THE OHIO STATE UNIVERSITY

ME3503 – Fluid Mechanics

SP26 – Final Project

Group # 4

Team members:

- Aaditya Patil
- Travis Ross
- Ashvin Rajmohan
- Anthony Macali

Table of Contents

1. Team Member Roles

Aaditya Patil	Initial research of airfoil & aircraft/sketch (1a&1b)/Part III
Anthony Macali	Airfoil area, lift, and drag calculations & Part II CFD Simulations
Travis Ross	Introduction, Part 1(d&f), Part IV
Ashvin Rajmohan	Initial research of aircraft/ Final formatting

2. Introduction

This project focuses on the design and analysis of a subsonic mid-size private business jet. The goal is to apply concepts from fluid mechanics and aerodynamics to develop a realistic aircraft and see how it would perform under typical flight conditions. Important values like lift, drag, wing geometry, and propulsion were determined using standard equations along with data from similar aircraft. Using real-world data helped keep the design within a realistic range and made the results more meaningful.

The project also looks at how different design choices affect overall performance. Things like wing size, airfoil selection, and cruise conditions all play a role in how efficient the aircraft is. This helps connect what we've learned in class to how an actual aircraft might be designed and evaluated in the real world.

In Part I, the aircraft is defined and analyzed through airfoil selection, wing design, and drag estimation, which are then used to determine the required propulsion and overall performance. Part II focuses on a computational fluid dynamics (CFD) study of the selected airfoil and compares simulation results to published data. In Part III, the wing is analyzed structurally by modeling it as a cantilever beam under realistic loading conditions. Finally, Part IV evaluates fuel cost, efficiency, and emissions to better understand the practical impact of the design. Together, these sections provide a complete look at how the aircraft performs from both engineering and practical perspectives.

Part I: DESIGN OF AN AIRCRAFT

1a) Problem definition

We are designing a subsonic midsize private business jet (turbofan) intended to carry 6-8 passengers for medium ranged travel. A jet that shares the same airfoil and is similar to our concept is the Cessna Citation II Bravo. Calculations and dimensions will come from data relating to this airplane. (Aerospace Engineering and Ocean Engineering)

Parameter	**Assumption**
Type of Aircraft	Midsized private business jet
# of Passengers	6-8 Passengers
Propulsion Type	Dual turbofan engine setup
Liftoff Velocity	107 knots or 55.05 m/s
Cruising Velocity	390 knots or 200.6 m/s
Cruising Altitude	35,000ft – 43,000ft or 10,668m – 13,106.4m
Takeoff Weight Estimation	13,300lbs or 6000kg
Fuselage Length	42ft or 12.8m

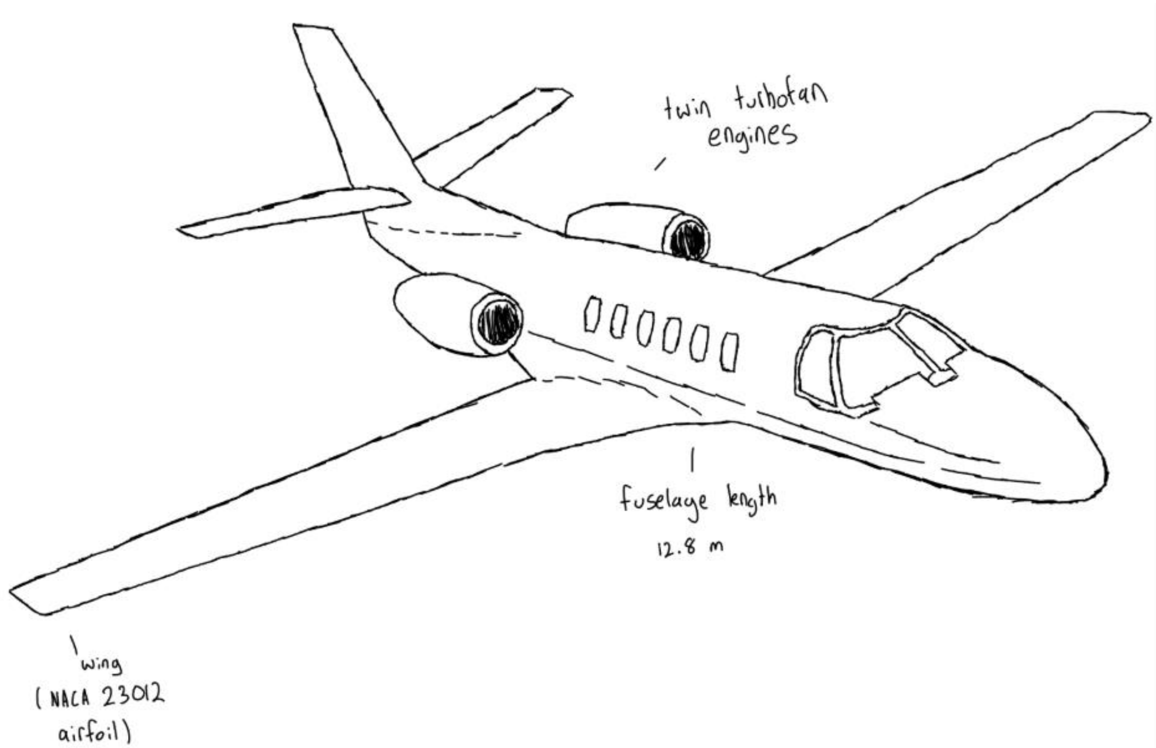

Figure 1: Sketch of Aircraft (Wings are pictured non-rectangular, in later design steps they are rectangular)

1b) Airfoil selection

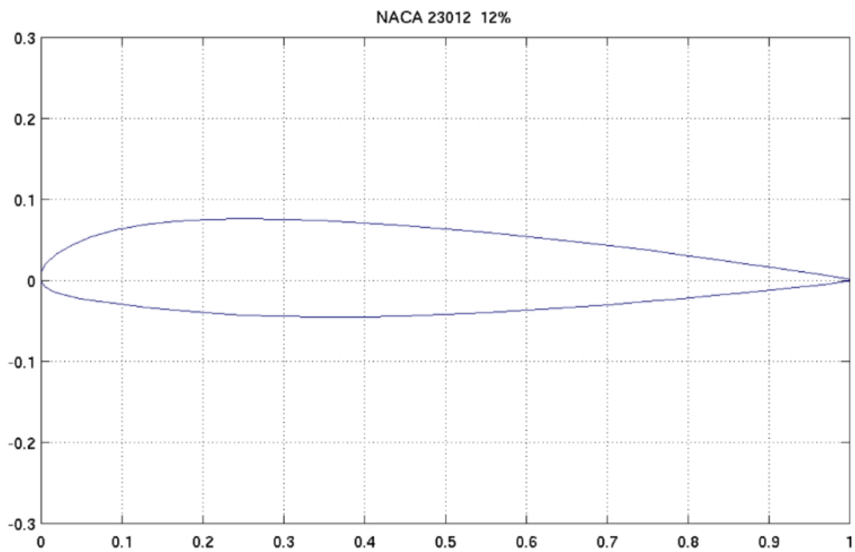

Figure 2: NACA 23012 Airfoil Geometry

The team decided to choose the **NACA 23012 Airfoil**. After doing extensive research, it became clear that business jets need an airfoil that excels at high-speed operation and high-altitude cruise efficiency. Midsized jets generally need an airfoil ranging from 12%-15% thickness and a relatively flat upper surface to minimize shockwave strength and delaying drag rise (Platt). Additionally, this airfoil needs to have a high maximum lift for shorter takeoff and landing at regional airports. The NACA 23012 meets all these criteria and is straightforward to model. As a bonus, this airfoil was actually the industry's flagship profile in the late 90s and early 2000s.

1c) Wing design

In the NACA report, we use airfoil data, air density, and gravity values that were provided, for consistency these values are used in our calculations. The standard density of dry air was given in an older unit standard, needing to be multiplied by gravity to be equivalent to the modern standard density units.

$$g = 9.80665\ \frac{m}{s^2}$$

$$\rho_{force} = 0.12497\frac{kgf * s^2}{m^4}$$

$$\rho = \rho_{force} g = (9.80665\ )(0.12497) = 1.22554\frac{kg}{m^3}$$

Using the estimated takeoff weight, a required lift is calculated below:

$$W = 6000kg$$

$$L = \ W * g = (6000)(9.80665) = 58839.9N$$

The angle of approach selected was chosen for its high coefficient of lift and its suitable gap from angles which would lead to stalling. From page 10 of NACA 23012 datasheet:

$$\alpha = 14^{\circ}$$

$$C_L\ @\ \alpha = 1.1$$

Area is solved for using the estimated takeoff velocity below:

$$V = 52.5\frac{m}{s}$$

$$A = \frac{2L}{C_L \rho V^2} = \frac{2(58839.9)}{(1.1)(1.22554)(55.05)^2} = 28.80495m^2$$

Similar aircraft to our design, including the Cessna Citation Bravo II use high aspect ratios. The structural challenges with longer wings increase costs, which is a reasonable design consideration for an aircraft in this luxury segment. A specific AR was chosen for an even wing length.

$$AR = 6.327$$

$$b = \sqrt{AR * A} = \sqrt{(6.33) * (28.80495)} = 13.5m$$

$$c = \frac{A}{b} = \frac{28.80495}{13.5} = 2.13371m$$

Overall, the wing design provides a reasonable first estimate for the required lifting surface of the midsize private business jet. Using the estimated aircraft weight, takeoff speed, air density, and selected lift coefficient, the required wing area was calculated so that the aircraft can generate enough lift during takeoff. The chosen wingspan and chord give the aircraft a practical rectangular wing approximation while still keeping the aspect ratio in a realistic range for a business jet. A higher aspect ratio helps improve aerodynamic efficiency by reducing induced drag, but it also creates greater structural challenges because longer wings experience larger bending moments. Because of this, the final wing dimensions represent a balance between lift generation, cruise efficiency, and structural practicality. In a real aircraft design, the wing would likely include taper, sweep, flaps, and a more detailed lift distribution, but this simplified model gives a strong first approximation for the aircraft's required wing geometry.

1d) Drag estimate

$$D = D_i + D_p$$

$$C_L = \frac{2W}{\rho V^2 S} = \frac{2(58839.9)}{(0.38)(200.6)^2(28.8)} \approx 0.3\ (rounded\ up)$$

$$C_{D_i} = \frac{C_L^2}{\pi e AR} = \frac{(0.3)^2}{\pi(0.85)(6.327)} = 0.0053$$

$C_{D_0} = 0.020$ (Zero-lift drag for typical subsonic business jets. Typically, 0.15-0.25)

$$C_D = 0.020 + 0.0053 = 0.0253$$

$$D = \frac{1}{2}\rho V^2 S C_D$$

$$D = \frac{1}{2}(0.38)(200.6)^2(28.8)(0.0253) \approx 5571N$$

The drag estimate shows that the aircraft would experience a realistic amount of resistance during cruise for a midsize private business jet. The total drag was estimated by combining the wing drag with the assumed fuselage drag, giving an approximate cruise drag of 5.6 kN. This value was then used later to estimate the power required for steady flight. The calculation is simplified because it treats the aircraft drag as a composite drag from major components rather than modeling every surface individually. It also relies on assumed drag coefficients and airfoil data, which means the result should be viewed as an engineering estimate instead of an exact value.

Induced drag would also affect the aircraft, especially during takeoff and climb when the lift coefficient is higher. At cruise, induced drag is usually lower because the aircraft flies faster and needs a smaller lift coefficient, but it still depends strongly on aspect ratio and wing efficiency. Overall, the drag estimate gives a useful first-order prediction of aircraft performance and helps connect the wing design to the propulsion requirement.

1e) Power requirement and propulsion estimate

The power required to maintain steady cruising can be calculated by the estimated drag forces found earlier, along with the cruise velocity. Since turbofan engines don't have perfect efficiency, an efficiency of 30% was assumed, which has been long proven to be a standard metric for midsized jets (NASA Glenn Research Center).

Power Needed

$D = Drag = 5571N$,

$$V = Cruise\,Velocity = 200.6\frac{m}{s}$$

$P = DV = 5571(200.6) = 1.118MW$

We must account for the efficiency of a turbofan engine:

Efficiency $\eta = 0.30$, so

$$P_{fuel} = \frac{P}{\eta} = \frac{1.12}{0.30} = 3.73MW$$

To solve for the propulsion estimate, we must use the equation: $\dot{m} = \frac{P_{fuel}}{h_{fuel}}$. The variable h_{fuel} is the lower heating value of typical jet fuel and is equal to $42.8\frac{MJ}{kg}$, so

$\dot{m} = \frac{3.73\times10^6}{43\times10^6} = \frac{0.0867kg}{s}$ or $312\frac{kg}{hr}$.

Based on these results, a twin turbofan engine setup proved to be ideal for our aircraft as it provides efficient high speed cruise performance and follows the trend for other business jets in this segment.

1f) Conclusions

The final aircraft design falls within a realistic range for a midsize business jet. The wing size, drag estimate, and overall performance are consistent with what would be expected for this type of aircraft, and the results suggest the design would work under typical flight conditions.

There are still some limitations due to the assumptions made in the calculations. Values such as air properties, drag coefficients, and lift distribution were simplified, so the results are more of an estimate than an exact prediction. In a real design process, more detailed analysis and testing would be needed. Even with these simplifications, the results give a solid first approximation and show how the concept from class can be applied to a real system.

Part II: CFD STUDY

In part II, an overview of CFD simulation methods and results used to obtain coefficients of drag and lift are given.

2g) Airfoil CFD simulation

An unstructured mesh was created using a triangular geometry with a first layer of thickness inflation to increase mesh fidelity at the boundary. This was included in obtaining more accurate separation results (Boehm et al.).

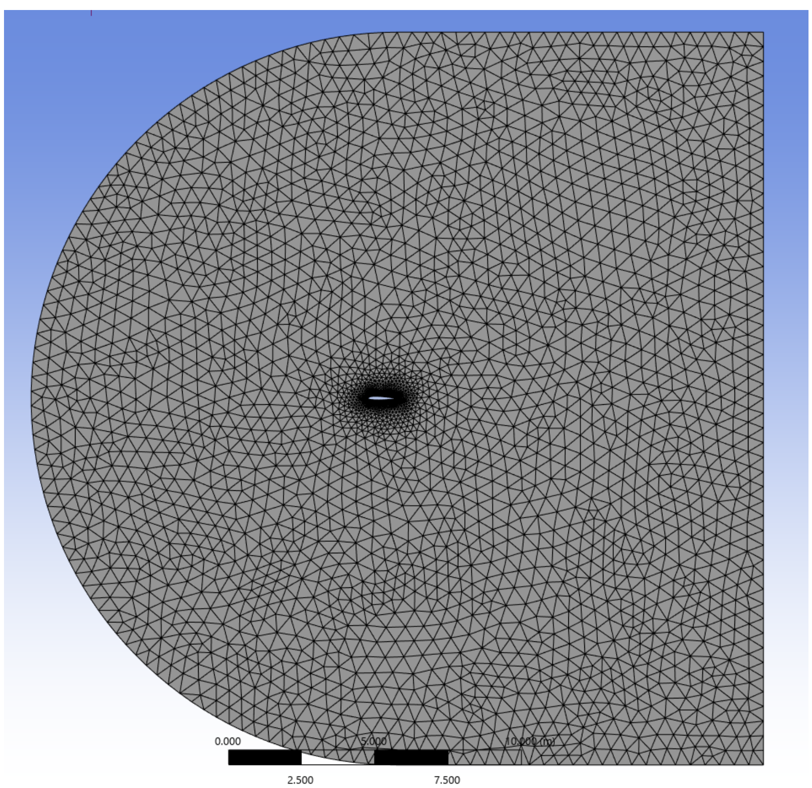

Figure 3: Mesh Overview

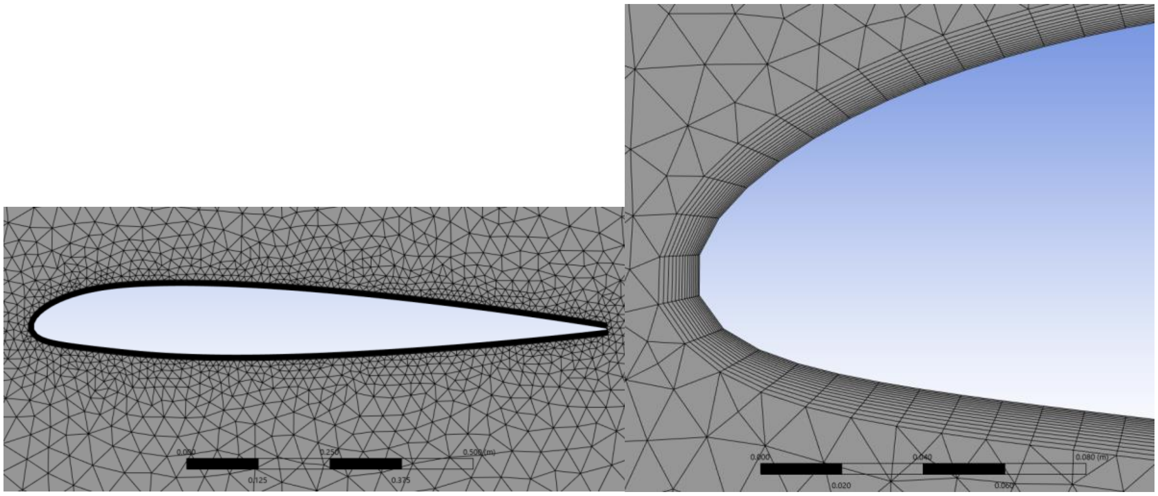

Figure 4: Zoomed Foil Boundary Mesh

Inviscid Simulations

For the Inviscid simulations, the x and y magnitudes corresponding to each angle of attack were calculated and rounded to the ten-thousandths place. Standard settings were used.

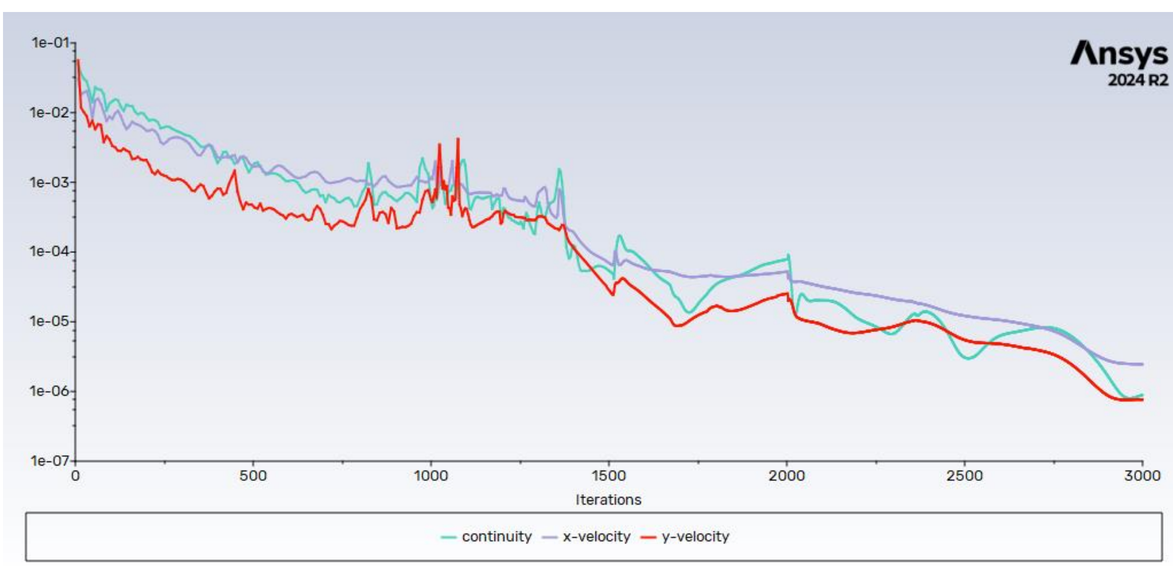

Figure 5: Inviscid 0 degree Simulation Convergence Plot

a=0 a=18

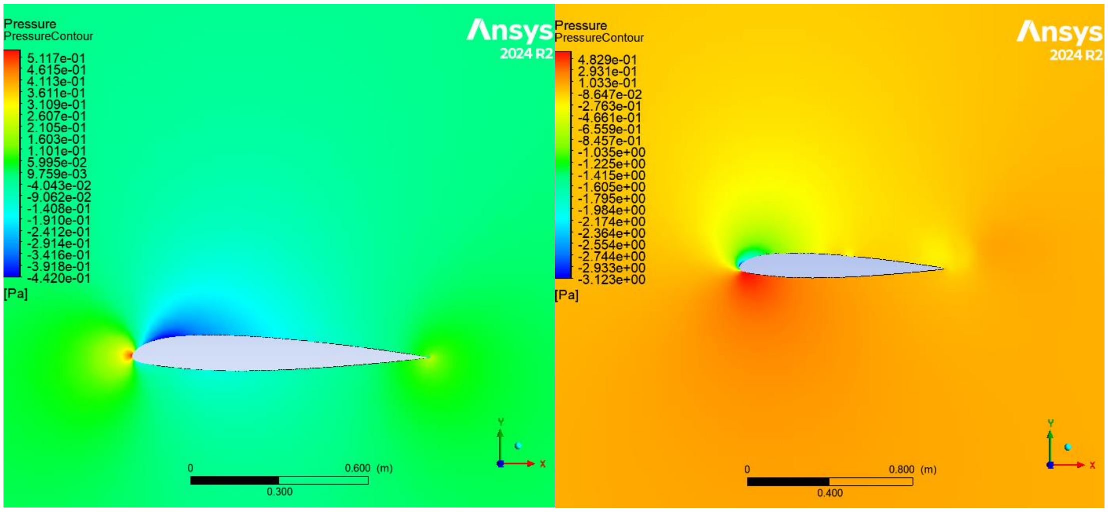

Figure 6: Inviscid Simulation Pressure contour plots for 0 and 18 degree angle of attack

a=0 a=18

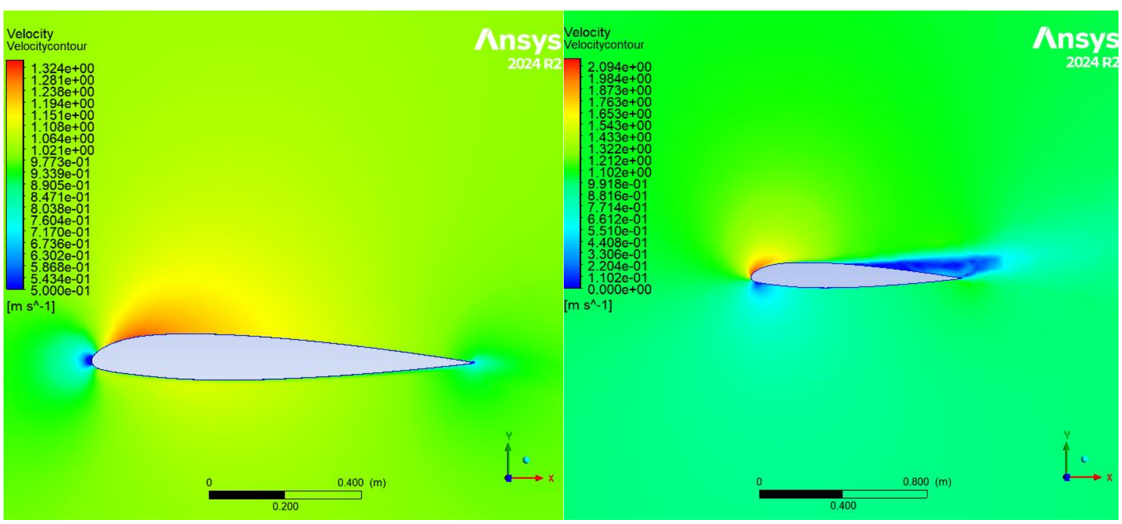

Figure 7: Inviscid Simulation Velocity contour plots for 0 and 18 degree angle of attack

a=0 a=18

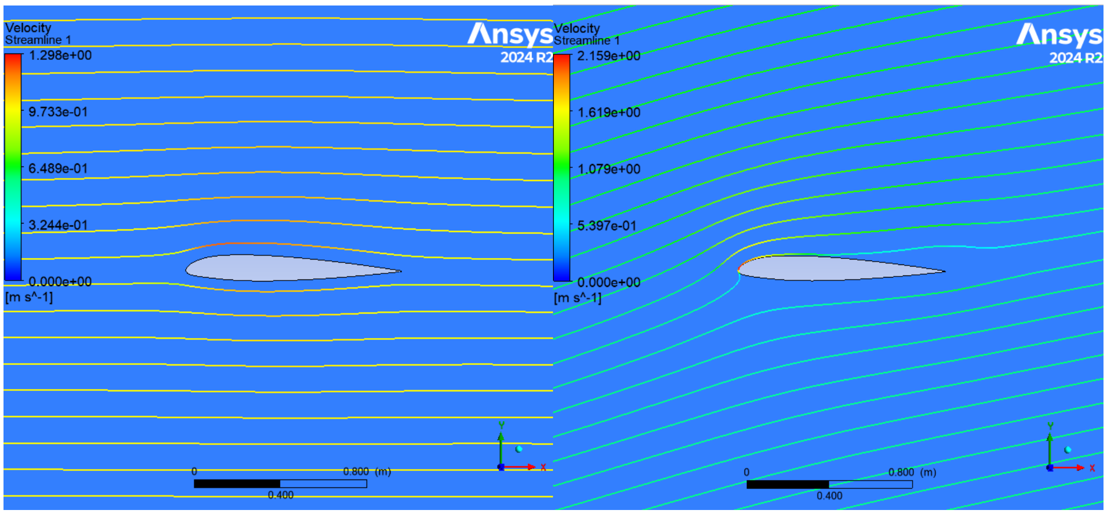

Figure 8: Inviscid Simulation Velocity Streamline plots for 0 and 18 degree angle of attack

	a=0	a=6	a=10	a=14	a=18
Cd	0.00333	0.006946	0.01697	0.051029	0.11479
Cl	0.1936	0.8453	1.1972	1.1648	1.1818

Table 9: Inviscid Simulation Coefficient Results

Viscid Simulations

For the Viscid Simulations, the SST-komega setting was chosen instead of Inviscid. Hybrid Initialization was also used with the automatic solved settings applied.

a=0 a=18

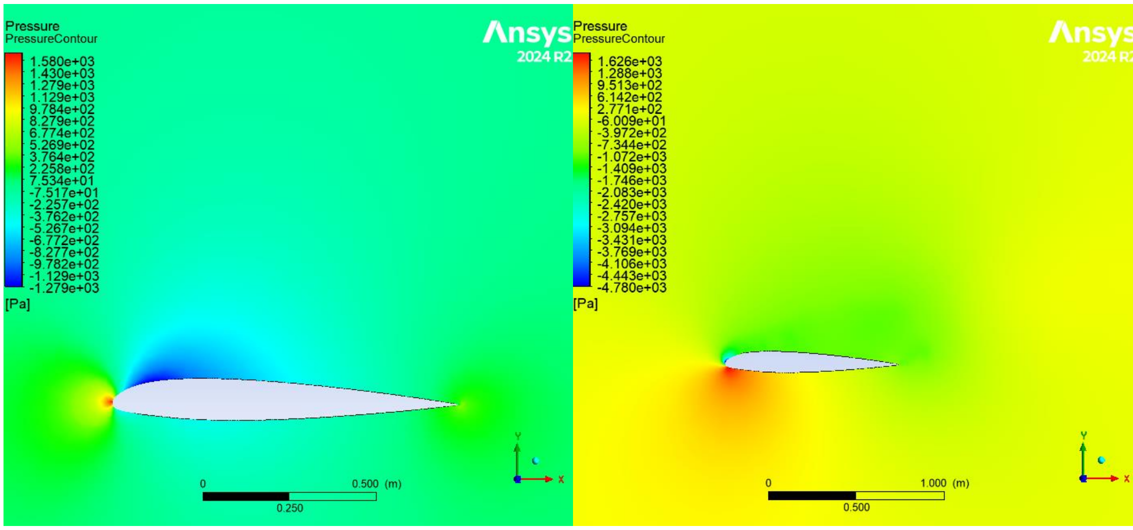

Figure 10: Viscid Simulation Pressure Contour plots for 0 and 18 degree angle of attack

a=0 a=18

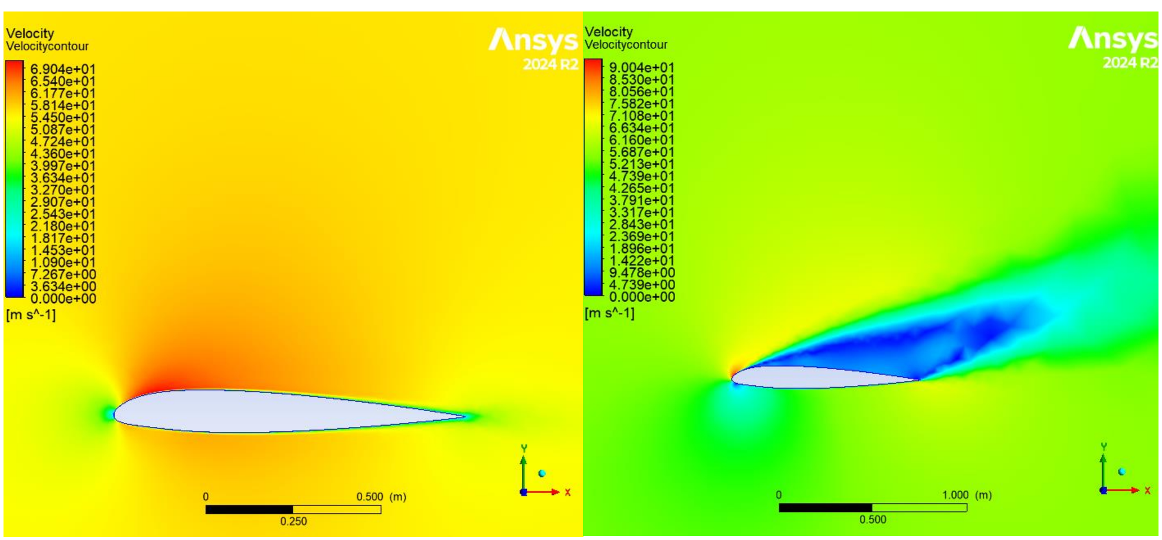

Figure 11: Viscid Simulation Velocity Contour plots for 0 and 18 degree angle of attack

a=0 a=18

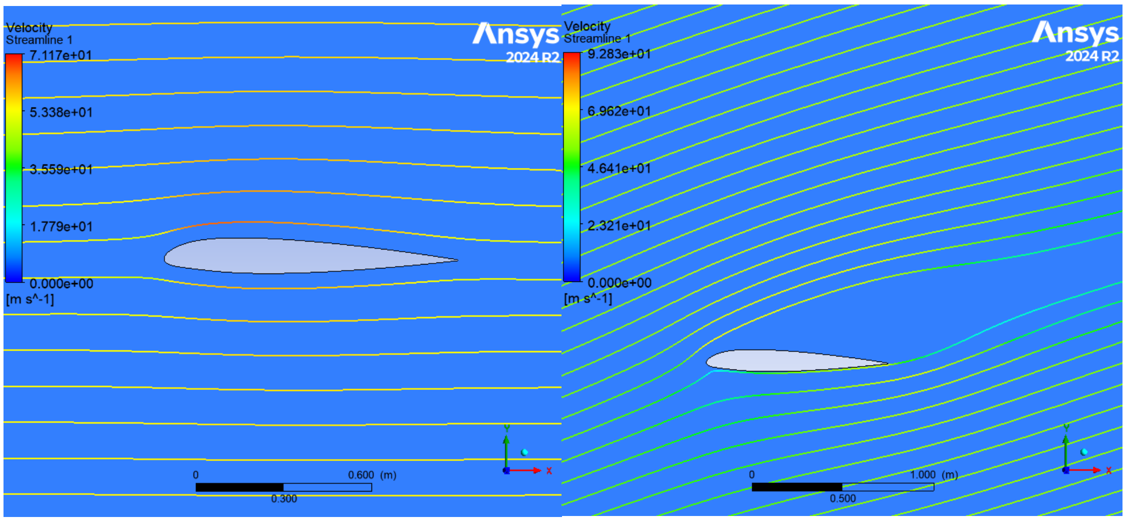

Figure 12: Viscid Simulation Velocity Streamline plots for 0 and 18 degree angle of attack

	a=0	a=6	a=10	a=14	a=18
Cd	0.010266	0.014824	0.027327	0.10892	0.21103
Cl	0.1664	0.7827	1.1056	0.8749	0.7662

Table 13: Viscid Simulation Coefficient Results

Results

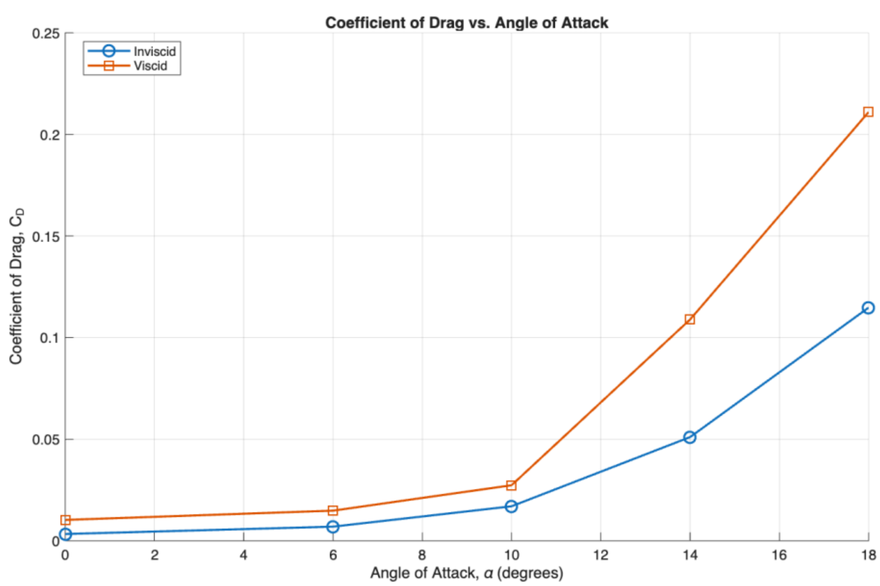

Figure 14: Coefficient of Drag vs angle of attack plot for Inviscid and Viscid Simulations

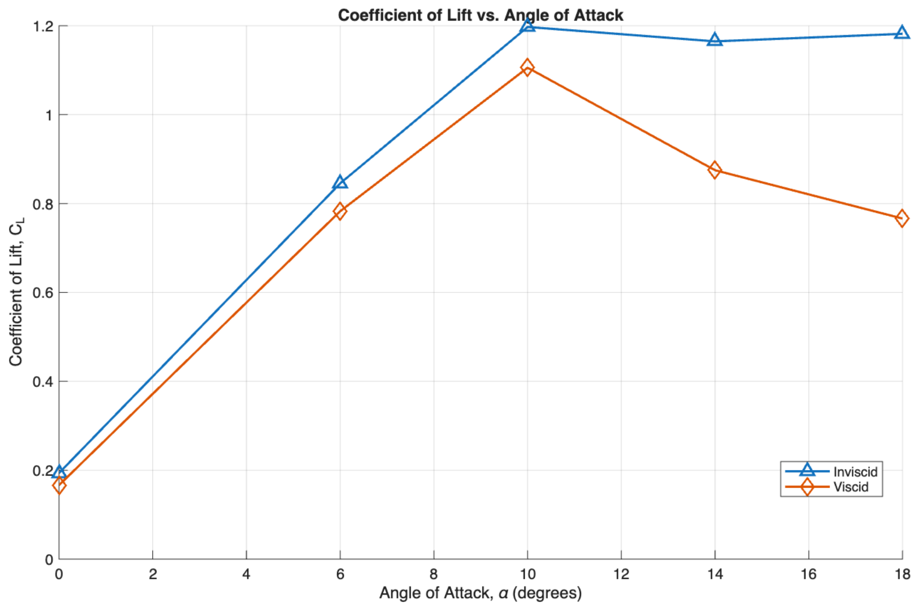

Figure 15: Coefficient of Lift vs angle of attack plot for Inviscid and Viscid Simulations

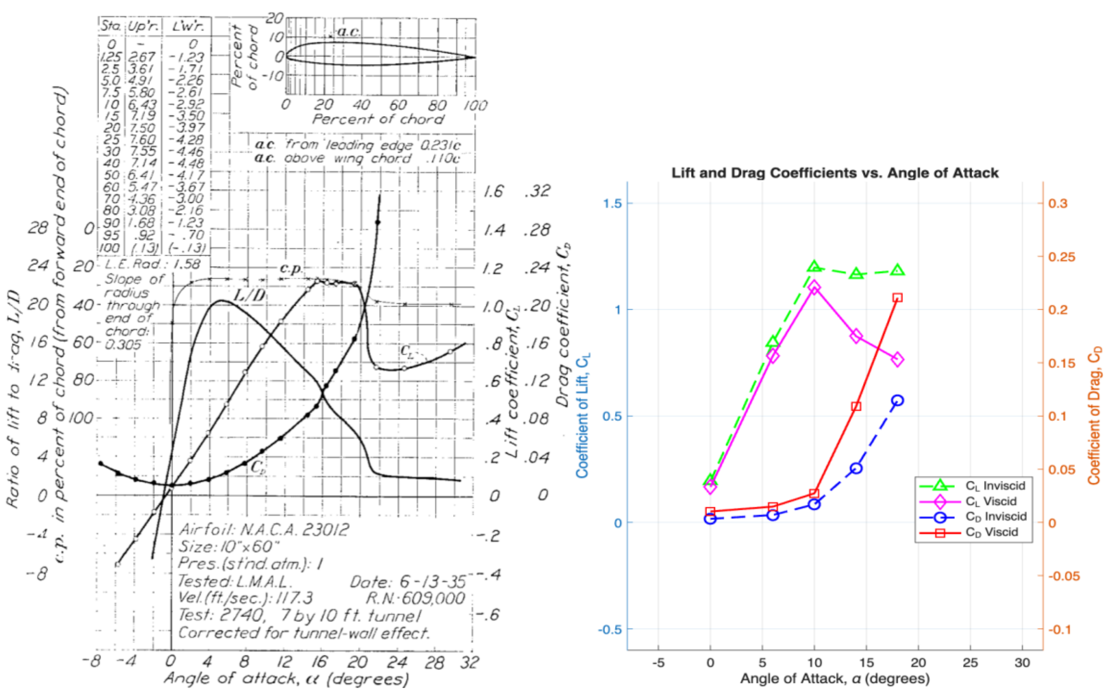

Figure 16: NACA Testing compared to CFD Simulated Coefficient Data

The Viscid Simulation coefficient of drag was very close to the tested NACA results, whereas the Inviscid simulation trended similarly, but was overall different. The coefficient of lift results were partially accurate, with close values on some of the Viscid data. In general, the CFD simulation results would be expected to differ from tested NACA airfoil results due to simplifications in the simulation setup and differences from real experimental conditions. The viscid simulation should better match the tested results because it accounts for fluid friction and boundary layer effects, while the inviscid simulation neglects viscosity, causing larger differences in drag and sometimes lift trends.

Part III: ENGINEERING WILD CARD

In Part III, the team conducted a structural analysis of the jet wing to determine its ability to withstand the loads of realistic flight conditions. To do this, the wing was modeled as a cantilever beam that is fixed to the fuselage, with load conditions present based on flight factors that apply an assumed load factor. Our analysis included step by step calculation of distributed lift load along the span, while also making sure to include fuel weight relief within the wings, a common feature of many business jets in this segment. The team then determined the maximum bending stress at the wing root by finding the resulting shear forces and bending moments. This value is then compared to the yielding strength of a typical aluminum alloy to see if the structural integrity of the wing can hold up to the proposed design with an adequate factor of safety (Federal Aviation Administration).

3h) Wing Structural Analysis Under Simplified Flight Conditions

Assumptions & Given Values:

- Maximum Takeoff Weight: 6000 kg
- Wingspan: 52 ft or 15.85 m
- Fuel Capacity: 4,824 lb or 2188.13 kg
- Load factor (estimated): n=2.5 (maneuver & gust loading) (Yaji Aluminum)
- Engine mounted on fuselage, so no wing-engine load assumed
- Fuel weight: fuel is partly stored in wings, reduces upward bending
- Cantilever wing setup, each wing fixed at fuselage

- Each wing is a simplified aluminum wing box

Total Aircraft Weight: $W = mg = 6000(9.8) = 58{,}800N$

Total Aircraft Load: $L_{total} = nW = 2.5(58000) = 147{,}000N$

Since each wing carries half the load $L_{wing} = \frac{147{,}000}{2} = 73{,}500N$

Our L value is $\frac{b}{2} = \frac{13.5}{2} = 6.75m$

To calculate for the upward lift load, $w_L = \frac{L_{wing}}{L} = \frac{73{,}500}{6.75} = 10{,}888.9\frac{N}{m}$

After doing extensive research on midsized private jets, we discovered that they generally store a variable amount of fuel in their wings, for this application let's assume that value is approximately 60% of the fuel weight (AN Aviation Services). We used criteria from the Cessna Citation II Bravo to get an understanding of how much weight fuel makes up in the jet – around 2,204kg.

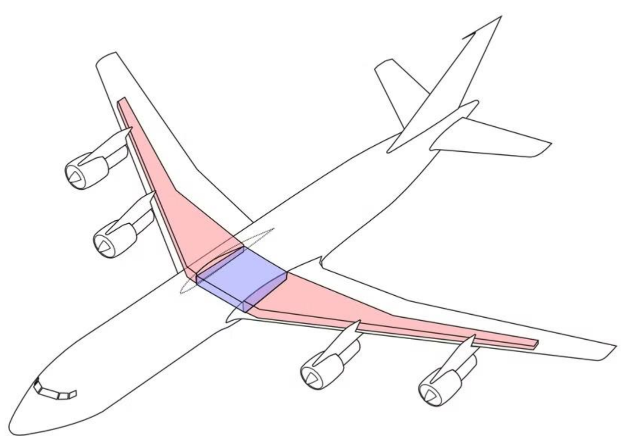

Figure 17: Example of fuel storage in wings (not our specific prototype)

So, the determined weight is $W_{fuel} = 2{,}204(9.8) = 21{,}599.2N$

If 60% is stored in the wings, $W_{fuel,\,wings} = 0.60(21{,}599.2) = 12{,}959.5N$.

This means that each wing has a weight of fuel of $6{,}479.8N$

Using our L value, the distributed fuel load is $w_f = \frac{6479.8}{6.75} = 959.97\frac{N}{m}$

This means that the net distributed load is $w_{net} = w_L - w_f = 10{,}888.9 - 959.97 = 9{,}928.9\frac{N}{m}$

With this value, we can calculate the shear force in the wings, $V = w_{net}L = 9{,}928.9(6.75) = 67{,}020.3N$

And then solve for the bending moment in each wing, $M = \frac{w_{net}L^2}{2} = \frac{9928.9(6.75)^2}{2} = 226.192.8N \cdot m$

The equation for our bending stress is $\sigma = \frac{Mc}{I}$.

Since the c and I values can't be exactly determined, we must approximate them.

We know that c is the distance from the neutral axis to the outer fiber, so using our chord value of 2.13m and airfoil thickness of 12%, we can calculate the actual thickness to be $t = 0.12(2.13) = 0.256m$

$$t = 0.12(2.13) = 0.256m$$

The neutral axis is $c = \frac{t}{2} = \frac{0.256}{2} = 0.13m$, but we used $0.15m$ for a more conservative estimate.

For I, the moment of inertia, we can use a rectangular wing box estimate which is a common simplification for this sort of application due to manufacturability simplicity. The formula is $I = \frac{bh^3}{12}$, where $b = width = 1.5m$ and $h = thickness = 0.25m$

Thus, $I = \frac{(1.5)(0.25)^3}{12} = 0.002m^4$.

Our final calculated bending stress ended up being $\sigma = \frac{(226{,}192.8)(0.15)}{0.0025} = 13.57MPa$

After ample research of aluminum alloys, we determined the yield strength to be $\sigma_y = 276MPa$.

This brings our factor of safety to: $\frac{\sigma_y}{\sigma} = \frac{276}{13.57} = 20.3$

Since the process of finding exact structural specifications of an aircraft is very difficult given the information we have on our jet, the team opted for a first-order approximation to estimate wing loading. A load factor of 2.5 was used to replicate maneuver and gust conditions, a constant that is compliant with the Code of Federal

Regulations. Assuming the wing was a cantilever beam, and had a simplified internal structure, the calculated factor of safety was much higher than standard practices. Since real aircraft wings experience complex loading, non-uniform lift distribution, and specific structural effects, a more accurate analysis would require the use of detailed geometry architecture for the wing structure and finite element analysis software.

Part IV: NON-ENGINEERING WILD CARD

In Part IV, the team evaluated the economic and environmental impact of the proposed aircraft design. This analysis focuses on operating costs, efficiency per passenger, and environmental considerations associated with fuel consumption.

Economic and Environmental Analysis of Aircraft Operation

Using the drag force calculated in Part I and the cruise velocity of the aircraft, the propulsion power required to maintain steady cruise can be determined from:

$$P = D \cdot V = (5571) \cdot (200.6) = 1.12MW$$

Since turbofan engines are not 100% efficient, we assumed the efficiency of:

$$\eta = 0.30$$

This falls within the average range of typical values for subsonic jet engines. The required fuel power is then calculated as:

$$P_{fuel} = \frac{P}{\eta} = \frac{1.12}{0.30} = 3.73MW$$

Using a standard jet fuel density of: (U.S. Energy Information Administration)

$$h_{fuel} = 43 \frac{MJ}{kg}$$

The fuel mass flow rate can be calculated:

$$m_{dot} = \frac{P_{fuel}}{h_{fuel}} = \frac{3.73}{43} = 0.0867\ \frac{kg}{s} = 312\ \frac{kg}{hr} \approx 688\frac{lb}{hr}$$

Converting this to a volumetric flow rate gives us:

$$\rho_{fuel} = 6.7\ \frac{lb}{gal}$$

$$V_{dot} = \frac{688}{6.7} = 103\ \frac{gal}{hr}$$

Assuming an average fuel cost of: (Engineering ToolBox)

C_{fuel} = \$6.00/gal

The estimated operating cost is:

$Cost_{hr} = (103) \cdot (6.00)$ =\$618/hr

Cost per Passenger-Mile

Using the cruise speed of the aircraft:

$$V = 390\ \frac{nmi}{hr}$$

The cost per distance traveled can be calculated as:

$$Cost\ per\ mile = \frac{618}{390} = 1.58$$

For a passenger capacity of 6–8 passengers, the cost per passenger-mile is:

$Cost_6 = \frac{1.58}{6} = 0.26$ *$/passenger-mile*

$Cost_8 = \frac{1.58}{8} = 0.20$ *$/passenger-mile*

Emissions Estimate

The environmental impact of the aircraft can be estimated using the carbon dioxide emission factor for jet fuel (SKYbrary Aviation Safety):

$$EF = 9.57\ \frac{kgCO_2}{kg\ fuel}$$

Using the previously calculated fuel consumption rate:

$$m_{dot} = 312\ \frac{kg}{hr}$$

The CO_2 emissions are:

$$m_{dot(CO_2)} = (312) \cdot (9.57) = 2985 \frac{kg}{hr} \approx 3.0\ metric\ tons\ \frac{CO_2}{hr}$$

Comparison to Similar Aircraft

Typical midsize business jets, such as the Cessna Citation Bravo (burn rate of 700-800 lb/hr), typically operate with fuel burn rates in the range of:

$$600 \leq m_{dot} \leq 1000\ \frac{lb}{hr}$$

Comparing this to our calculated fuel consumption of:

$$m_{dot} = 688\ \frac{lb}{hr}$$

This falls within this range, indicating that the assumptions and calculations used in this design are reasonable and consistent with industry data. However, due to the smaller passenger capacity, emissions per passenger remain higher compared to commercial aircraft.

Sustainability Tradeoffs

The proposed aircraft offers advantages in speed, flexibility, and accessibility to smaller airports, making it well-suited for business and private travel. However, these benefits come at the cost of reduced environmental efficiency.

Because the aircraft carries only 6–8 passengers, the fuel consumption and emissions per passenger are significantly higher than those of commercial airliners. This creates a tradeoff between operational convenience and environmental impact.

Potential improvements to reduce environmental impact include:

- Use of sustainable aviation fuels (SAF)
- Increased turbofan efficiency
- Using lightweight materials
- Improving aerodynamic performance

While these advancements can reduce emissions, they often introduce higher costs and additional design complexity.

Conclusion

Overall, the aircraft falls within a realistic range for both cost and fuel consumption when compared to similar midsize business jets. Increasing the number of passengers improves cost efficiency, but the overall operating cost is still relatively high due to fuel consumption.

From an environmental standpoint, the emissions per passenger remain high because of the limited passenger capacity. This highlights the tradeoff between convenience and environmental impact that comes with private aviation, especially when compared to commercial air travel.

REFERENCES

Aircraft Owners and Pilots Association. *Cessna Citation II/Bravo Performance Data*. AOPA, https://www.aopa.org/news-and-media/all-news/2015/february/05/t_ql

Engineering ToolBox. *Fuels – Higher and Lower Calorific Values*. Engineering ToolBox, https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

"Fuel Capacity Specifications of Cessna Citation II Bravo." *Wikipedia*, https://en.wikipedia.org/wiki/Cessna_Citation_II

"Fuel Storage in Wings to Offset Upward Lift Forces." *Aero Analysis*, https://an.aero/why-is-fuel-stored-in-the-wings-of-aircraft/

SKYbrary Aviation Safety. *Jet Fuel Properties*. SKYbrary, https://skybrary.aero/articles/jet-fuel

U.S. Energy Information Administration. *Carbon Dioxide Emissions Coefficients*. https://www.eia.gov/environment/emissions/co2_vol_mass.php

U.S. Government. *Code of Federal Regulations, Title 14, Part 25 – Airworthiness Standards*. Electronic Code of Federal Regulations, https://www.ecfr.gov/current/title-14/chapter-I/subchapter-C/part-25/subpart-C

"Yield Strength of Aluminum." *Yajia Aluminum*, https://yajialuminum.com/yield-strength-of-aluminum/