

Aircraft Mass and Flight Performance

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INTRODUCTION

Research Question:

How does aircraft mass affect the rate of climb and fuel consumption in a simulated flight environment?

Background:

Why does aircraft performance matter?

Aircraft performance matters for efficiency and sustainability of flight as well as safety of the aircraft and passengers. If the aircraft underperforms that is a risk to safety however if an aircraft overperforms, that shows our current means of estimation are not very accurate. This research paper aims to investigate the effect of aircraft mass on flight performance, specifically on the fuel burnt and the rate of climb.

Why is mass important?

Different aircraft have different maximum takeoff weights. If an aircraft is carrying a mass greater than the maximum takeoff weight this brings significant risk to the aircraft. Since greater masses results in greater weights, and greater weights result in an aircraft having to produce more lift it would have to generate a greater lift to keep the aircraft airborne which the aircraft might not be capable of producing. This can be proved through the equation

$$W = mg$$

where W represents weight (N), m represents the mass(kg) and g represents the gravitational acceleration ($9.81m/s^2$)

Aim:

This research paper investigates how varying payload masses on the same control aircraft affect the performance of the aircraft, in this case the rate of climb and fuel consumption. To eliminate inconsistencies that come with experimenting in dynamic real world conditions, this experiment will take place in a simulator. To eliminate confounding variables from transient takeoff dynamics, the experiment will begin at an altitude of 5000ft and conclude at an altitude of 10000ft.

BACKGROUND THEORY

Mass and Weight:

Mass refers to how much matter is inside of an object. Mass is typically measured in kg. Weight however refers to the amount of gravitational force acting on an object at any given time, measured in newtons. On Earth a mass of 1kg has a weight of 9.81N however on the Moon a mass of 1kg has a weight of 1.6N.

Lift and Aircraft Mass:

We understand that a heavier object requires a greater lift because of the equation (this equation only represents how much lift is required for steady level flight)

$$L = m \cdot g$$

where l represents the lift in newtons, m represent the mass in kg and g represents the gravitational acceleration in m/s^2 . We can substitute in numbers to make it easier to understand.

$$L = 23 \cdot 9.81$$

Where 23 kg represents the mass of the aircraft and the 9.81 representing the gravitational acceleration on Earth, we find the lift to be 225.63N however if we increase the mass by 7kg changing the equation to:

$$L = 30 \cdot 9.81$$

We find that the lift of the aircraft increases by approximately 30.43% or 68.67N proving if we increase the mass of the aircraft the lift of the aircraft required for steady level flight also increases.

Lift Equation:

Lift is the opposing force to gravity in flight. Lift is calculated through the equation:

$$L = \frac{1}{2} \rho v^2 S C_l$$

L represent the lift in newtons, ρ represents the air density in kg/m^3 , v represents the velocity or airspeed in m/s, S represents the area of the wing in m^2 and C_l represents the lift coefficient, a dimensionless efficiency number (has no unit)

Rate of Climb:

Rate of climb refers to how quickly the aircraft gains altitude. It is calculated with the formula:

$$\text{Average rate of climb} = \frac{\text{final altitude} - \text{initial altitude}}{\text{time to climb}}$$

Fuel Consumption:

Fuel consumption refers to the amount of fuel burnt by an engine in a specific amount of calculated with the formula:

$$\text{Fuel burn rate} = \frac{\text{Fuel used}}{\text{Time of Climb}(h)}$$

Fuel burn rate is calculated in kg/h (kilograms per hour), the fuel used in kg and the time of climb in hours. If the time of climb in is minutes you would use this equation instead:

$$\text{Fuel burn rate} = \frac{\text{Fuel used}}{\text{Time of climb}(m)} \times 60$$

The reason fuel is calculated in kg or lbs instead of litres or gallons is due to the fact that volume of an amount can change whereas the mass stays the same. For example, on a cold day in Alaska the particles of the jet fuel would be more concentrated leading to a lesser volume whereas on a hot day in Dubai the particles would be in less proximity to each other leading to a greater volume but the same mass across both examples.

Excess Power

This equation refers to the mathematical bridge that connects aircraft mass, gravitational acceleration and power of the engine to the rate of climb in an aircraft. The equation is:

$$P_{climb} = mgv_{vertical}$$

The equation states that the power used to gain altitude measured in watts (W) is equal to the mass of the aircraft in kilograms (kg) multiplied by the gravitational acceleration force (which on Earth is $9.81m/s^2$) multiplied by

the vertical velocity in metres per second (m/s^2). To change the formula and make the vertical velocity ($v_{vertical}$) the subject, the equation would look like:

$$v_{vertical} = \frac{P_{climb}}{mg}$$

Gravitational Potential Energy.

Gravitational Potential Energy (GPE) refers to how much energy an object possesses due to its position within a gravitational field. An object on the floor would have a Gravitational Potential Energy store less than an object suspended on the wall by a rope due to the height from the ground. The equation for GPE is:

$$GPE = m \times g \times h$$

Where m refers to the mass of an object in kilograms (kg), g referring to the gravitational acceleration of the object ($9.81m/s^2$ on Earth) and h referring to the height of the object from the ground below in metres (m). GPE is calculated in joules (j)

RELATIONSHIP BETWEEN POWER AND RATE OF CLIMB

Power is represented by the formula:

$$P = \frac{E_{GPE}}{t}$$

P represents the power in watts (W), E_{GPE} represents energy, in this case Gravitational Potential Energy, and t represents the time in seconds (s). If we take another equation:

$$GPE = m \times g \times h$$

Where m refers to the mass of an object in kilograms (kg), g referring to the gravitational acceleration of the object ($9.81m/s^2$ on Earth) and h referring to the height of the object from the ground below in metres (m). GPE is calculated in joules (j). Since we know GPE or E_{GPE} is equal to $m \times g \times h$ we can derive the formula to make the new equation:

$$P = \frac{m \times g \times h}{t} \text{ or } P_{climb} = \frac{m \times g \times h}{t}$$

And since

$$v_{vertical} = \frac{h}{t}$$

We can derive the formula to find the relation of power and Gravitational Potential Energy to rate of climb to be:

$$P_{climb} = mgv_{vertical}$$

CONVERSION BETWEEN FUEL FLOW RATE AND FUEL BURNT.

To convert between fuel flow rate and fuel burnt we have to take the average fuel flow rate in kg/h and convert it to calculate how much fuel flow takes place per second. You do this by dividing the kg/h by 3600. The formula to calculate fuel burn is: $\text{fuel burnt} = \text{average fuel flow rate (kg/s)} \times \text{time (s)}$

Difference between IAS and TAS

IAS refers to the indicated airspeed of the aircraft which is the raw indication of aircraft speed shown directly in gauges on the aircraft. It does not reflect the true speed of which the aircraft is operating at as it ignores the atmospheric conditions. The SI unit for IAS is m/s however in aviation a more unconventional approach is used with the unit KT, referring to knots. 1 knot is equivalent to 1 nautical miles per hour. TAS refers to the actual speed of the aircraft moving through the air. As an aircraft gains altitude the surrounding air density decreases, reducing the drag on the aircraft. TAS accounts for this change in air density whereas IAS does not. At sea level on a standard day the IAS and TAS are the same. TAS has the SI unit of m/s but modern aviation uses the unconventional unit of KT.

Angle of Attack and Flight Path

Angle of attack refers to the angle between an aircraft's chord line to the direction of air flowing relative to the aircraft. The chord line is the imaginary straight line from the leading edge of the wing to the trailing edge. Flight path refers to the actual direction of flight in an aircraft. The formula relating flight path angle, the pitch angle and the angle of attack is:

$$\gamma = \theta - \alpha$$

This equation is only true in zero wind flights, the true equation is an approximation.

HYPOTHESIS

Hypothesis:

I hypothesise that as the mass loaded onto the aircraft increases, this will increase the force of lift required to sustain the aircraft in flight causing the speed of the aircraft to decrease. With the speed of the aircraft decreasing, the rate of climb performance is expected to decrease. The fuel consumption would then increase due to the increased time of flight between 5000ft and 10000ft. As the mass configuration of the aircraft increases I predict that the angle of attack will decrease because of a larger weight being applied on the aircraft due to the greater mass.

Mathematical Justification:

$$M \uparrow \Rightarrow P_{required} \uparrow \Rightarrow \text{fuel burn rate} \uparrow$$

M refers to the mass, $P_{required}$ refers to the power required and fuel burn rate refers to the mass of fuel consumed by the engine per hour

$$M \uparrow \Rightarrow W \uparrow \Rightarrow l_{required} \uparrow \Rightarrow ROC \downarrow$$

M refers to the mass, W to the weight applied on the object, $l_{required}$ refers to the lift and ROC refers to the vertical rate at which an aircraft gains altitude.

$$M \uparrow \Rightarrow W \uparrow \Rightarrow \alpha \downarrow$$

M refers to the mass, W to the weight and the lowercase letter alpha (α) refers to the mean angle of attack of the aircraft.

Variables:

Primary dependent variables:

- The rate of climb
- The amount of fuel consumed

Secondary dependant variables

- Fuel flow rate
- Engine N1%
- TAS (true airspeed)
- IAS (indicated airspeed)
- AoA

Control variables

- Aircraft model and maintenance
- Weather conditions
- Atmospheric pressure
- Fuel amount
- Engine power
- Aircraft centre of gravity

Independent variables

- Mass of the aircraft

METHODOLOGY

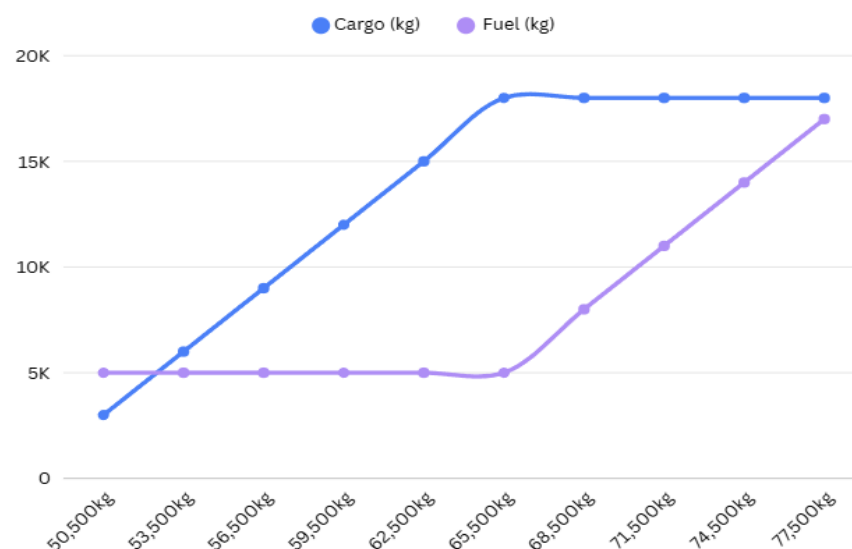
Simulation Environment:

The simulation will take place in a controlled environment. The pressure set to 1013qnh msl and the temperature set to 15 celsius msl, with minimal winds and wind gusts, zero clouds, no cloud coverage and no precipitation. All 10 experimental trials and 3 replicate tests are to be completed in the same environment and to begin in the same airport of departure.

Aircraft Configuration:

The aircraft will increase in mass loaded over the course of the 10 trials. For the first 6 trials weight will be loaded onto the cargo carrier of the aircraft with 5 tonnes of fuel loaded. On the 7th trial till the 10th trial, 18 tonnes will be loaded onto the aircraft cargo areas (18tonnes is the maximum amount of cargo that can be loaded on the aircraft at any given time) and an increase in fuel loaded in the aircraft, acting as extra mass to follow through with our experiment. The aircraft has an operating empty weight (OEW) of 42.5 tonnes with a maximum takeoff weight (MTOW) of 79tonnes. The mass configurations of the aircraft can be seen in figure 1.

Figure 1:



Experimental Procedure:

The aircraft will include 10 experimental trials, each repeated with 3 replicate tests to assess repeatability and to reduce influence of random variation. The aircraft will be loaded onto the airport of choice (OMDB for this experiment) and begin takeoff at a designated runway (30R at OMDB for this experiment). Using the electronic flight bag (EFB) located to the left of the pilot, the aircraft will be loaded with the masses required using it, refer to figure 1 to understand how much cargo and fuel is to be loaded onto the aircraft for each trial. The recording will then commence and the aircraft will be set to the N1% of 80%. The parking brake will then be removed and the aircraft will take off. At around ~2500ft the aircraft will be able to sustain a pitch angle of +5.0 degrees and will be kept at that pitch angle for the remainder of the trial. The trial will end once the aircraft exceeds an altitude of 10000ft. Complete all 10 experimental trials and 3 replicate tests per trial. The 3 replicate tests per experimental trial are used to calculate a mean average of results collected from the raw data table.

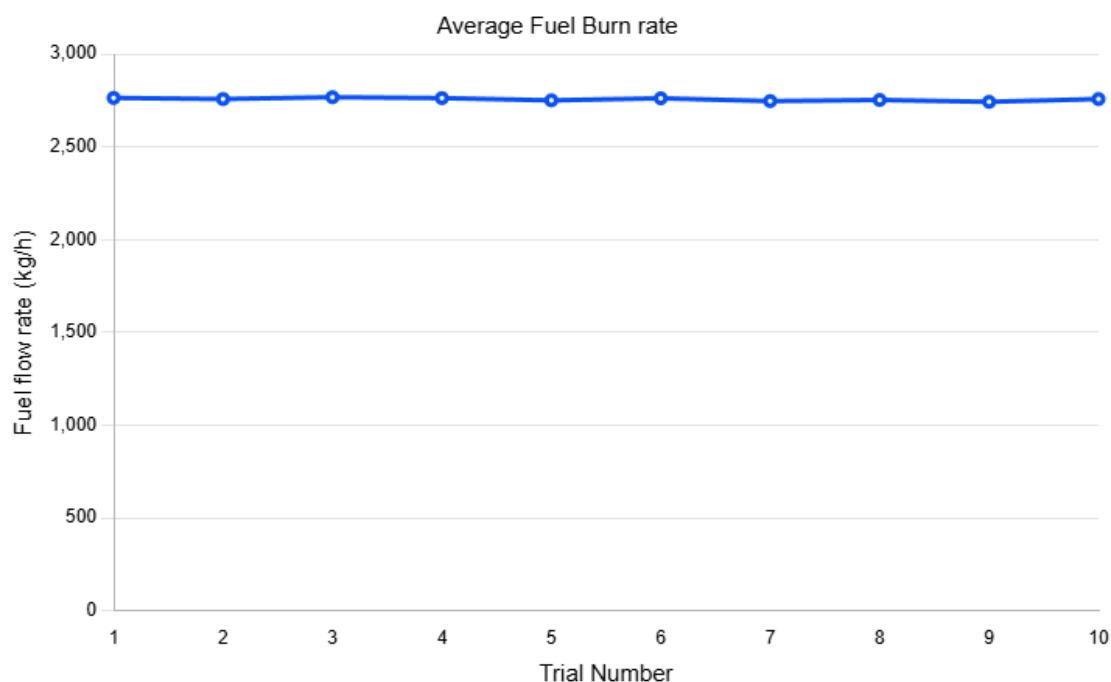
Data Collection:

The recordings will be transferred to a designated folder stored in the computer. Using the editing software of choice, the length of the flight reigning from the moment it reaches 5000ft (or the next closest altitude) to the moment it reaches an altitude of 10000ft (or the next closest altitude) will be isolated. Record the length of the

video in the format min:sec. Then record the relevant and necessary instrumentation data, which for this experiment is time taken, fuel flow rate, TAS, IAS and engine N1% every +500ft of elevation gain for every replicate test and experimental trial. After collecting all of the data, then calculate the fuel burnt and the climb rate of the aircraft. Refer to background theory section 2.4 and 2.5 for relevant information about fuel consumption and rate of climb and their formulas.

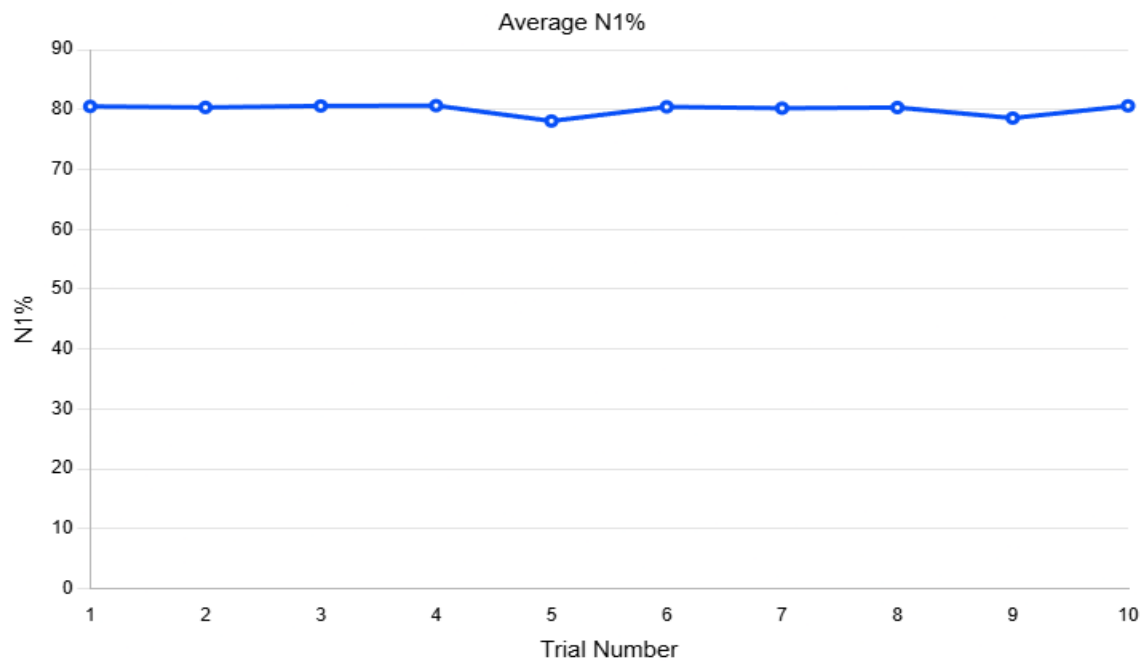
RESULTS

Average Fuel Burn rate (per engine) (figure 2)



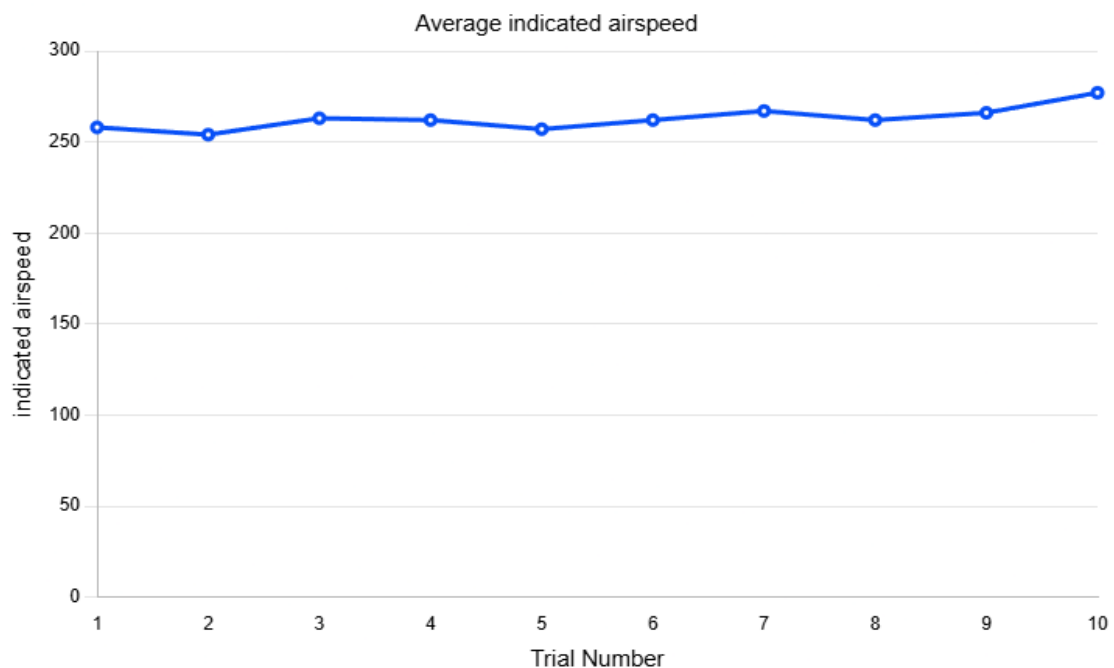
The data in figure 2 represents the average fuel burn rate for each experimental trial across all 10 trials. The data clearly shows how across all mass configurations (refer to figure 1 for mass configurations) fuel burn rate across one of the twin engines of the a320 neo stays constant. This indicates that engine power has stayed relatively consistent across ten trials due to the fact the engine did not require to use more energy from the fuel on the aircraft to sustain a higher engine N1%.

Average N1% (figure 3)



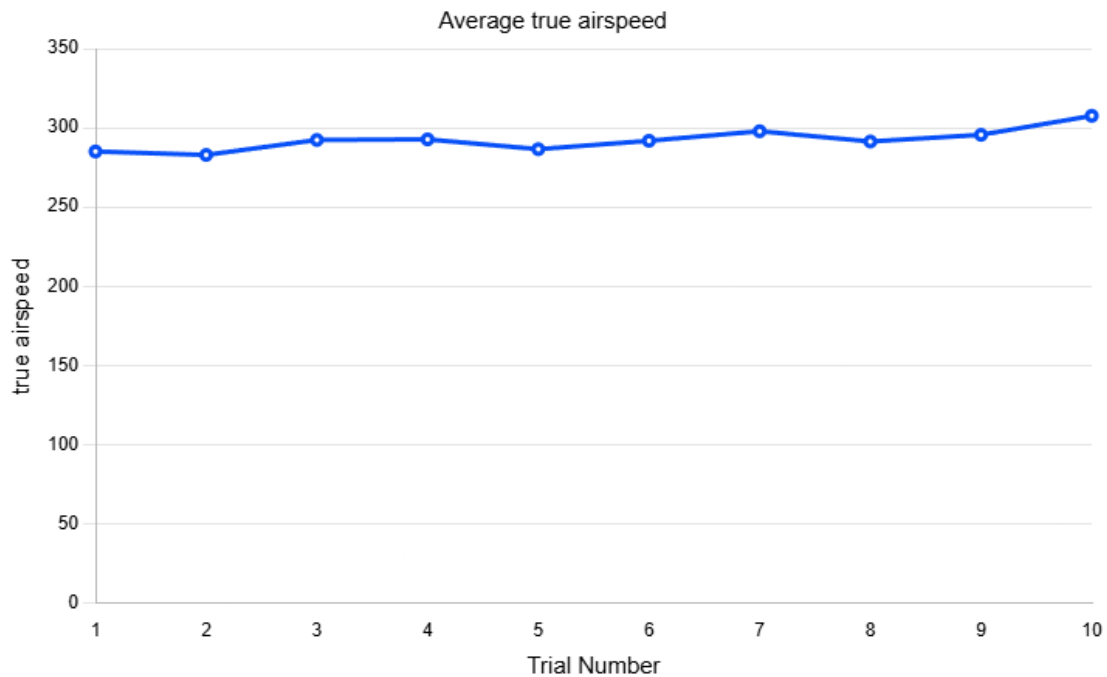
This graph represents the average N1% across all experimental trials and replicate tests. The graph shows the consistency of the N1%, constantly above 79.5% and lower than 81.5%. This indicates that the engine was operating at a relatively consistent rate across all the experimental trials and the fuel burn rate also stayed relatively consistent across all trials.

Average Indicated Airspeed (figure 4)



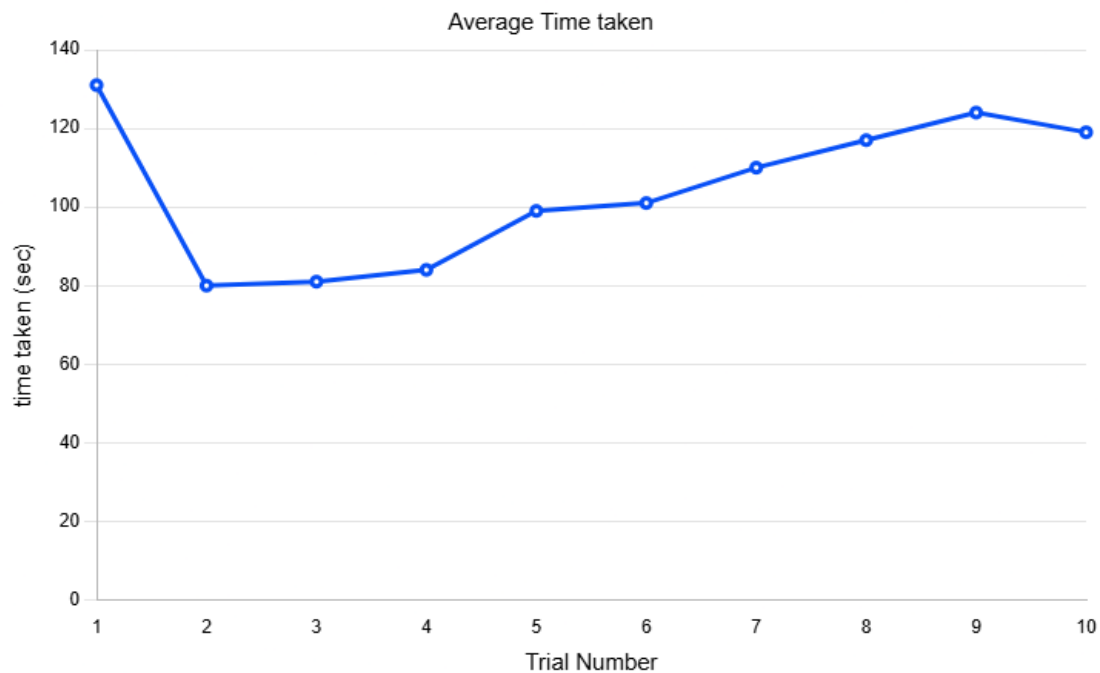
The graph above represents the average indicated airspeed across all of the experimental trials and replicate tests. No clear overall trend can be identified from the data of the graph. Between tests 1 through 8 the average indicated airspeed fluctuates between ~250 KT – ~270KT. Between trials 9 – 10 the mean IAS shows an increasing trend, refer to background theory part 2.10 for the meaning of IAS and the difference from TAS.

Average True Airspeed (figure 5)



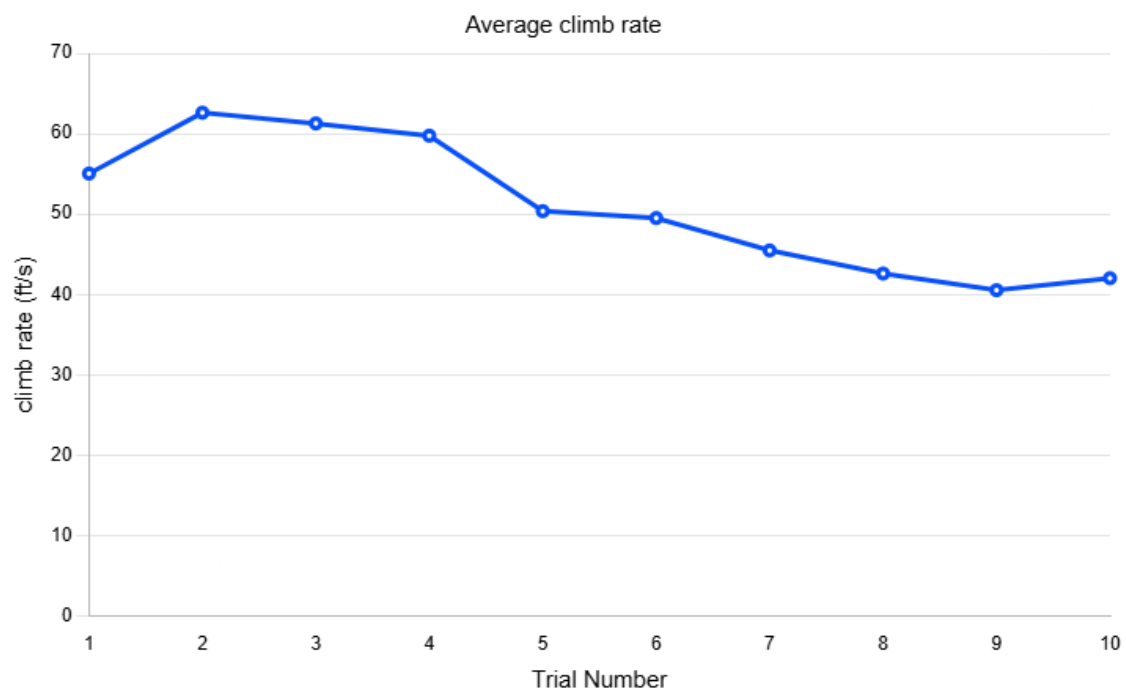
The graph above represents the average true airspeed across the experimental trials and replicate tests. From the data no clear overall trend can be identified. Through experimental trials 1 – 8 the mean true airspeed fluctuates between ~280KT – ~300KT . From experimental trials 9 through ten an upward trend can be noticed. Refer to background theory part 2.10 for the meaning of TAS and the difference from IAS.

Average Time Taken to climb 5000ft (figure 6)



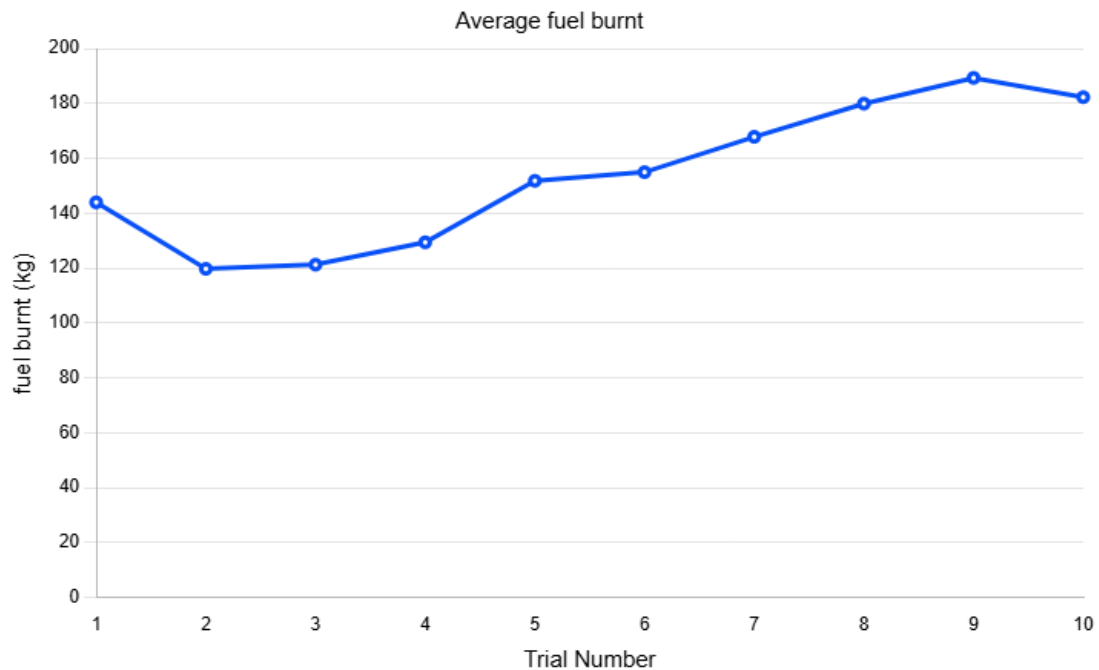
The graph above represents the mean time taken for the aircraft to climb 5000ft. A clear upward trend can be identified. The first few experimental trials have times between 80 seconds and 85 seconds however the later trials have a mean time taken of 120 seconds. This graph represents an upward trend for the time taken (y axis) as the experimental trial (mass configuration, x axis) increases.

Average Climb Rate (figure 7)



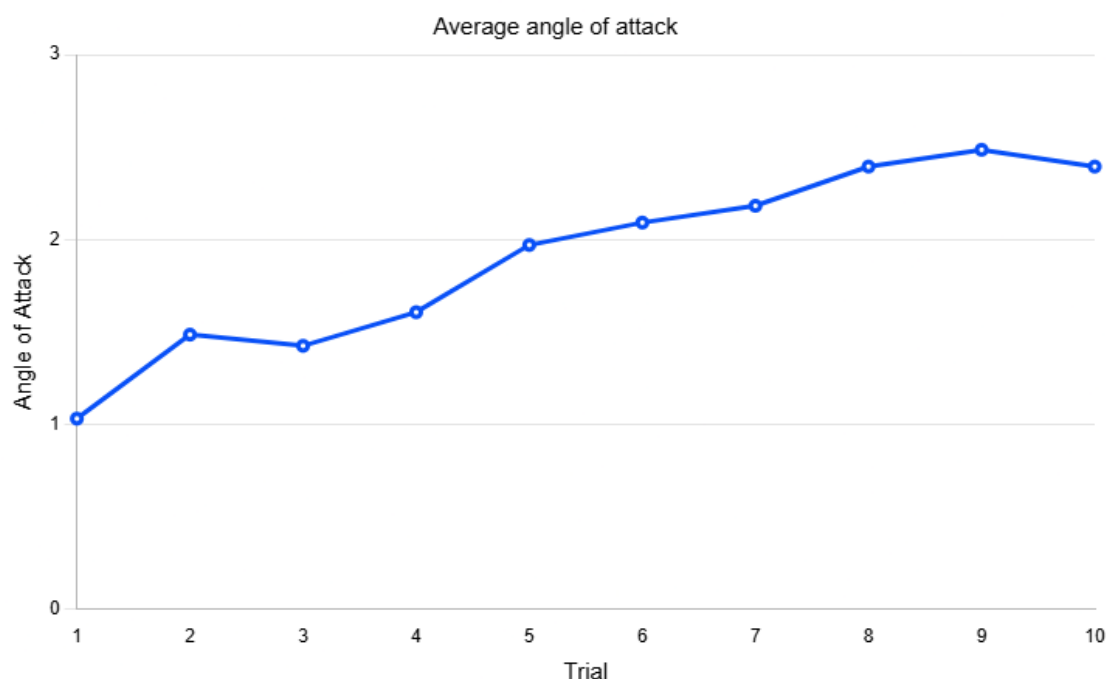
The graph above represents the mean climb rate across the different experimental trials and mass configurations. A downward slope can be identified proving that as the mass of the aircraft increases the rate of climb decreases. Across the 10 experimental trials the mean climb rate decreased considerably, by approximately 23.63%.

Average Fuel Burnt (figure 8)



The graph above represents the fuel burnt in the experimental trials. The fuel burnt is measured in kg. An upward trend can be identified from the graph, with the first trial having burnt ~140kg of fuel and the final trial burning ~180kg. The graph represents a substantial increase of fuel burnt at 26.63% increase from the first trial.

Average Angle of Attack (figure 9)



The graph above represents the mean angle of attack across the 10 experimental trials. An upward trend can be identified from the graph above. The mean angle of attack increases by 132.35% across the 10 experimental trials and 3 replicate tests per trial.

CONCLUSION

The data obtained from the experimental trials and replicate tests allows for analysis of the relationship between aircraft mass and flight performance. The analysis indicates that aircraft mass affects key flight parameters, including fuel consumption and rate of climb.

Across tests 1 – 8, the indicated airspeed and the true airspeed fluctuated with no apparent relation to mass. In tests 9 and 10 however, both indicated airspeed and true airspeed have an upward trend. This goes against the predicted relationship between mass of the aircraft and the velocity of the aircraft. However, across all of the tests, the rate of climb decreased and the time taken for the aircraft to climb 5000ft starting at an altitude of 5000ft generally increased. Alongside that the AoA of the aircraft increased across the tests. With the pitch angle approximately maintained at a constant of +5 degrees this resulted in the flight path angle to decrease. This explains why the aircraft speed fluctuated but the rate of climb decreased steadily. The decrease in flight path caused a greater proportion of the velocity to be directed in the horizontal vector direction rather than the vertical direction.

Across the tests the mean flow rate stayed consistent. This is consistent with the experimental control of the engine at 80% N1. However as the mass configuration of the aircraft increased the fuel consumed did as well. This is due to the increased time of flight as the fuel flow rate stayed the same, meaning not one flight would have consumed more fuel than the other if the time frame of the flight stayed constant in both tests.

A simple mathematical model to relate the rate of climb to the flight path angle to predict vertical speed is:

$$ROC \approx (V_{TAS} \times 1.68781) \sin(\theta - \alpha)$$

This mathematical model represents the kinematic relationship between the rate of climb and the speed of the aircraft. We multiply the vertical true airspeed by 1.68781 due to 1KT being approximately 1.68781ft/s

EVALUATION AND FUTURE WORK

Limitations:

There were many limitations in this research paper, mainly the fact that the data was collected from an aircraft simulator and not from real world evidence. Other limitations include manual data collection and limited experimental conditions. Also the N1% and pitch angle were held manually, due to human error mistakes may have occurred in the experimenting process.

Improvements:

To improve this research paper I would like to use more than one aircraft simulator to collect the data for my experiments and develop a more efficient way for data collection, and a method to maintain a pitch angle of exactly +5 degrees and an engine N1 of exactly 80%. As well as that more experimental trials should have taken place with more replicate tests to further drive out inconsistencies in the data recording.

Future Work:

In the future I would like to investigate the accuracy and error rate of the mathematical model I derived from the conclusion of my research paper. I would also like to make a mathematical model for the relation including aircraft fuel consumption.

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End of research paper