimated $8 billion is spent on Air Force energy each yearof which aviation fuel costs the Air Force approximately $6.88 billion (Energy, 2017).

The Reason for Fuel Savings

The Air Force projects that the potential cost savings from reducing the fuel required on the ground are, "For every pound of excess fuel carried, up to 3% more will be burned each hour" (AMC Pamphlet 11-3, 2015). Assuming a trans-Atlantic flight of 5 hours, a reduction of 10,000 pounds of fuel would result in 1,500 pounds of fuel saved and $305.56 in fuel cost savings based on the cost of aviation jet fuel, currently priced at $1.70 per gallon (Daily Jet Fuel Spot Prices, 2021). Additionally, jet fuel prices rise again, as shown in Figure 1, after a sharp fall in 2020 (Jet Fuel Monthly Price - U.S. Dollars per Gallon, 2021). Given that fuel expenses “makeup nearly 40-50 percent of airlines overall operating cost” (Arushi & Drews, 2011), a reduction in fuel consumption will lead to cost reductions for aircraft operators. Furthermore, the Defense Logistics Agency published a fuel shortlist for the JP-8 aviation fuel type is listed as $2.37 per gallon current as of September 2020 (Defense Logistics Agency (DLA), 2020).

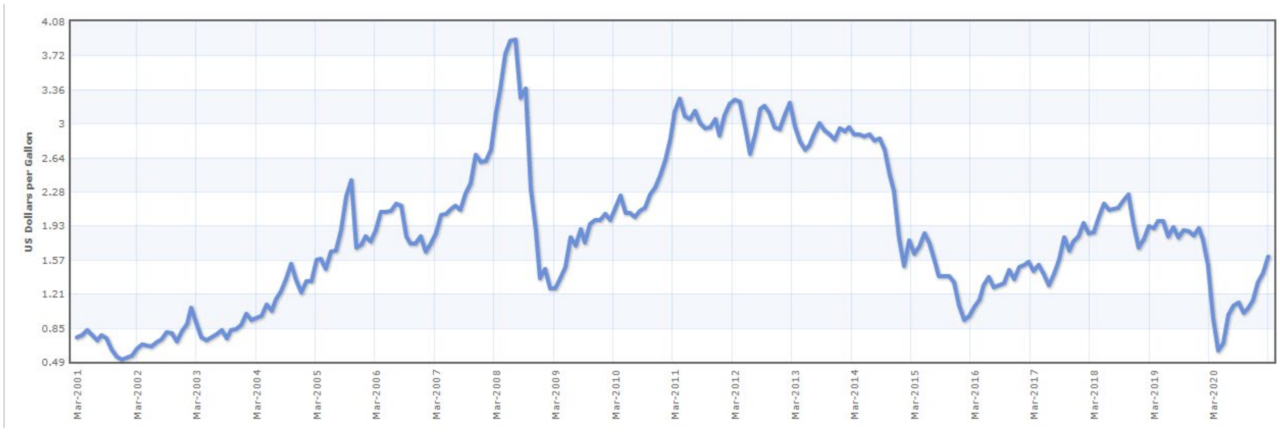


Figure 1: Jet Fuel Price in U.S. Dollars per Gallon

(Jet Fuel Monthly Price - U.S. Dollars per Gallon, 2021)

General Issue

Currently, there is little guidance for the required fuel load for the Boeing C-17 Globemaster III for the pre-flight, start, pre-taxi, taxi, and takeoff phases of ground operations. The current guidance provides a single fuel consumption number for all phases before climb, often referenced as start, taxi, and takeoff (STTO) fuel. This baseline model is too simplistic and does not factor in location or variance but relies on conservative fuel flow and taxi time estimates.

This simplicity results in inaccuracy. Inaccuracy leads to reduced aircrew confidence. The variance between planned fuel consumption and actual fuel consumption is higher than necessary by not considering environmental and location-specific factors. This fuel consumption delta between planned and actual impacts trust proportional to the size of the deviation. This reduction in trust can result in aircrews seeking additional fuel to cover deviations they have noted previously. AFMAN 11-255 Volume 3 states, “When a PIC (Pilot in Command) believes the fuel load is insufficient to execute the sortie, the PIC will contact the FM (Flight Manager) to identify and resolve the differences. The PIC is the final authority for adding additional fuel if the PIC and FM do not reach an agreement” (Department of the Air Force, Flight Manager Responsibilities and Procedures, Air Force Manual 11-255 Volume 3, 2018).

Problem Statement

The problem is that the current fuel consumption model utilized for fuel planning is too simplistic and results in large errors between planned and actual fuel consumption. When fuel consumption planned is less than actual, aircrew confidence in the plan is reduced and when fuel consumption planned is greater than actual, additional fuel is being consumed unnecessarily.

Research Focus

This research focuses on developing a holistic model for the C-17 ground operations, consisting of the following phases: pre-flight, start, pre-taxi, taxi, and takeoff. The Model for the taxi phase will account for location-specific factors, and the Model for the takeoff phase will account for aircraft and environmental factors. While several different Air Force aircraft have similar issues regarding lacking a holistic model for establishing STTO fuel, this research will only focus on the C-17. This research then compares the new Model against the current Air Force model to gauge model accuracy.

Research Objectives

1. Establish a fuel consumption model for ground and takeoff operations before climb that accounts for environmental and location-specific factors.

2. Compare the new and current fuel consumption models against actual data to assess accuracy.

Methodology

This research utilized a quantitative methodology using the Air Force Military Flight Operations Quality Assurance (MFOQA) data consisting of 1,121 files covering 494,124 entries from the flight data recorder. Actual fuel consumption was assessed by phase to increase the Model's accuracy.

Assumptions

This study assumes certain standard practices among the C-17 Aircraft Commanders regarding the amount of time required to pre-flight, start, and delay before taxiing the aircraft. Additionally, there are several different ways to taxi the aircraft regarding speed and engine utilization and different takeoff techniques that will not be addressed. Also, some aircraft data would "time skip," resulting in a loss of fuel flow data while the aircraft was at a stop. The Time Skipping issue necessitated using the last known fuel flows and applying them across time gaps which ranged from a few seconds to several minutes.

Limitations

The study had several limitations given by both the publications and data. The aircraft technical orders 1C-17A-1 and C-17A-1-1 did not contain specific fuel flows and also only provided general fuel flow expectations for a few phases during ground operations. The study used data from the aircraft to derive these constants; however, there may be added variables that are not addressed by this study. Additionally, some of the data contained Global Positioning System (GPS) coordinates which had "drifted," making comparisons of taxi lengths more complex and less confident. Finally, only a few variables are used during the regression study, and other factors such as runway slope, engine life, and wind velocity may have additional effects on the aircraft performance during STTO. For example, an engine's age can significantly affect the amount of bleed air provided during engine start, potentially impacting the amount of time and fuel required.

Implications

While the Air Force continues to make great strides in measuring and implementing changes in-flight with regards to fuel optimization, they are also lagging well behind the civilian industry to make those same changes on the ground. With the discoveries made by this research, the Air Force may eliminate wasteful practices and establish safe, clear-cut guidance to Aircraft Commanders concerning expected fuel usage during ground operations.

Research Project Structure

This research shows the effectiveness of the new Model for ground planning. Chapter II contains a literature review of the last decade of aviation ground fuel planning practices and the current technical and operational guidance of the C-17. Chapter III covers the methodology used to collect and analyze the data, culminating in building a dynamic linear fuel model. Chapter IV shows the analysis and findings of the data comparison between the baseline flat model and the proposed Model. Finally, Chapter V summarizes the findings, recommends a new course of action, and explores future research considerations.

Literature Review

Overview

This chapter details the relevant literature used to define the issue and create the methodology in the next chapter. The literature was divided into five different phases of ground operations: pre-flight, start, pre-taxi, taxi, and takeoff. Each section contains a summary of both the aircraft technical orders and procedures and research that has been or is being conducted in other sectors specific to aircraft ground operations.

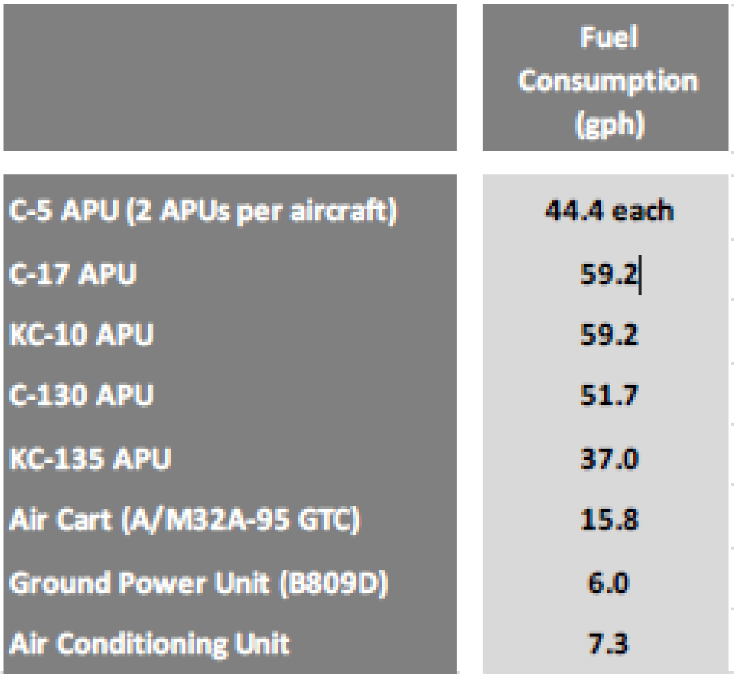
Pre-flight Phase

The Pre-flight phase of ground operations is defined as Aircrew arrival to the aircraft, typically 2 hours before takeoff, to placing the first engine start button in the start position.

During a typical mission, the aircraft utilizes power from a more efficient Ground Power Unit (GPU) instead of the aircraft's Auxiliary Power Unit (APU). The GPU can burn up to 6 times less than the APU (AMC Pamphlet 11-3, 2015). Therefore, U.S Air Force aircraft usually remain on GPU power until 30 minutes before Engine Start and delay the excessive fuel load until necessary for pre-flight operations (AMC Pamphlet 11-3, 2015). However, the C-17 technical order does note that "because of high electrical load demands on the ground, both APU and external electrical power sources should be used, simultaneously, to power their respective sides when available (Air Force, Technical Order 1C-17A-1, 2020). Typically, the first aircrew member who arrives at the aircraft starts the APU in addition to the GPU during the Aircraft Interior Safety Inspection – Power On Checklist.

A 2015 RAND study analyzed aircraft APU usage and noted that a reduction in APU use by 30 minutes would result in a reduction of 1.1 million gallons of fuel and annualized fuel savings of $4.0 million from the C-17 aircraft alone (Mouton, et al., 2015). The difference in fuel consumption can be seen in Table 1, which shows that the C-17 APU uses, on average, 9.87 times the fuel used by a B809D Ground Power Unit.

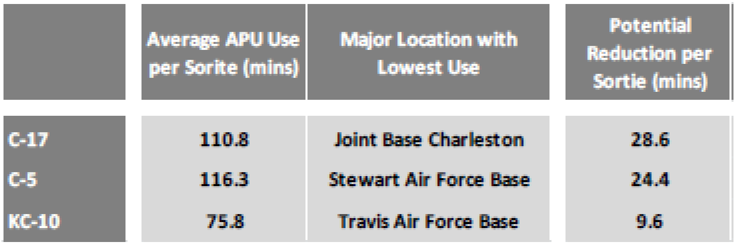
Table 1: RAND Study: APU and AGE Fuel Consumption



	Fuel Consumption (gph)
C-5 APU (2 APUs per aircraft)	44.4 each
C-17 APU	59.2
KC-10 APU	59.2
C-130 APU	51.7
KC-135 APU	37.0
Air Cart (A/M32A-95 GTC)	15.8
Ground Power Unit (B809D)	6.0
Air Conditioning Unit	7.3

The C-17 average APU use is 110.8 minutes or just shy of the two-hour crew show timeline, as shown in Table 2. The RAND study also notes that a 28.6-minute reduction in APU is feasible since “APU use for C-17 flights from Joint Base Charleston is almost 30 minutes shorter than the overall average” and that “if the APU practices established could be replicated elsewhere, fuel-saving would improve significantly” (Mouton, et al., 2015).

Table 2: RAND Study: Average and Lowest APU Use Data



	Average APU Use per Sorite (mins)	Major Location with Lowest Use	Potential Reduction per Sortie (mins)
C-17	110.8	Joint Base Charleston	28.6
C-5	116.3	Stewart Air Force Base	24.4
KC-10	75.8	Travis Air Force Base	9.6

Finally, the U.S. Air Force's C-17 flight manual notes that "APU Fuel Consumption is approximately 420 pounds per hour" (Air Force, Technical Order 1C-17A-1-1, 2020). It should be noted that the average APU fuel usage per hour found in the RAND study, 59.2 gallons per hour, equates to 397.215 pounds per hour, just below the rate established by the technical order. Overall, the expected APU fuel burn during the Pre-flight phase would be 840 pounds.

Starting Engines Phase

The Starting Engines phase of ground operations is defined as the time from completing the Pre-flight Phase to when all four engines reach idle with the APU shut down. For the flight recorder data, the end of the Starting Engines phase is when all four engines are registering fuel flow. The technical order guides two different engine starts, a standard engine start, and a simultaneous engine start procedure.

The standard engine start uses the APU as both the electrical and pneumatic source for starting all four engines. Additionally, the standard method is to "start engines No 1, 2, 3, and 4 one at a time and in sequence" (Air Force, Technical Order 1C-17A-1, 2020). Each Engine start cycle consists of four phases: the starter engagement, fuel introduction, Exhaust Gas Temperature (EGT) rise, and sustainment. There is also an additional Delay phase that may apply to only specific engines depending on checklist requirements.

The starter engagement phase begins once a crew member presses the engine start button, activating the solenoid and allowing pneumatic pressure, beginning engine rotation. This phase has no fuel flow component and uses bleed air from an external source, either APU or Engine.

The fuel introduction phase begins after the fuel is introduced to the engine and at 20% N2 and continues until the EGT begins to rise, a process usually referred to as light off in other aircraft. Engine fuel flow during this stage averages between 400-500 pounds per hour and limited to no more than 700 pounds per hour by the aircraft (Air Force, Technical Order 1C-17A-1, 2020).

The EGT Rise phase continues until idle power is achieved, the EGT stabilizes, and N2 equals approximately 62%, depending on the ambient conditions. Engine fuel flow during this stage averages between 800-1,000 pounds per hour and will steadily rise until it reaches a peak value, normally 200 pounds per hour above the normal ideal range (Air Force, Technical Order 1C-17A-1, 2020).

Finally, the last phase is the sustainment phase, characterized as the delay time between completing a checklist and starting the next engine. Sustainment fuel flows, characterized by the engines' normal idle range, burns 800-1,200 pounds per hour, depending on ambient conditions (Air Force, Technical Order 1C-17A-1, 2020).

Aircraft technical orders constrain the times associated with each stage of the start cycle. The Starter Engagement phase has a maximum of 20 seconds, after which the aircrew must discontinue start if the Exhaust Gas Temperature (EGT) does not rise within this time (Air Force, Technical Order 1C-17A-1, 2020).

Similarly, during the EGT rise phase, the technical order states that the “elapsed time to idle is typically 30 seconds or less” (Air Force, Technical Order 1C-17A-1, 2020). The final phase, sustainment, depends on the time required to finish the checklist and the start time needed for each remaining engine.

The second Starting Engines procedure is the Simultaneous Engine Start, characterized by the simultaneous start of two engines. The specific subset of this procedure addressed in this paper is the Reduced Engine Start Sequence, which reduces engine start time and APU usage by starting Engines 2 and 3 together with bleed air provided by the APU and Engine 1, respectively. Additional time is saved due to Engine 1 providing the bleed air for the Engine 4 start, allowing the APU to be cooled down and then shut down much earlier than on a standard engine start.

The overall expect fuel required for a standard engine start of four engines would be 445.17 pounds when calculated for the times and fuel flows given by the technical order.

Pre-Taxi Phase

The Pre-Taxi phase of ground operations is defined as the time from completing the Starting Engines phase until the point when fuel flow increases and is followed by aircraft movement. For the flight recorder data, the end of the Pre-Taxi phase is when ground speed is greater than 0.1 nautical miles per hour.

A 10-minute pre-taxi phase follows the Starting Engines phase, during which the engines burn at approximately 4,000 pounds per hour (Air Force, Technical Order 1C-17A-1-1, 2020). This phase would result in approximately 666.67 pounds being burned during the Pre-Taxi Phase.

Taxi Phase

The Taxi phase of ground operations is defined as the time from completing the Pre-Taxi phase to registering an increased fuel flow followed by constant ground and airspeed increase. For the flight recorder data, the end of the Taxi phase is when fuel flow on all four engines exceeds 1,500 pounds per hour, the left and right brake pedals are released, ground speed increases above zero, and the aircraft position changes.

The Taxi phase of ground operations is the most impactful portion on fuel use due to the significant variations in taxi distance, delays, and surface conditions. In fact, “congestion consumes about 18 percent extra fuel due to varying fuel needs under stop and go situations” (Nikoleris, Gupta, & Kistler, 2011). Researchers target the ground phase by suggesting the incorporation of “rapid taxiways and preplanning optimum taxiway paths (to) reduce conflicts and increase the operational efficiency” (Kazda & Caves, 2015). Delays are, therefore, a significant factor since “31.4% of the taxi time was related to delays due to other aircraft, including delays in queues behind other aircraft at the runway” (Ravizza, Atkin, & Edmund, 2014). The researchers concluded that “airport design, layout, and distance between various facilities dictate aviation operational efficiency” (Schlumberger, 2012) and that “reducing roll distance and subsequent rolling time (would result in) less fuel consumption” (Singh, Sharma, & Srivastava, 2018).

Seasonal factors may also increase delay times due to congestion. In general, researchers find that “any disruption affecting the airport airside (i.e., runway) capacity of the already heavily congested airport causes a significant escalation of congestion and aircraft/flight delay; these generally increase with increasing duration of the disruptive event” (Janic, 2009). Airport congestions issues mean that flat line, static linear, and dynamic linear based models for taxi times become less useful as airport congestion increases, especially when influenced by other variables. Because of this, the aviation industry shifted to a more generalized linear model which, “allows for response variables with error-distribution models other than the normal distribution” (Lian, Zhang, Desai, Xing, & Luo, 2018). In other words, the Air Force flat-line model is several generations out of date compared to the progression of the rest of the industry.

In order to account for the delay and congestion variable, the U.S. Air Force’s guidance establishes 15 minutes as the required time for taxi noting that, “Regulations dictate a fixed amount of fuel for the start, taxi and takeoff, normally sufficient for a 15-minute taxi” (AMC Pamphlet 11-3, 2015). Similarly, the civilian aviation industry also establishes that the “Landing and Takeoff (LTO) cycles are broken down into 19 minutes for taxi-out” (Clemons, Reynolds, Chati, & Balakrishnan, 2018). However, both models are too simplistic and do not account for variations in airport design and distances, as mentioned above.

Research showed that the average departure delay times at civilian airfields averages 9 minutes across 13.2 million taxi events (Deshpande & Arikan, 2012). Additionally, as the volume of aircraft taxiing increases, the average delay time will increase. Clewlow, Simaiakis, and Balakrishnan found that “even a simple model of arriving aircraft accounts for 71% of the variability in Taxi-out times" (Clewlow, Simaiakis, & Balakrishnan, 2010). The more complex regression model they developed accounted for 86% of the variance with an average intercept of 8 minutes for aircraft delays at John F. Kennedy Airport (Clewlow, Simaiakis, & Balakrishnan, 2010). Also, in a study conducted by the Federal Aviation Authority, taxi delays accounted for 5.1 minutes of the ground delay, with gate delay accounting for an additional 7.2 minutes (Kettunen & Knorr, 2005).

It is significant to point out that during the literature review the most recent articles shifted from analyzing fuel-efficiency models with regards to aircraft operations and instead focused on more creative solutions to aircraft congestion as aircraft delays have shifted the cost. The civilian shift from fuel focus to airfield congestion again underscores that the Air Force, which generally operates out of military airfields, is still operating off a simplistic flat-line fuel model that does not account for congestion.

Gross Weight of the aircraft limits taxi speeds and times for the C-17. Maximum taxi speed is no more than 40 knots at all times with the additional restriction that any time the total gross weight is greater than 490,000 pounds, or the total fuel weight exceeds 165,000 pounds, the respective taxi speeds must be at or below 20 knots if the engines are used symmetrically or 15 knots if they are used asymmetrically (Air Force, Technical Order 1C-17A-1, 2020). One technique, seen in Figure 2 that is used by the C-17 calculates taxi time with the assumption that each turn will take approximately 15 seconds to complete, during which ground speed will average 5 knots (Department of the Air Force, Air Force Tactics, Techniques, and Procedures 3-3. C-17A, 2021).

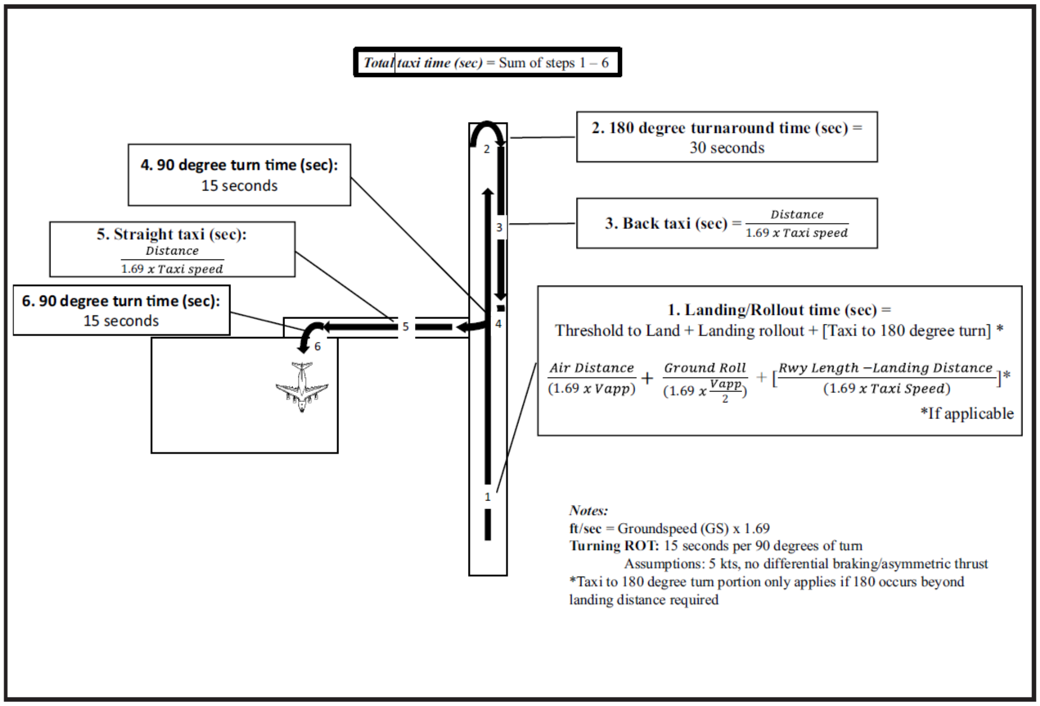
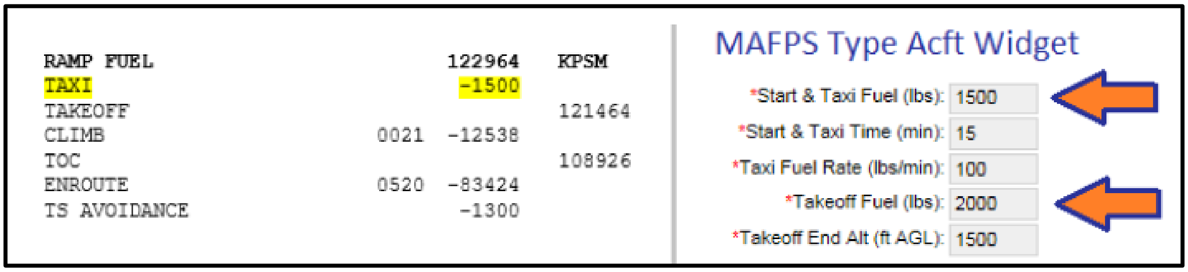


Figure 2: AFTTP 3-3 Total Taxi Time Visual and Equation

Finally, the Taxi Fuel calculated by the FM's during all C-17 missions requires a flat 1,500 pounds for Start and Taxi as well as 2,000 pounds for takeoff up to an altitude of 1,500 feet, as seen in Figure 3 (Air Mobility Command, MAFPS AMC Standard Report (ASR) Computer Flight Plan Key, 2018).



```
RAMP FUEL                        122964   KPSM
TAXI                              -1500
TAKEOFF                                   121464
CLIMB                     0021   -12538
TOC                                       108926
ENROUTE                   0520   -83424
TS AVOIDANCE                      -1300
```

MAFPS Type Acft Widget

*Start & Taxi Fuel (lbs): 1500
*Start & Taxi Time (min): 15
*Taxi Fuel Rate (lbs/min): 100
*Takeoff Fuel (lbs): 2000
*Takeoff End Alt (ft AGL): 1500

Figure 3: Flight Management Fuel Plan Example

The C-17 mission computer (MC) fuel planning pages also contain a default value for C-17 taxi fuel. The computer "normally calculates the fuel load from constants for a pre-takeoff taxi at the origin and computations based on the flight plan contents," and this value defaults to 2,500 pounds (Air Force, Technical Order 1C-C-17A-1-2: Mission Computer, 2020). The operational procedures for the C-17 do not address taxi fuel requirements and mainly focused on the in-flight phase; however, it does establish an expected fuel burn for Ground Operations/ERO (Engine Running Offload) of 100 pounds per minute or 6,000 pounds per hour (Department of the Air Force, C-17 Operations Procedures, Air Force Manual 11-2C-17 Volume 3, 2019).

Finally, the 2015 Air Force RAND study suggested that "often not all engines are required for taxiing an aircraft because even the idle thrust produced by a subset of the engines is sufficient to move the aircraft on the ground" and "by using only the engines required for taxiing, overall fuel use can be reduced" (Mouton, et al., 2015). The potential savings identified by the RAND study was approximately 4.3 million gallons or $16.2 million in annualized fuel savings (Mouton, et al., 2015). The increased efficiency of Reduced Engine Taxi are further highlighted by Major Wells in the 2017 study of cost savings that showed that "the MAF can reduce fuel consumption and resource utilization by approximately 38.9 percent during the taxi phase per sortie if pilots perform reduced-engine taxi procedures in lieu of four-engine taxi procedures during surface operations before initial takeoff" (Wells, 2017).

Takeoff Phase

The Takeoff phase of ground operations is defined as the time from completion of the Taxi phase to when the aircraft Weight on Wheels switch is disengaged, indicating a transition from ground to air mode. It should be noted that most definitions of the Takeoff phase go beyond the achievement of takeoff speed, the speed at which the main gear leaves the ground (Air Force, Technical Order 1C-17A-1-1, 2020). These definitions also include a continued acceleration and climb over a 50-foot obstacle portion which, once achieved, then transitions to the beginning of the Climb Phase of In-Flight Operations.

A variety of factors impact takeoff performance and, therefore, the fuel requirements for this phase of ground operations. Temperature and elevation both interact to affect performance since "as the air warms up, the air density ρ decreases, with the same payload (and thus the same lift), takeoff speeds need to increase" (Ren & Leslie, 2019). Ren and Leslie also point out that as global temperatures increase, the fuel requirements for each takeoff will likely increase. Additionally, Stolzer used gross weight and airspeed to develop his regression model for fuel flow prediction (Stolzer, 2003).

Unlike other phases of flight, the C-17 takeoff only requires a fuel allowance of 2,000 pounds and covers both the takeoff phase and a climb to 1,500 feet Above Ground Level (AGL), phases of ground and flight operations (Air Force, Technical Order 1C-17A-1, 2020). Additionally, this fuel is calculated in the FM fuel model as a part of the climb fuel per the MAFPS (Mobility Air Force Flight Planning System) Climb definition, "fuel and time required from brake release to TOC (Top Of Climb)" (Air Mobility Command, MAFPS AMC Standard Report (ASR) Computer Flight Plan Key, 2018).

Since this fuel value applies to both a ground and flight phase of operation, it is not helpful to Model either phase except as a control measure to identify outliers.

Finally, flight planning software, CFPS, utilized by C-17 pilots for personal mission planning, defaults to a flat STTO value of 1,000 pounds for all ground operations.

C-17 STTO And Ground Operations Fuel Model

Based on the C-17 technical and operational literature, the total fuel required for ground operations can be divided into three separate baseline models for comparison: taxi, flight manager, and flight publications. First, the baseline taxi model which covers the Start and Taxi phases consumes 1,500 pounds of fuel based on the technical order, expected ground fuel burn, Mission Planning, and the 15-minute taxi time requirement. Second, the flight manager model which covers the Start, Taxi and Takeoff phases and adds 1,000 pounds for takeoff to the baseline taxi model. The takeoff addition is based on the mission planning software, and taking 50 percent of the takeoff/climb fuel. The total fuel consumed for the baseline flight manager model is 2,500 pounds which is in line with the aircraft Mission Computer default value. Finally, the baseline flight publications model which covers all phases of ground operations consumes 4,452 pounds by summing the Pre-flight, Start, Pre-Taxi, Taxi, and Takeoff phase fuel consumption values from the publications of 840, 445, 667, 1,500, and 1,000 pounds, respectively as shown in Figure 4.

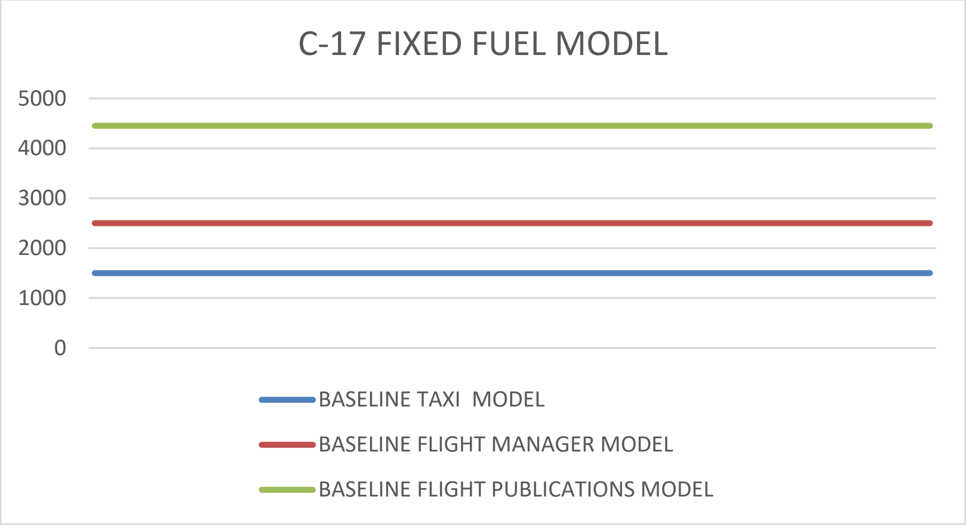


Figure 4: Current C-17 Fixed Fuel Model

Summary

This chapter summarized the current Air Force statutes concerning fuel efficiency. It also provided an overview of the literature used to address fuel modeling during the Preflight, Start, Pre-Taxi, Taxi, and Takeoff phases of ground operations. Finally, it discussed C-17 specific guidance and technical instructions regarding ground operations and the expected burn rates of the aircraft fuel. All five phases of ground operations were combined into a holistic model for a baseline to compare the Model developed in the next chapter, Methodology.

Methodology

This chapter details the methodology used to develop, analyze and compare the models for all 5 phases for C-17 ground operations. The methodology's primary focus is on three phases: pre-taxi, taxi, and takeoff, with the development of each corresponding portion of the Model dependent upon the aircraft information available for that phase. The data examined includes 140 individual C-17 aircraft taxi and takeoff events.

Data Source and Description

This research utilized 1,121 files of data covering 2,038,500 events across 181 airfields worldwide. The aircraft computer records data from the aircraft sensors and systems every second, providing 250 different categories of information per second. In total, over 566.25 hours were analyzed. Filtering the data against specific parameters of interest narrowed the scope to only aircraft events on the ground instead of in flight.

Parameters of Interest

From the 250 data categories, 56 are potentially impactful on the STTO phase of operations analysis. Of those 56, the Model used only 21 for both model development and data analysis, where ten columns shown in Table 3 identified aircraft location, phase of operation, and aircraft identification, and the other 11 columns shown in Table 4 enabled statistical analysis of the aircraft's performance during the taxi and takeoff phases.

Table 3: Data Used for Aircraft Identification

Data Identification	
COLUMN	**DESCRIPTION**
AOA	Angle of Attack
SN	Tail Number
BASE	Base
GMT	Greenwich Mean Time
WOW	Weight on Wheels
LATITUDE	Latitude
LONGITUDE	Longitude
RECORDING-SESSION-ID	Recording Session ID
LBP	Left Brake Pedal Position
RBP	Right Brake Pedal Position

Table 4: Data Used for Aircraft Analysis

Data Analysis	
COLUMN	**DESCRIPTION**
TIME	Time
GW	Gross Weight
HP1	Pressure Altitude
TAT	Total Air Temperature
FQT	Total Fuel Quantity
GS	Ground Speed
IAS	Indicated Air Speed
FF1	Fuel Flow 1
FF2	Fuel Flow 2
FF3	Fuel Flow 3
FF4	Fuel Flow 4

Data Filtering

Filtering the data allowed the determination of the aircraft's location and its phase of flight. A Weight on Wheels value of "true" indicated ground operations and stable fuel flows for all four engines provided the data needed to create the Takeoff model as well as a comparison for the Taxi and Takeoff Models. The data was separated into three phases; Pre-Taxi, Taxi, and Takeoff.

Two specific issues came up during the data filtering step of the research. First, some of the data during the taxi phase had instances of "time jumps" during which an aircraft computer skipped anywhere from seconds to several minutes of data. These jumps only occurred during prolonged periods of aircraft delay during taxi with fuel flows remaining constant both before and after the gap. To account for the missing data points, the length of the skipped time period was calculated and multiplied against the average fuel flow from before and after the time jump. Table 5 below shows an example of a 177 second time jump during which the aircraft remained stopped, but the computer ceased to record any data. The missing fuel used equated to 201.39 pounds which were then added back into the data set.

Table 5: Time Jump of 177 seconds

TIME	GS	IAS		FF1	FF2	FF3	FF4
7153	0	0		1024	1024	1024	1024
7154	0	0		1024	1024	1024	1024
7331	0	0		1024	1024	1024	1024
7332	0	0		1024	1024	1024	1024
7333	0	0		1024	1024	1024	1024

The second issue also appears during the taxi phase and deals with the accuracy of the aircraft location. The aircraft reported position often failed to align with the pavement's actual location. While not usually an issue for aircraft departing on the first sortie of the day, as shown in Figure 5, with each landing and subsequent departure, the error increased and resulted in some cases of erroneous positions over one mile from the airport taxi surfaces. While this issue did not impact the accuracy of the time or fuel consumed, a correction enabled a more accurate model comparison with the data and accounts for any aircraft taxi deviation for additional uploads or downloads. The correction itself utilizes a reference latitude and longitude of the expected aircraft position based on a specific taxi point, and accounting for the difference in erroneous latitudes and longitudes allows us to shift the positions as seen in Figure 6.

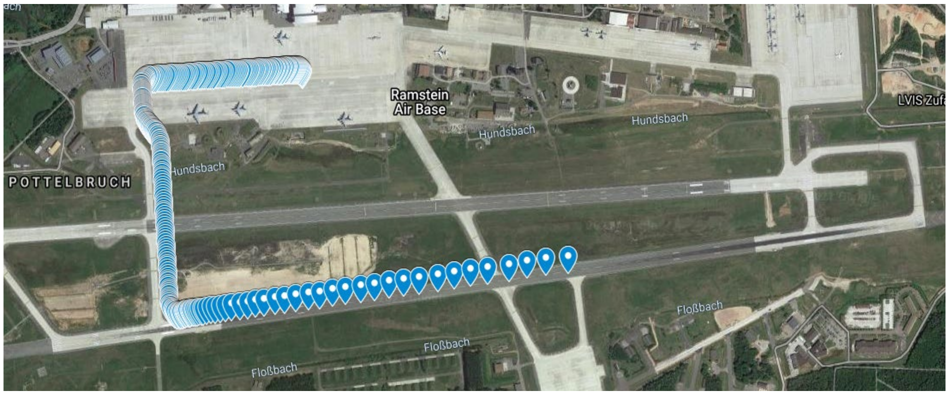


Figure 5: Taxi path at ETAR aligned to the pavement

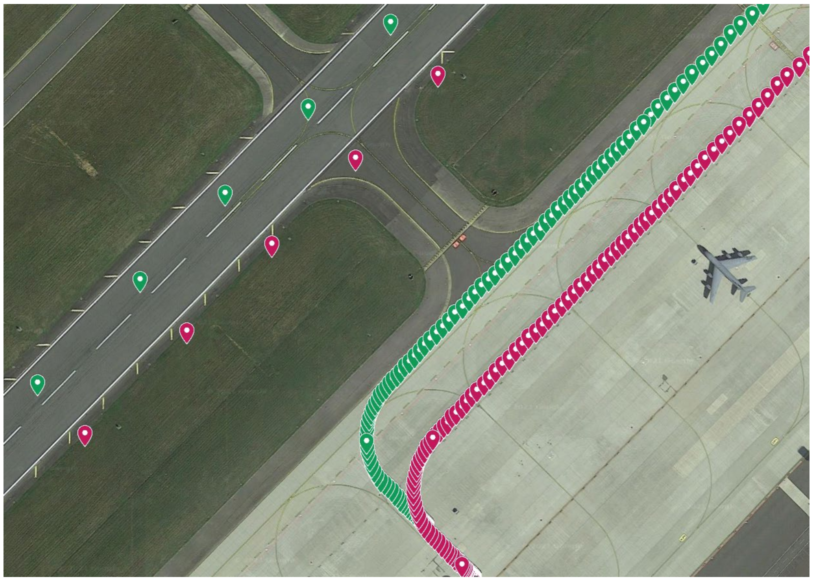


Figure 6: Taxi path at LICZ with alignment error shown (red) and correction applied (green)

The Takeoff phase included a combined analysis of fuel flow, ground speed, indicated airspeed, and brakes to identify when the aircraft transitioned from the Taxi phase to the Takeoff phase of ground operations. A rise in fuel flow greater than 1500 pounds per hour on each engine in a continuous rise to takeoff power combined with a release or non-actuation of the brake pedals followed by increasing ground and indicated airspeeds marked the start of the Takeoff phase. This phase lasted until the WOW switch indicated that the plane was airborne, with any aborted takeoffs not utilized for this analysis, as shown in Table 6.

Table 6: Takeoff Data Set Example

TIME	GS	IAS	AOA	FF1	FF2	FF3	FF4	WOW
10076	8	0	-1.25	1408	1408	1280	1024	TRUE
10077	8	0	-1.25	1664	1536	1408	1152	TRUE
10078	8	0	-1.25	1664	1664	1536	1280	TRUE
10079	10	0	-1.25	2304	2176	1792	1408	TRUE
10080	10	0	-1.25	4480	3968	2816	1920	TRUE
10081	12	0	-1.25	5632	5376	4352	2432	TRUE
10082	12	0	-1.25	6144	6016	5632	3328	TRUE
10083	16	0	-1.25	6272	6272	6144	4992	TRUE
10084	18	0	-1.25	6272	6272	6272	5760	TRUE
10085	22	0	-1.25	6016	6144	6272	6016	TRUE
10086	24	0	-1.5	6528	6528	7040	6144	TRUE
10087	28	33	-1.5	10368	11392	11136	11008	TRUE
10088	34	41	-1	11776	11904	11904	11648	TRUE
10089	40	48	-0.75	11520	11648	11520	11648	TRUE
10090	46	54	-0.75	11392	11392	11392	11264	TRUE
10091	52	62	-0.75	11392	11392	11392	11264	TRUE
10092	58	68	-0.25	11264	11264	11264	11264	TRUE
10093	64	74	0.5	11264	11264	11264	11136	TRUE
10094	68	81	-0.25	11136	11136	11136	11136	TRUE
10095	74	86	0.25	11136	11136	11136	11008	TRUE
10096	80	91	-0.5	11008	11136	11136	11008	TRUE
10097	84	97	0	11136	11136	11136	11008	TRUE
10098	90	100	0.5	11008	11008	11136	11008	TRUE
10099	94	107	-0.25	10880	11008	11008	10880	TRUE
10100	98	109	2.75	11008	10880	11008	10752	TRUE
10101	104	112	8.25	10880	10880	10880	10752	TRUE

Finally, the Takeoff Regression model utilized 48,445 individual lines of data corresponding to 28 airfields that serviced military and civilian aircraft (see highlighted airfield in Table 7). The airfields were randomly selected from 181 airfields in the data set as shown in Table 7 and covered a wide range of conditions while decreasing the amount of time required for correcting time and position errors. Seventy individual takeoff events were used for both the training and test sets for the Takeoff Regression model.

Table 7: Airfield List

AIRFIELD ICAO							
ETAR	OKBK	MHTG	KLRF	EDDN	KNZY	KWRB	CYQX
LICZ	KINS	EKKA	LEZL	OERY	KGEG	KBOI	SAZS
HDAM	ENVA	RJGG	DRRN	EDRB	KBTM	KSEA	KGPT
LTAG	EGUN	KEWR	KNYL	KNYG	OJAM	KMCO	KGRK
ORBI	HECA	KMGE	PGUA	KLFI	KSKF	CYOW	MTPP
LERT	LLBG	EHLW	RKSO	KLSV	PHKO	KSAT	OKAS
KLSF	LTAC	OMDW	OEKK	KFFO	PHJR	KMYF	MHSC
KCHS	OLBA	KLRD	KTOL	KNTU	KRIC	LSZH	KNQX
KHOP	LGSA	LJLJ	RODN	KMSY	LIPA	KEGI	KSUA
KPOB	DTTA	LRBS	KBHM	GVAC	OEKM	KDTN	KAEX
KTCM	DAAG	LYBE	KDHN	LIRA	OERK	EDFH	MSLP
KMWH	KMYR	KMXF	PHBK	KNKT	KMMT	KWRI	LTCC
KZ	LEMO	VVNB	OAKB	EDDV	PHNL	KSVN	HUEN
OAIX	KPAM	VTBU	ESSA	KBKF	PHNG	ORBD	MGGT
ETAD	KCEF	RJOI	EVRA	KDOV	RJSM	SADM	KMCN
OOMS	TJIG	RJTY	EVRS	KMUO	ROTM	KLGF	KDPG
OTBH	TJSJ	KSBN	PWAK	SKBO	PAMR	OJMS	OMAM
MUGM	MNMG	KMSP	KBUR	SKCG	PAFR	KPSP	MPTO
OJAQ	MUHA	WSAP	KGUC	KELP	KTPF	ORER	KDMA
HEAZ	ORAT	KGRF	KCOS	MMCS	KVAD	KHST	KVQQ
LTBA	OBBI	KRIV	KMHK	KNEL	LRCK	SPJC	KADW
LTAI	KNGU	KBYS	KSWF	OAKN	KBGR	SKME	KORF
		KDEN	KEDW	OADY	KSUU	KDYS	

The following sections show model development for each phase of ground operations, including dynamic fuel models for the taxi and takeoff phases and fixed fuel models for the Preflight, Start, and Pre-Taxi phases.

Pre-flight Phase

The Pre-flight phase simply reflects the time required for checklists and preparing the aircraft for engine start. This time is assumed to be two hours and incorporates only the APU fuel flow. Equation 1 gives the Total Fuel required for Pre-flight.

$$F_{pre-flight} = t_{pre-flight} * ff_{APU} \tag{1}$$

Where:

$F_{pre-flight}$ = Total Fuel for Pre-flight Preparations
$t_{pre-flight}$ = Delay Time for Pre-Flight (hours)
ff_{APU} = APU Fuel Flow

Engine Start Phase

In order to calculate the Engine Start Fuel model for the aircraft, this research assessed the time required to start each engine, the phases of each engine start, and the fuel flow required for each of those phases: starter engagement, fuel introduction, EGT rise, and sustainment. Figure 7 and Figure 8 utilize the technical data obtained and standardized procedures from the publication to show the two types of engine starts.

It must be noted that the Starting Engines model includes fuel burned by the APU after stable fuel flow has been established on all four engines. However, the Pre-Taxi Model was derived from data is recorded once fuel flow was established on all four engines. This overlap results in some or all of the APU Cooldown fuel and time being used twice, first in the Engine Start model and then again as part of the data analysis to build the Pre-Taxi phase.

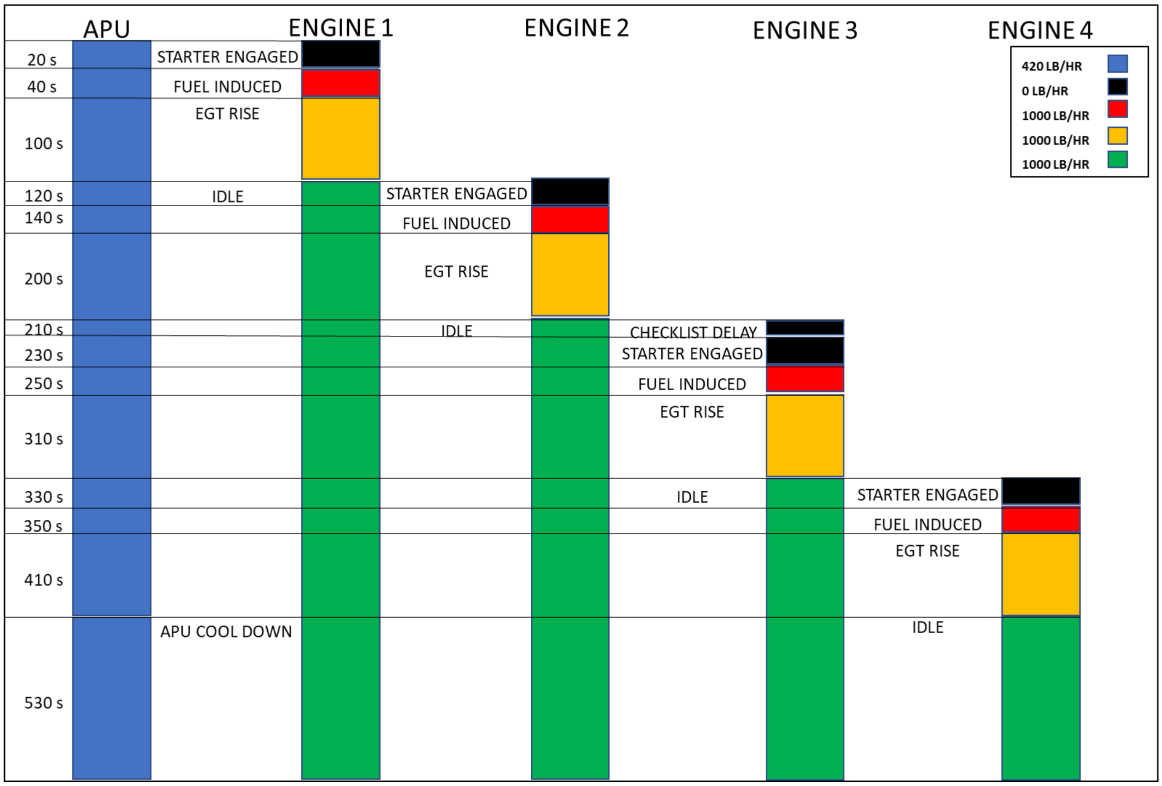


Figure 7: Standard Engine Start Process

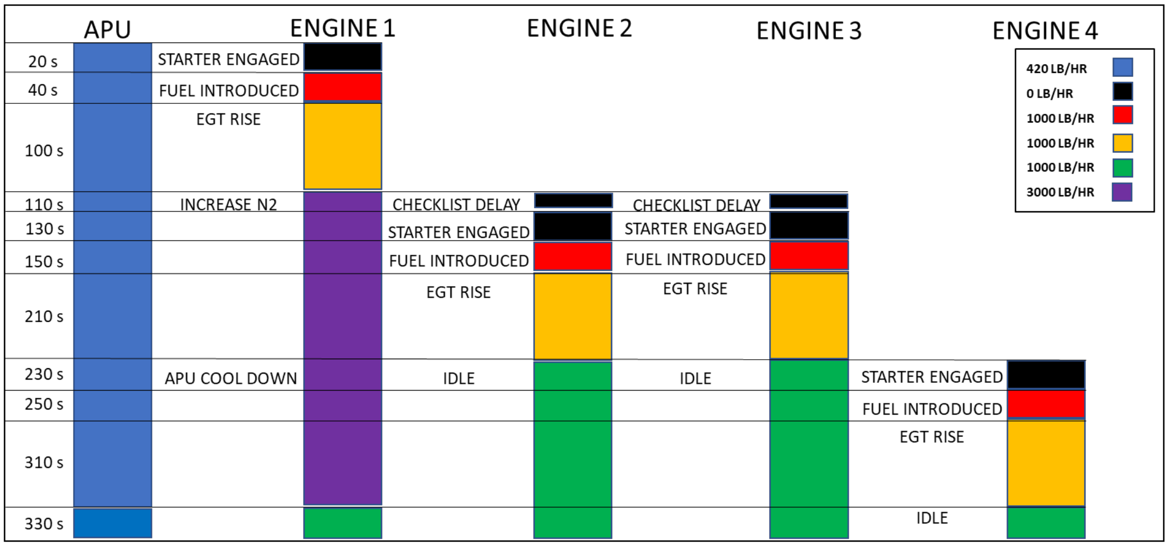


Figure 8: Reduced Engine Start Process

The Standard Engine Start model consists of 5 distinct sections of time. Since the start is sequential, each engine start represents a block of time, with one delay after engine two and an APU cooldown phase. Similarly, the Total Fuel calculation consists of five distinct blocks: four-engine starts events, six engine sustainment events (accounts for engines that are already running during each engine start), one delay event (checklist delay with two engines running), one APU sustainment event (reflects the total time for all engines to start sequentially), and one APU cool down event. This research assumes equal event times for each engine, with constant fuel flows derived from the C-17 publications, to calculate the actual fuel required for each engine start. The equal time assumption means that the only change in total fuel used by each engine is dependent on the sustainment fuel required for each engine as the other engines went through their start sequences. Each engine start consists of starter engagement, fuel introduction, EGT rise, and idle phases, paired with a corresponding constant fuel flow. The following equation shows each of the five phases and gives the total fuel required for a standard engine start.

$$\begin{aligned} F_{normal} = (4 * (t_a * ff_a + t_b * ff_b) + 6 * \left(ff_{idle} * (t_c + t_a + t_b)\right) \\ + 2 * (ff_{idle} * t_d) + (ff_{APU} * t_d) + (ff_{APU} * t_e) + 4 \\ * \left(ff_{APU}(t_c + t_a + t_b)\right) + 4 * (ff_{idle} * t_e))/3600 \end{aligned} \tag{2}$$

Where:

F_{normal} = Total Start fuel for a Standard Engine Start
t_c = Time from Starter Engagement to Fuel Introduction (seconds)
t_a = Time from Fuel Introduction to EGT Rise (seconds)
ff_a = Fuel Flow from Fuel Introduction to EGT Rise
t_b = Time from EGT Rise to Idle Power (seconds)
ff_b = Fuel Flow from EGT Rise to Idle Power
t_b = Time from EGT Rise to Idle Power (seconds)
t_d = Delay Time for Checklists (seconds)
t_e = Time for APU Cooldown (120 seconds)
ff_{idle} = Idle Fuel Flow

ff_{APU} = APU Fuel Flow

For a Reduced Engine Start, the Total Fuel calculation consists of six distinct blocks: four-engine start events, two engine sustainment events (accounts for engines that are already running during each engine start), two engine sustainment events at increased power (accounts for Engine 1 providing bleed air for two engine starts), one delay event, one APU sustainment event, and one APU cool down event. The APU cooldown event depends on the time required to start Engine 4 since it begins its cool down during the last engine start sequence. Equal engine start times and fuel flows across all four engines is assumed. The following equation shows all six phases and gives the total fuel for a Reduced Engine Start.

$$F_{Reduced} = (4 * (t_a * ff_a + t_b * ff_b) + 2 * \left(ff_{idle} * (t_c + t_a + t_b)\right) + 2 * \left(ff_{N2} * (t_c + t_a + t_b)\right) + (ff_{N2} * t_d) + (ff_{APU} * t_d) + 3 * \left(ff_{APU} * (t_c + t_a + t_b)\right) + \left(ff_{APU} * \left(t_e - (t_c + t_a + t_b)\right)\right) + 4 * \left(ff_{idle} * \left(t_e - (t_c + t_a + t_b)\right)\right))/3600 \tag{3}$$

Where:

$F_{Reduced}$ = Total Start fuel for a Reduced Engine Start
ff_{N2} = Fuel Flow at Increased Power (70-75% N2)

Finally, this research compared the Model against a real-world observation taken during aircraft ground operations to validate the assumptions of time and fuel flow. It should be noted that the constant time assumption is fundamentally flawed due to the differences in aircraft engine age having a corresponding effect on the bleed air provided for engine start and thus the amount of time required for each engine.

Pre-Taxi Phase

The Pre-Taxi phase consists of idle time and throttle advancement before movement. Idle time reflects the delay time required for checklists, and coordination for ground taxi and throttle advancement reflects the time and increased fuel flow endeavoring to transition the aircraft into movement. Throttle advancement fuel flow is dependent on several factors, including aircraft gross weight, winds, and pavement slope. Idle time and throttle advancement time together are assumed to be five minutes based on the Aircraft Technical Order, and it incorporates the fuel for all four engines running and the APU shutdown. Fuel flow for the idle time remains the same constant during the Engine Start phase. The following equations give the Total Fuel required for Pre-Taxi.

$$F_{pre-taxi} = \frac{t_{pre-taxi_{idle}} * (4 * ff_{idle})}{60} + \frac{t_{pre-taxi_{adv}} * (4 * ff_{adv})}{3600} \qquad (4)$$

Where:

$F_{pre-taxi}$ = Total Fuel for Pre-Taxi Delay
$t_{pre-taxi_{idle}}$ = Delay Time for Pre-Taxi (minutes)
ff_{idle} = Fuel flow at idle
$t_{pre-taxi_{adv}}$ = Advancement Time for Pre-Taxi (seconds)
ff_{idle} = Fuel flow during throttle advancement

Taxi Phase

The total fuel required for the Taxi Phase can be broken down into two components for our Model. The first component is the fuel flow based on ground speed from the start of the taxi to the start of takeoff, and the second is a reasonable delay constant to account for any possible airfield congestion, weather issues, and checklist requirements. As seen in Figure 9, the C-17 required a significant fuel flow increase in the pre-taxi phase to overcome surface friction and then maintains desired taxi speed by a sufficient reduction in fuel flow to a near idle state.

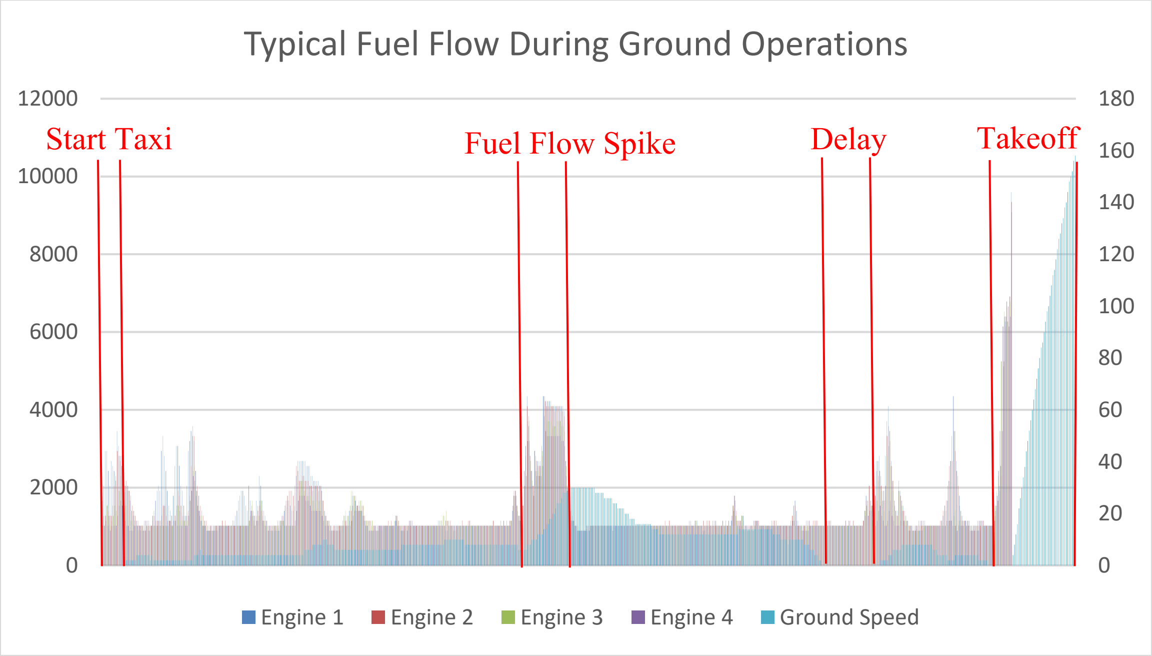


Figure 9: Taxi and Takeoff Fuel Flow versus Ground Speed

The Taxi model average fuel flows and taxi speeds were derived from the aircraft data and the Aircraft Technical Order. The flight recorder data yielded a constant of 5,636.8 pounds per hour (all four engines) for fuel flow, and both the data and Technical Order agreed that the average taxi speed is ten nautical miles per hour (knots).

To calculate the taxi range for each aircraft, this research used the Haversine formula to establish the great circle distance from the aircraft parking location to the runway used for takeoff. The Haversine formula in Equation 5 accounts for the curvature of the earth and allows for a more accurate measurement of the distance traveled by the aircraft.

$$c \; = r * ARCCOS(COS(\varphi_1) * COS(\varphi_2) + SIN(\varphi_1) * SIN(\varphi_2) * COS(\lambda_1 - \lambda_2) \qquad (5)$$

Where:

c = Hypotenuse Triangular Distance in Nautical Miles
r = Radius of the Earth in Nautical Miles (3440.0647948)
φ_1 = Latitude of Origin Point in Radians
φ_2 = Latitude of Takeoff Point in Radians
λ_1 = Longitude of Origin Point in Radians
λ_2 = Longitude of Takeoff Point in Radians

Runway heading and the bearing from the taxi start point to the takeoff point assisted in the determination of the angle between the runway and the vector from the takeoff point to the start taxi point.

Figure 10: Estimating Taxi Distance using Pythagorean and Haversine

$$\beta_1 = DEG\left(ATAN2\left(COS(\varphi_1) * SIN(\varphi_2) - SIN(\varphi_1) * COS(\varphi_2) * COS(\lambda_2 - \lambda_1), SIN(\lambda_2 - \lambda_1) * COS(\varphi_2)\right)\right) \quad (6)$$

Where:

β_1 = Bearing from Origin to Takeoff
DEG = a function to convert radians to degrees
φ_1 = Latitude of Origin Point in Radians
φ_2 = Latitude of Takeoff Point in Radians
λ_1 = Longitude of Origin Point in Radians
λ_2 = Longitude of Takeoff Point in Radians

Then to account for the fact that aircraft cannot taxi directly to the runway but must utilize taxi surfaces instead, this research used the Pythagorean Theorem. The Pythagorean Theorem is applicable since once the angle and length of a triangle's side are known, the lengths of the other two sides of the triangle can be derived. Since the hypotenuse distance is given by the Haversine formula and the angle can be measured by subtracting the bearings from the ramp origin to the takeoff points. Equations 7 through 9 were used to determine the total distance traveled.

$$a = c * COS(\beta_1 - \beta_2) \tag{7}$$

$$b = c * SIN(\beta_1 - \beta_2) \tag{8}$$

$$Total\ Distance\ Traveled = a + b \tag{9}$$

Where:

a = Adjacent Triangular Distance in Nautical Miles
b = Opposite Triangular Distance in Nautical Miles
c = Hypotenuse Triangular Distance in Nautical Miles
β_1 = True Bearing from Origin to Takeoff
β_2 = Inverse Takeoff True Bearing

This research derived the Total Distance Traveled calculation for each of the corresponding taxi events and then divided it by a constant aircraft taxi speed to obtain the expected fuel utilization time for the taxi phase of ground operations. Additionally, since each time the aircraft stops, a significant fuel flow is required to overcome friction and start the taxi, this research included a fuel flow for throttle advancement multiplied by the time advance and the number of events.

$$F_{taxi} = \frac{D_i * ff_{idle}}{60} + \frac{TDT}{S} * ff_{taxi} + \frac{Stops * ff_{adv} * t_{adv}}{3600} \tag{10}$$

Where:

F_{taxi} = Taxi Fuel Consumed
D_i = Delay Time for each airfield (i)
TDT = Total Distance Traveled
Stops = Number of Stops during Taxi
S = Taxi Speed Constant (10 knots)
ff_{idle} = Idle Fuel Flow (4,391 pounds per hour)
ff_{taxi} = Taxi Fuel Flow Constant (5,637 pounds per hour)
ff_{adv} = Taxi Fuel Flow Constant (14,929 pounds per hour)

The Delay Time can be set to either a specific airfield or a type of airfield based on the data collected. This Model used three specific airfield types: Military, Civilian, and Dual-Use. The Model uses a constant of five minutes for all military fields and nine minutes for civilian and dual-use airfields based on the literature review. The number of stops is assumed to be one for the Model, and the average fuel flow of 14,929 pounds per hour and 10 seconds was derived from the data for the throttle advancement portions.

Takeoff Phase

As stated in the Data Filtering section, the Takeoff portion of the data analysis measured the time and fuel utilized once brake release occurred in conjunction with increasing fuel flow, ground speed and indicated airspeed until the weight on wheels no longer registered. Brake release is an identifying factor because there are two methods for conducting a takeoff. The first, a rolling takeoff, is where power is increased without brakes or and the second, a static takeoff where brakes are applied until maximum power is reached and then the brakes are released.

In order to create the Takeoff model, this research applied a regression analysis using three of the significant factors that impact aircraft performance: gross weight, pressure altitude, and temperature. As measured by the aircraft, the temperature was averaged across a five-minute time period, including most of the takeoff and some of the taxi segment, to ensure no outliers impacted the data. This research did not use the last quarter of takeoff temperature data due to increased skin friction on the aircraft due to air passage over the sensors leading to increased temperature readings as the aircraft gained speed. Similarly, pressure altitude was derived by the same process from the aircraft data and compared against the known field elevation to control for outliers.

Finally, the aircraft gross weight was selected from the moment of brake release and the start of the takeoff roll. However, a correction was applied since while the aircraft operating weight is constant, the fuel weight measurements would increase or decrease at a rate of several hundred pounds at varying intervals that averaged every 10 seconds. These variances occur due to fuel sloshing during aircraft movement and potential errors in gauge readings; however, even errors over 200 pounds only represented a deviation of 0.04 percent of the aircraft's total gross weight (assuming a total gross weight of 500,000 pounds). Therefore, this research analyzed each takeoff's data to determine the fuel used and compared that against the total fuel reported by the computer to ensure that the total fuel reflected the actual fuel in the tanks.

Summary

This chapter outlined the methodology used to create a fuel model for the start, taxi, and takeoff phases for each of the 140 aircraft taxi and takeoff events. In the next chapter, this research compared the models developed against the data and analyzed the results.

Analysis and Results

Overview

This chapter lists the findings from the pre-flight, engine start, pre-taxi, taxi, and takeoff models and compares those models to the aircraft data. The results suggest that the current models do not sufficiently cover all aspects of ground operations and result in overestimating the required ground fuel.

Pre-flight Model Results

The Preflight Model used the 1.5 hours APU usage recommended by the RAND study in conjunction with the APU fuel flow of 420 pounds per hour stated by the technical order. The model result yielded a flat fuel load of 630 pounds required for Pre-flight fuel usage, a decrease of 210 pounds from the baseline model.

Engine Start Model Results

The standard engine start model results yield a 445.17-pound total fuel use over 530 seconds of the start time, as shown in Table 8. The use of fuel was relatively evenly spread for each engine and showed exponential growth dependent on time, as shown in Figure 12.

Table 8: Standard Start Fuel Model Results

Standard Engine Start					
PHASE	**Expected Burn (lb/hr)**	**Time (hrs)**	**Expected (lb)**	**Running Clock (hrs)**	**Total Times (sec)**
APU	420.00	0.11	47.83	0.00	0.00
Starter 1 Engaged	0.00	0.01	0.00	0.01	20.00
Fuel 1 Induction	500.00	0.01	2.78	0.01	40.00
EGT Rise 1	1000.00	0.02	16.67	0.03	100.00
Sustain 1	1000.00	0.09	86.11	Concurrent Run	
Starter 2 Engaged	0.00	0.01	0.00	0.03	120.00
Fuel 2 Induced	500.00	0.01	2.78	0.04	140.00
EGT Rise 2	1000.00	0.02	16.67	0.06	200.00
Sustain 2	1000.00	0.06	58.33	0.06	210.00
Starter 3 Engaged	0.00	0.01	0.00	0.06	230.00
Fuel 3 Induction	500.00	0.01	2.78	0.07	250.00
EGT Rise 3	1000.00	0.02	16.67	0.09	310.00
Sustain 3	1000.00	0.03	27.78	Concurrent Run	
Starter 4 Engaged	0.00	0.01	0.00	0.09	330.00
Fuel 4 Induction	500.00	0.01	2.78	0.10	350.00
EGT Rise 4	1000.00	0.02	16.67	0.11	410.00
APU Cool down (Sustain 1,2,3,4)	4420.00	0.03	147.33	0.15	530.00
TOTAL START			**445.1667**		

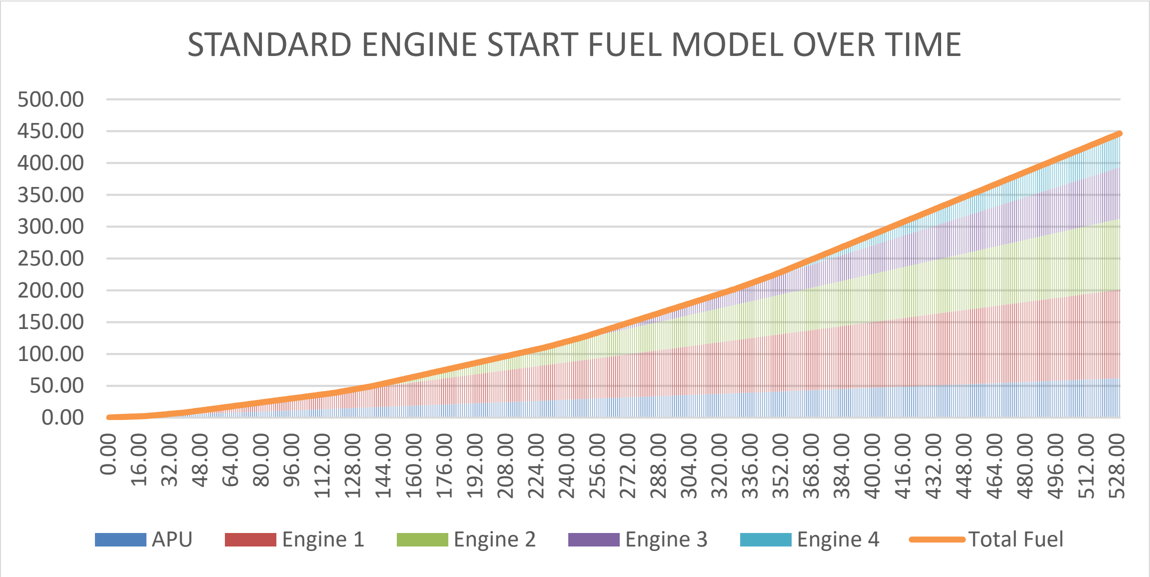


Figure 11: Standard Engine Start Fuel Model

The reduced Engine Start model results yield a 374.61-pound total fuel use over 330 seconds of the start time, as shown in Table 9. The use of fuel was similar to a standard start, except that the fuel used for Engine 1 would account for most fuel use due to the higher fuel flow required for starting two of the engines, as shown in Figure 12.

Modeling comparisons between the two types of engine starts show that the reduced Engine Start model is more efficient in both time and fuel use by both 37.7% and 15.8%, respectively.

Table 9: Reduced Start Fuel Model Results

Reduced Engine Start					
PHASE	**Expected Burn (lb/hr)**	**Time (hrs)**	**Expected (lb)**	**Running Clock (hrs)**	**TOTAL TIMES (s)**
APU	420	0.086111111	36.1667	0	0
Starter 1 Engaged	0	0.005555556	0.0000	0.005555556	20
Fuel 1 Induction	500	0.005555556	2.7778	0.011111111	40
EGT Rise 1	1000	0.016666667	16.6667	0.027777778	100
Sustain 1	3000	0.058333333	175.0000	0.030555556	110
Starter 2 Engaged	0	0.005555556	0.0000	0.036111111	130
Fuel 2 Induced	500	0.005555556	2.7778	0.041666667	150
EGT Rise 2	1000	0.016666667	16.6667	0.058333333	210
Sustain 2	1000	0.030555556	30.5556	Simultaneous Start	
Starter 3 Engaged	0	0.005555556	0.0000		
Fuel 3 Induction	500	0.005555556	2.7778		
EGT Rise 3	1000	0.016666667	16.6667		
Sustain 3	1000	0.030555556	30.5556		
Starter 4 Engaged	0	0.005555556	0.0000	0.063888889	230
Fuel 4 Induction	500	0.005555556	2.7778	0.069444444	250
EGT Rise 4	1000	0.016666667	16.6667	0.086111111	310
APU Cool down (Sustain 1,2,3,4)	4420	0.005555556	24.55556	0.091666667	330
TOTAL START			**374.6111**		

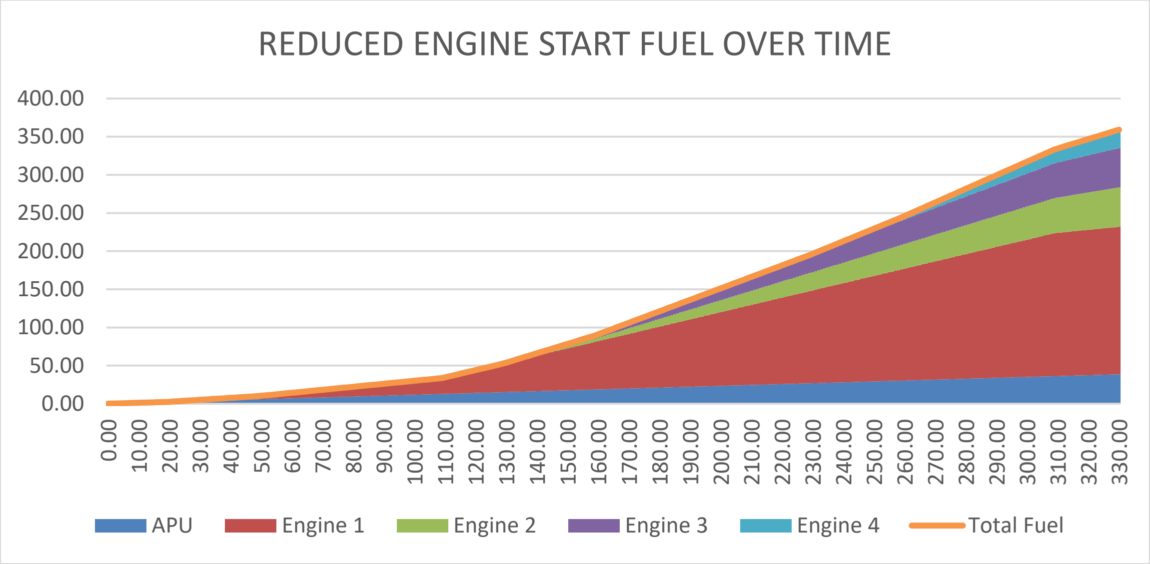
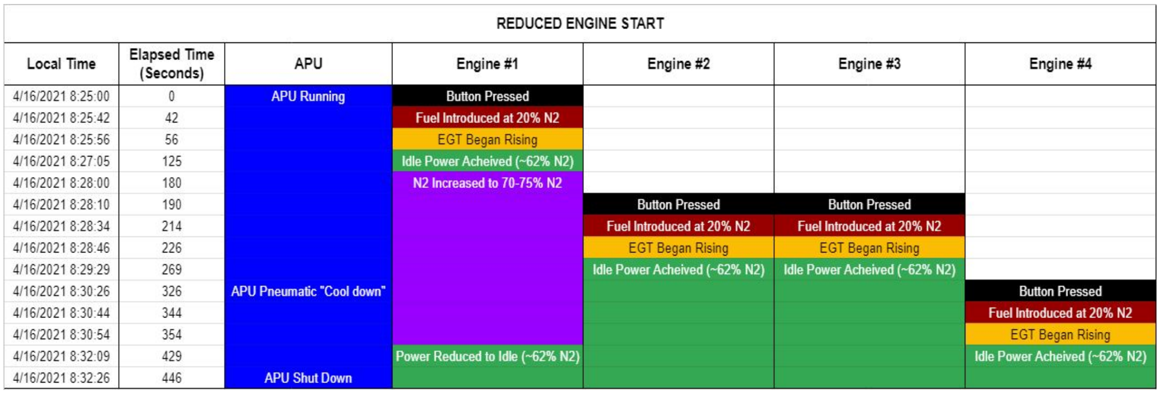


Figure 12: Reduced Engine Start Fuel Model



REDUCED ENGINE START

Local Time	Elapsed Time (Seconds)	APU	Engine #1	Engine #2	Engine #3	Engine #4
4/16/2021 8:25:00	0	APU Running	Button Pressed			
4/16/2021 8:25:42	42		Fuel Introduced at 20% N2			
4/16/2021 8:25:56	56		EGT Began Rising			
4/16/2021 8:27:05	125		Idle Power Acheived (~62% N2)			
4/16/2021 8:28:00	180		N2 Increased to 70-75% N2			
4/16/2021 8:28:10	190			Button Pressed	Button Pressed	
4/16/2021 8:28:34	214			Fuel Introduced at 20% N2	Fuel Introduced at 20% N2	
4/16/2021 8:28:46	226			EGT Began Rising	EGT Began Rising	
4/16/2021 8:29:29	269			Idle Power Acheived (~62% N2)	Idle Power Acheived (~62% N2)	
4/16/2021 8:30:26	326	APU Pneumatic "Cool down"				Button Pressed
4/16/2021 8:30:44	344					Fuel Introduced at 20% N2
4/16/2021 8:30:54	354					EGT Began Rising
4/16/2021 8:32:09	429		Power Reduced to Idle (~62% N2)			Idle Power Acheived (~62% N2)
4/16/2021 8:32:26	446	APU Shut Down				

Figure 13: Actual Reduced Engine Start

Overall, the Reduced Engine Start model performed well, but it needs to incorporate an additional delay before starting Engine 1, and delay times need to be extended to predict crew behavior better.

Pre-Taxi Model Results

In order to validate our five-minute Pre-Taxi assumption, this research compared the 300-second model equivalent with 2,045 data points captured after all four engines completed their start cycles but before ground speed increase, indicating the start of the taxi. The Model overpredicts aircraft Pre-Taxi times by 0.02 percent and accounts for all Pre-Taxi times at the 100th percentile, as shown in Table 10.

Table 10: Pre-Taxi Delay Times - Rank and Percentile Test

Percentile	
100	295
99	116
95	62
50	14
Model	300

Note that 50 percent of the Pre-Taxi delay times are 14 seconds or less. This number is surprisingly small since some portion of APU Cooldown, Checklist completion, and Taxi coordination is usually completed during this phase. The delay data may be due to the time skips observed in the taxi data and requires further analysis.

Compared with the actual fuel used versus the Model's prediction, we find that the five-minute, 366.02-pound Model over predicts the actual fuel required before taxi, as shown in Table 11. However, unlike in the time percentile test, there are significant outliers regarding fuel consumed as the Model underpredicts the actual data for the fuel required in several instances, as shown in Table 12. One issue was that the indicated ground speed filtered the actual data, but this would not filter out the increased fuel flows resulting from the increase of power at the start of the taxi to overcome gross weight, slope, and friction as the aircraft begins to move.

Table 11: Pre-Taxi Fuel - Rank and Percentile Test

Actual			Model
Percentile	**Fuel**	**Time**	**Fuel**
		300	366.0225
99.5	242.6	165.55	201.9834
99	205.2818	116	141.5287
95	108.1956	62	75.64465
50	22.11556	14	17.08105

Table 12: Pre-Taxi Fuel Outliers

FILE_SEGMENT	FF_CONSUMED	Pre-Taxi Delay (Second
1580861-6.csv_4.0	1189.12	295
1655791-2.csv_3.0	487.6444444	111
1620361-4.csv_2.0	460.1955556	237
1639531-9.csv_4.0	313.8133333	149
1642351-7.csv_3.0	308.7288889	61
1607351-7.csv_1.0	282.9511111	221

Taxi Model Results

Both Taxi distance and gross weight are positively correlated with the amount of fuel used as seen in Figure 14. These correlations are further explored in a regression analysis of gross weight and taxi distance which yielded an R Square of 36.4 percent, accounting for 36 percent of the variance, with both variables attaining a statistically significant p-value of 0.00195 for gross weight and 4.24^{-7} for taxi distance. However, with two-thirds of the variance unaccounted for, this research explored the impacts of aircraft delays on fuel use.

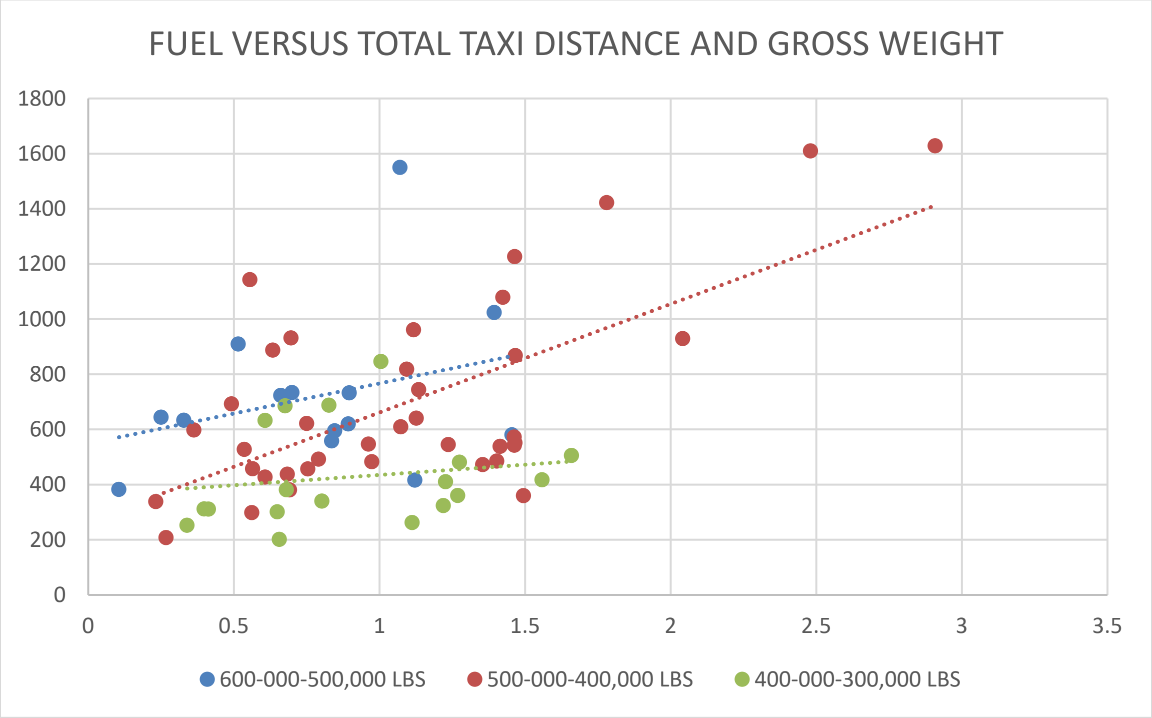


Figure 14: Taxi Fuel versus Taxi Distance and Weight

When compared against the 15-minute planning factor for taxi times, this research discovered that 65 of the 70 aircraft, 93%, had fewer taxi times, averaging only 7.73 minutes, thereby resulting in excess fuel loads, as seen in Figure 15. Filtering the data further by the type of airport: military, civilian, or dual-use and using an ANOVA Single Factor test determined if there existed a statistical difference between the averages. Our data support the hypothesis that the taxi time means of 6,79, 9.03, and 9.43 minutes are not equal for military, dual-use, and civilian airfields, respectively, as shown in Figure 16. All averages were below the required 15 minutes established by the U.S. Air Force, with only two military bases, ETAD and HEAZ, exceeding the criteria. Additionally, two civilian airfields, LZSH and LTBA, and one dual-use airfield, KCHS, exceeded the 15-

minute criteria, although two of those, KCHS and LTBA, averaged below the threshold with only a single sortie exceeding it.

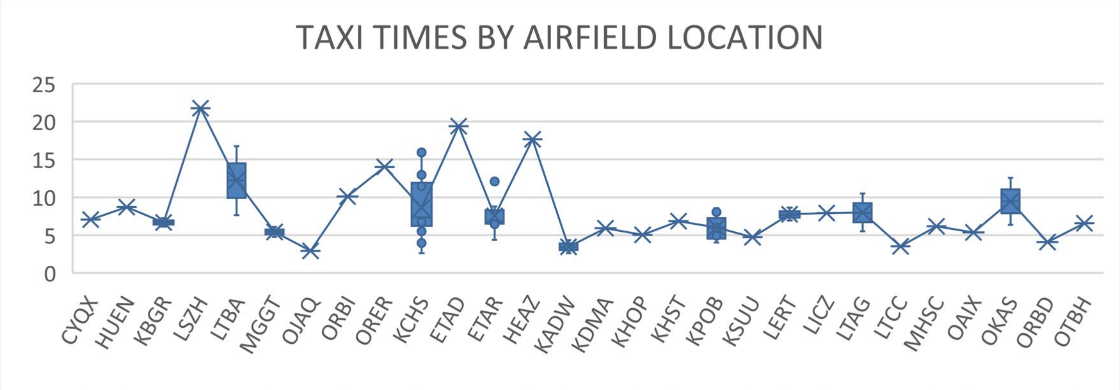


Figure 15: Taxi Times by Airfield Location

Table 13: ANOVA Taxi Time by Airfield Type

Anova: Single Factor						
SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
MIL	35	237.675	6.790714286	8.771262342		
DUAL	23	208.8291667	9.079528986	18.70126722		
CIV	12	113.1	9.425	29.73279987		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	102.3520846	2	51.17604231	3.307375787	0.042675969	3.133762315
Within Groups	1036.711597	67	15.47330742			
Total	1139.063682	69				

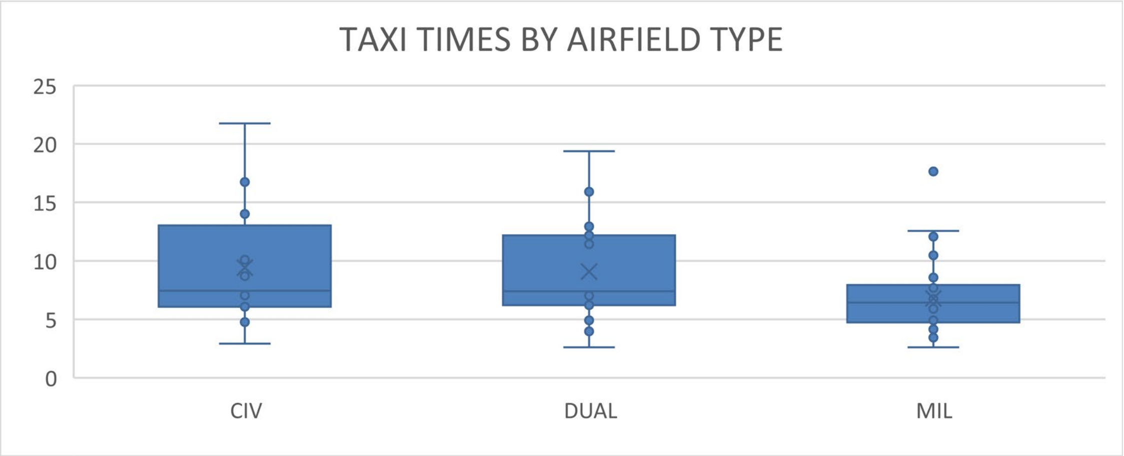


Figure 16: Taxi Times by Airfield Type

The data shows that the 15-minute taxi metric currently used overestimates the actual taxi times used at dual-use, civilian, and military airports by 33 percent for Duel and Civilian Airfields and 50 percent for military Airfields as shown in Figure 16. On average, the total time needed to taxi, with delays, is 6.79 minutes at military airfields and 9.1 and 9.4 minutes at Dual and Civilian airfields, respectively, as seen in Table 13. This research broke this data down further into the actual delay times in order to validate the constant, D_i, used by the Taxi model in Equation 10.

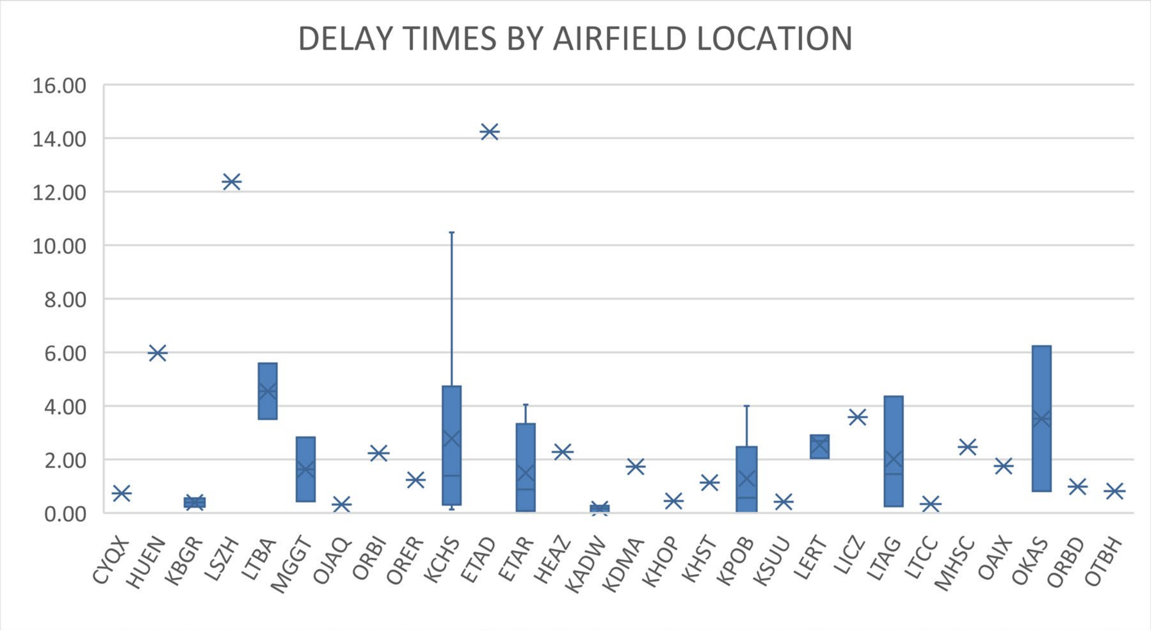


Figure 17: Taxi Delay Times by Airfield Location

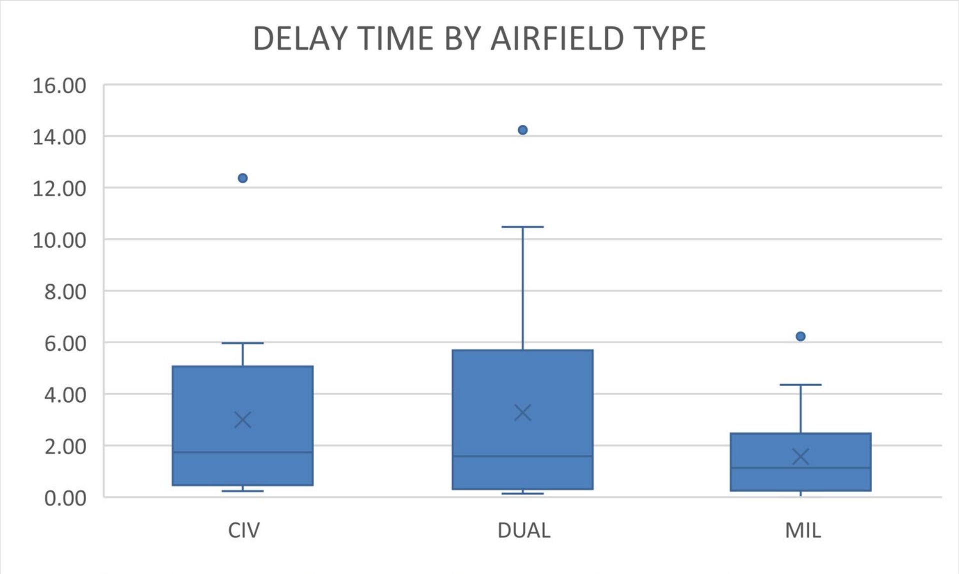


Figure 18: Taxi Delay by Airfield Type

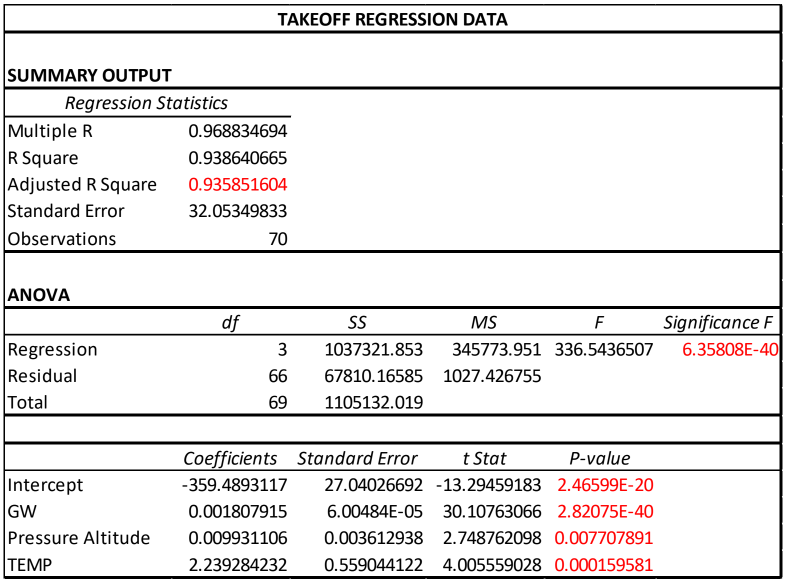
Surprisingly, the data showed a significant decrease in delay on average compared to the Model with civilian, dual-use, and military airfields averaging 3.00, 3.28, and 1.57 minutes respectively. These delays were smaller than previous research estimates of nine and five minutes for civilian and military fields, respectively. While this highlighted that the constants were conservative, it also highlighted the potential for significant outliers, with 6 of the 70 data points exceeding the Model.

Finally, the average taxi speeds and fuel flows totaled for all four engines were found to be approximately 9.74 knots and 5,636.80 pounds per hour, respectively. These findings validated the constants used by the taxi model during movement portions. The Delay fuel flow used the average idle fuel flow of 4,392.27 pounds per hour.

Takeoff

This research analyzed the takeoff data using multiple regression. The optimal Model selected had takeoff fuel consumed as the dependent variable and the aircraft gross weight, pressure altitude, and temperature as the independent variables. A summary of the statistics showed that gross weight, pressure altitude, and temperature significantly impacted fuel flow during takeoff, as shown in Table 14.

Table 14: Takeoff Data Regression Analysis



TAKEOFF REGRESSION DATA

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.968834694
R Square	0.938640665
Adjusted R Square	0.935851604
Standard Error	32.05349833
Observations	70

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	1037321.853	345773.951	336.5436507	6.35808E-40
Residual	66	67810.16585	1027.426755		
Total	69	1105132.019			

	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	-359.4893117	27.04026692	-13.29459183	2.46599E-20
GW	0.001807915	6.00484E-05	30.10763066	2.82075E-40
Pressure Altitude	0.009931106	0.003612938	2.748762098	0.007707891
TEMP	2.239284232	0.559044122	4.005559028	0.000159581

The regression analysis resulted in the following Equations 10 and 11.

$$F_{takeoff} = \beta_0 + \beta_1 * e + \beta_2 * t + \beta_3 * w \qquad (11)$$

$$F_{takeoff} = -361.88 + 0.009 * e + 2.318 * t + 0.0018 * w \qquad (12)$$

Where:

$F_{takeoff}$ = Takeoff Fuel Consumed
e = Pressure Altitude in feet
t = Temperature in degrees Celsius
w = Gross Weight in pounds

Each regression coefficient had a normal distribution in their residual plots, although the pressure altitude coefficient demonstrated a small amount of curvature. Figure 19 demonstrates the Model's effectiveness for 125 takeoffs sorted by residual size.

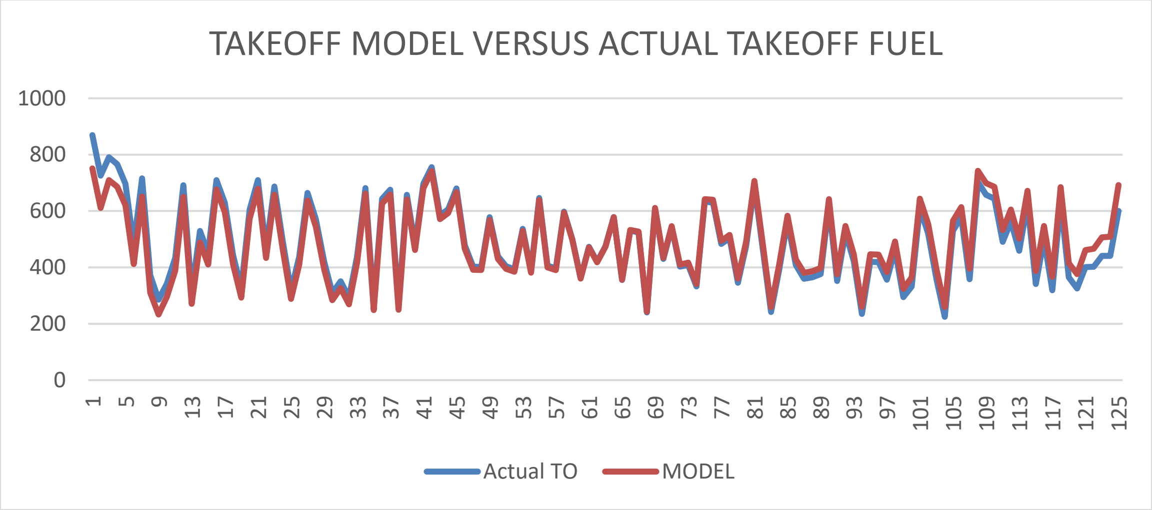


Figure 19: Takeoff Model Comparison against Regression Data

The Takeoff model was then applied against the validation data set that was not used in developing the regression. As seen in Figure 20, the Takeoff Fuel model closely followed actual takeoff fuel consumption with an overall average difference of five pounds of fuel. The overall difference peaked at each side of the graph, with two locations under-fueling by approximately 100 pounds and two locations over-fueling by 85 pounds.

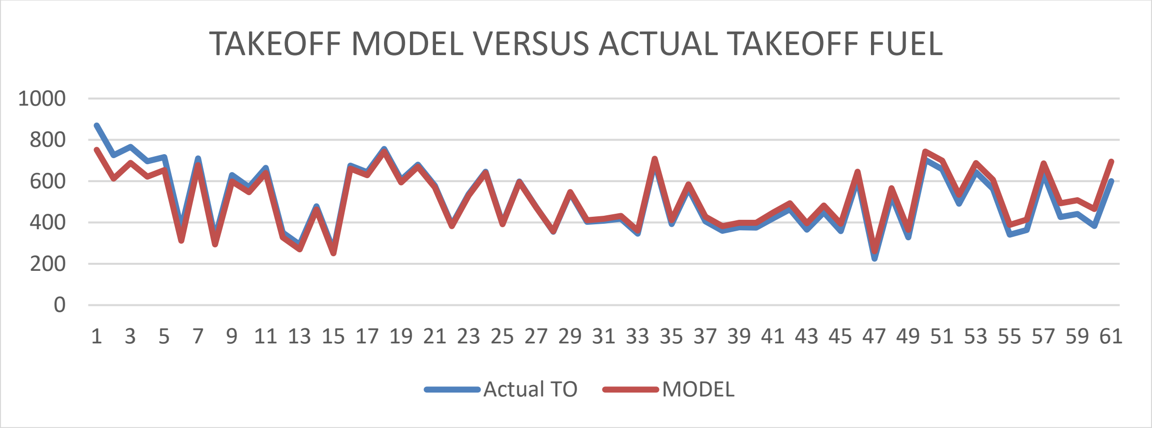


Figure 20: Takeoff Model Comparison versus Actual Takeoff Fuel

The pre-flight, start, pre-taxi, taxi, and takeoff models were compared against the current C-17 fixed fuel model to determine whether it creates a more accurate model without incurring significantly more risk.

Model Comparison

The Sum of Squares Error, Mean Square Error, and Standard Error of the Baseline Taxi model and the Taxi model are compared in Table 15.

Table 15: Taxi Model Statistics Comparison

	Baseline Taxi Model	Taxi Model
SSE	7,120,209.65	4,797,067.85
MSE	104,708.97	70,545.12
SE	323.59	265.60

All three measures show that the baseline model of 1,500 pounds versus a Taxi model, which accounts for location delays and taxi distances measured against data-driven fuel flows, performs far better with less waste. For example, using the actual delay times in the Model instead of the location-specific ones, the Model closely approximates the real-world fuel use, as seen in Figure 21.

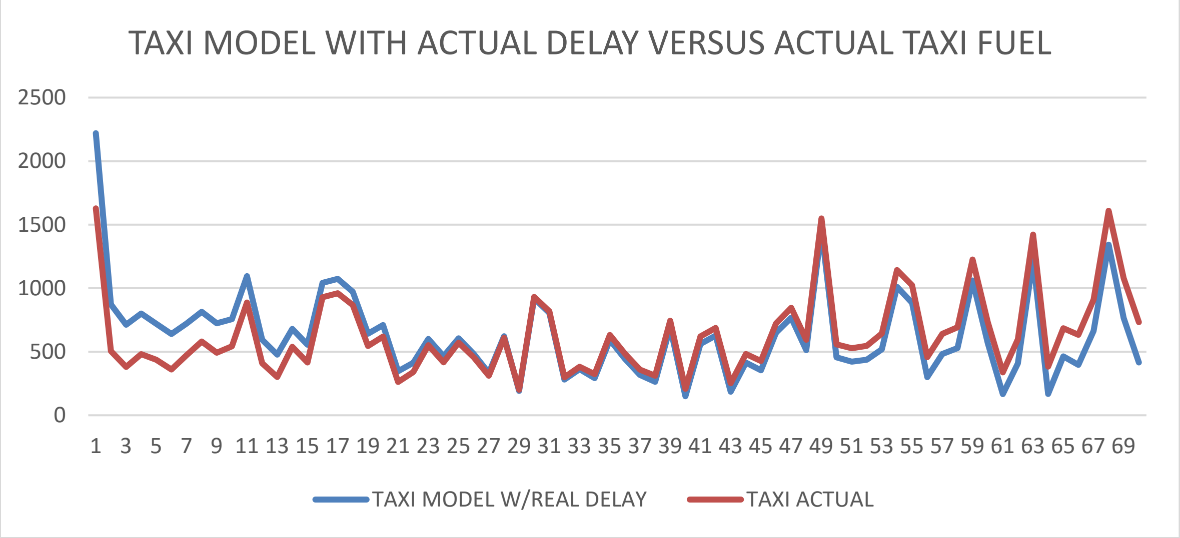


Figure 21: Taxi Model Comparison against Actual Taxi Fuel

When all three models are compared in Figure 22, we see that the Taxi model, which used a basic delay of five minutes for military airfields and nine minutes for civilian and dual-use airfields, suffers from the delay times and overestimates the amount of fuel needed in over 66 percent of the locations; however, the risk of underestimating the required fuel is limited to only three locations. When compared with the 1,500 pounds baseline model, the Taxi Model is both more fuel-efficient and less risky since it underestimates the required fuel in four different locations. Finally, we see that the Taxi Model, which uses the data derived delay times of 3.00 minutes, 3.25 minutes, and 1.57 minutes for civilian, dual-use, and military airfields, performs better than all models with increased efficiency with only a slight increase in risk.

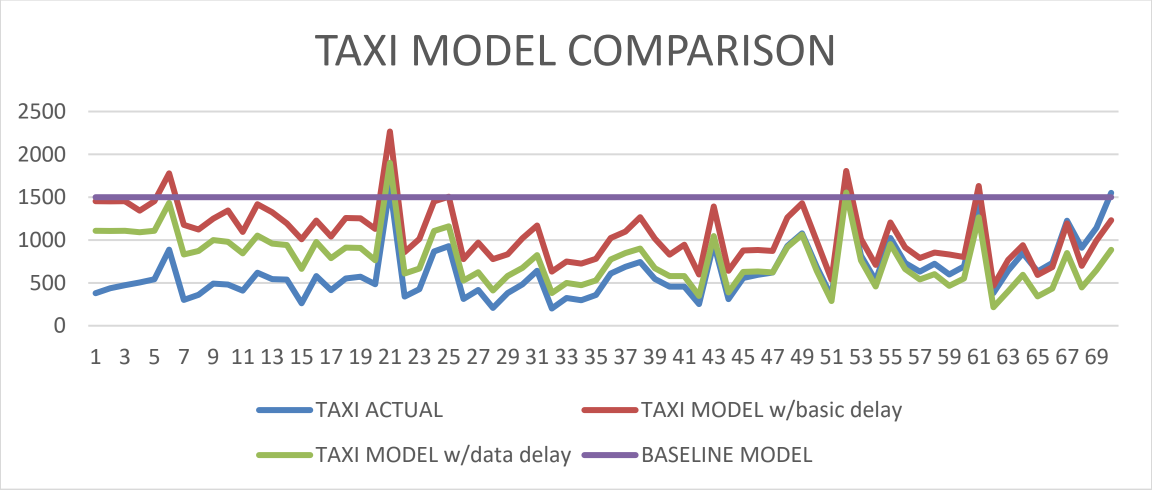


Figure 22: Taxi Model Comparison

The following comparison, Figure 23, overlays the Takeoff Fuel model with the Taxi model and compares the total against both the actual fuel required and the baseline 2,500-pound fuel model. The data shows that when incorporating the Takeoff Fuel model, it only increases the required fuel on average by 457.78 pounds, well below the 1,000-pound increase used by the current C-17 fuel model. Fuel efficiency increases when compared with both the baseline and the taxi-only Model, and the risk of under-fueling the aircraft remains extremely low.

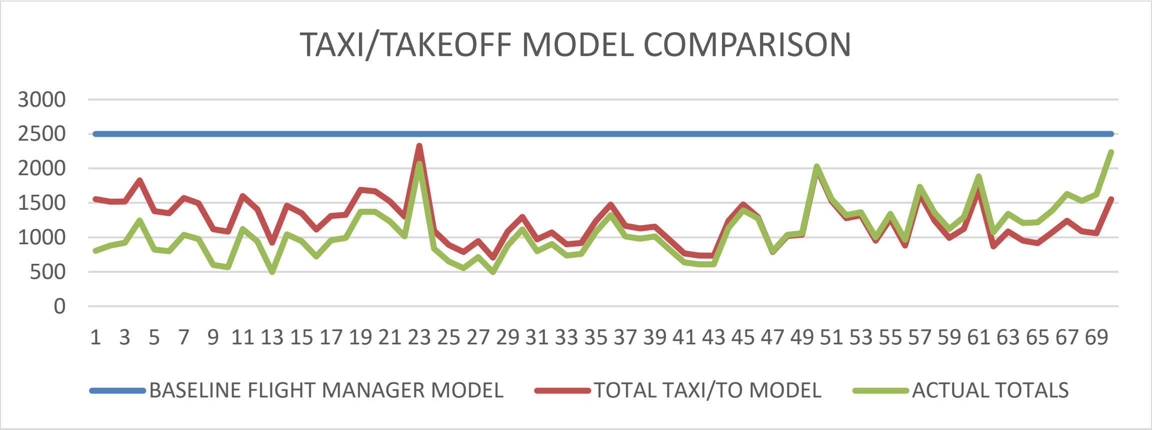


Figure 23: Taxi and Takeoff Model Comparison

When this research compared the models concerning airfield type and location below in Figure 24, fuel savings were the most significant at military airfields, followed by dual-use and then civilian airfields. Conversely, the most significant variation in the Model predicted fuel load versus actual fuel load occurred at dual-use and civilian airfields.

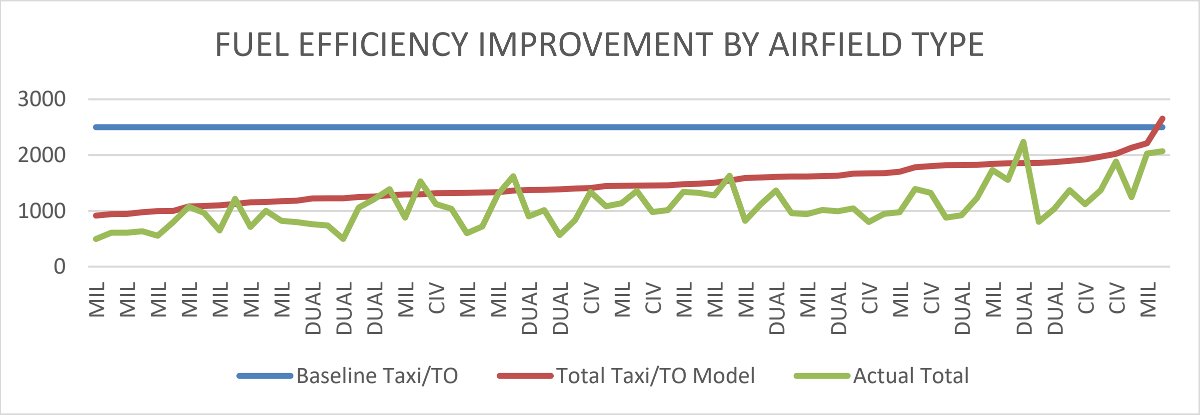


Figure 24: Taxi/Takeoff Comparison by Airfield

The final comparison of the models includes all five phases of ground operations. As seen in Figure 25, the entire ground operations model outperforms the FM fixed Model, which consistently underpredicts the actual fuel required for all phases of flight. Furthermore, the average difference between the baseline fuel and the used fuel was approximately 283.66 pounds, representing an under-fueling of 10.19 percent less than required for ground operations. Compared with the baseline, the amount of risk was 24613.00 pounds across the 70 aircraft sorties.

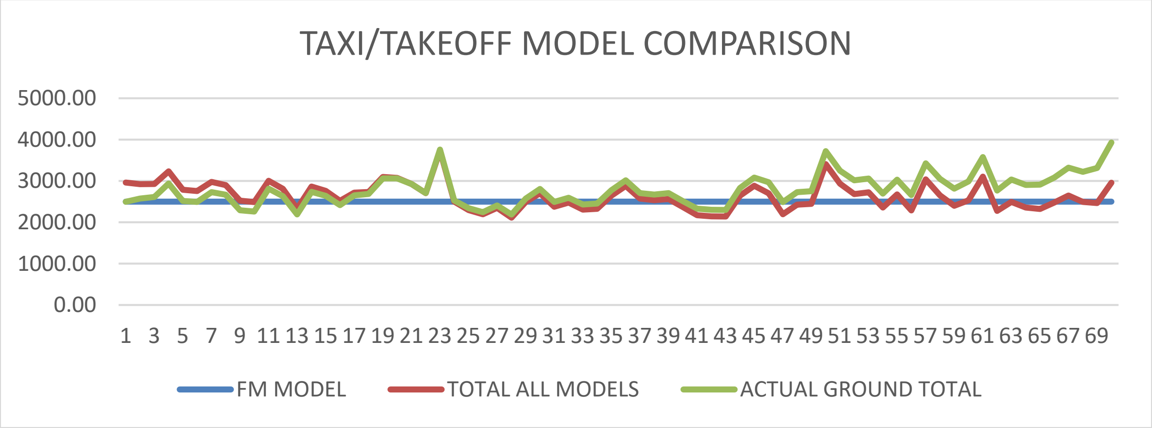


Figure 25: Total Ground Fuel Model Comparison

The Ground Fuel model was far more effective than the baseline in predicting the amount of fuel required at each location; however, the Ground Model still under predicted the actual fuel used by 148.00 pounds on average.

Summary

This chapter detailed the pre-flight, start, pre-taxi, taxi, and takeoff fuel model results and compared them against the current fixed fuel model utilized by the C-17. It showed that the developed Ground model outperforms the Baseline model.

Conclusion and Recommendation

Overview

This chapter details the findings and conclusion of this study and identifies future actions and recommendations for avenues of research. The primary objectives of this paper are to:

1. Establish a fuel consumption model for ground and takeoff operations before Climb that accounts for environmental and location-specific factors.

2. Compare the new and current fuel consumption models against actual data to assess accuracy.

This research created a ground operations fuel model from aircraft technical orders, flight data recorder data, operational procedures, and regression analysis, which revealed significant differences between the current baseline fuel model, the new ground operations fuel model, and the real-world fuel used.

Conclusion of Research

The results support using the ground operations fuel model over the use of the baseline fixed fuel model currently used by the C-17 Flight Managers. The Ground model accurately predicted the required fuel across 70 taxi and 70 takeoff events while reducing the overall fuel load by 457.78 pounds for each aircraft during the STTO events. Furthermore, the regression model for takeoff performed excellently at predicting takeoff fuel using three variables: gross weight, temperature, and pressure altitude, achieving an R Squared value of 0.9374 with statistically significant p-values across all variables. Additionally, the study established a model for pre-flight, start, and pre-taxi fuel that until now did not exist for the C-17 but still accounted for 56.9 percent of the total fuel used by any aircraft during ground operations. In the end, the Model still overpredicted the amount of fuel required, thereby driving the need for an established decision point on the acceptable risk of potential aircraft delay versus fuel savings.

Significance of Research

The significance of this study is twofold. First, it establishes realistic fuel requirements for pilots, thus removing subjectivity with a "one-size" fits all fixed fuel model. The ground operations fuel model allows pilots to see actual fuel requirements based on known variables at any location and may provide a cap on over-fueling aircraft above the 2,500 pounds currently stipulated by the aircraft or the 1,500 pounds assigned by the mission planners for the taxi. In effect, the baseline fuel model increased the risk to the mission if crews did not account for the unknown requirements of fuel during the pre-flight, start, and pre-taxi phases. Establishing a model for these phases will increase aircrew confidence in the overall fuel plan while simultaneously reducing risk and increasing efficiency.

Secondly, as seen in the literature review, a reduction of fuel by 10,000 pounds will save $305.56 on each aircraft flight. Applying the Ground Operations Fuel Model to 70 aircraft events analyzed in this study reveals an opportunity for the Air Force to save 127,131.67 pounds of fuel, a net savings of $5.415.59 with only a slight increase in risk. These fuel savings directly result from a vastly more inefficient and risky fixed fuel model to an airfield-specific model that accounts for all phases of ground operations.

Recommendation for Future Research

Future research needs to focus on testing the taxi delay constants and the takeoff regression model by defining and refining the variables that impact ground operations. For example, this study did not factor in runway/airfield slope or engine life, which are two variables that could have significant impacts on the required fuel during both taxi and takeoff. Additionally, the engine start data set had significant variances in both start time and fuel, highlighting the potential to use more variables than the fixed times and fuels derived from the technical order.

Additionally, the pre-flight, start and pre-taxi models created in this study are fixed and do not account for any variables other than a constant time and fuel flow. As with any fixed model, these models are less efficient and far more prone to error. Future research can identify additional variables specific to the aircraft and its location, allowing a more dynamic model to replace this one.

Other avenues currently under examination, such as aircraft towing to departure points or different, more advanced modeling techniques for MFOQA data, will also increase the efficiency of the STTO model while keeping risk at an acceptable level for mission planners.

Conclusion

This research shows the risk and inefficiencies of using a fixed fuel model and provided a ground operations model compared against real-world data. Using the FY14 and FY15 C-17 mission utilization rates, this research calculates that the application of this Model could have saved 8,598,550.62 and 8,641,048,92 pounds of fuel, respectively (Air Mobility Command, Fuel Efficiency Program, 2018). These fuel savings equate to savings of over $2,450,000 each year at a minimum when only applied to the C-17. However, if the Air Force can apply these changes for each Weapon System assigned to the Mobility Air Forces, these cost savings could significantly reduce the 8,131,674,586.67 pounds of fuel, 58.29 percent of the total fuel used by the United States Air Force.

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14. ABSTRACT

The purpose of this research is to establish and measure a C-17 Ground Fuel Model that accounts for variance in conditions and locations. Currently, the United States Air Force only uses a single mission design series specific fuel consumption number for the start, taxi, and takeoff phases. The Baseline Model does not account for fuel consumption variations during ground operations due to environmental or location-specific conditions.

The research methodology used the aircraft technical orders and procedures to build a fixed fuel model for the pre-flight, start, and pre-taxi phases of ground operations. The taxi phase model utilized the Haversine Formula with data derived average fuel flows and location-specific delay times. Finally, the takeoff model used regression analysis with location-specific pressure altitudes and temperatures combined with aircraft Gross Weights to model takeoff fuel requirements.

Overall fuel accuracy was increased by 32.6 percent. All models have significantly reduced fuel requirements from the baseline model while only incurring a small risk of under-fueling aircraft

15. SUBJECT TERMS

C-17, Fuel Efficiency, Ground Fuel, Start Taxi Takeoff, Flight Data Recorder, Fuel Flow Model, Aircraft Modeling^

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