Aero 481 - Aircraft Design
Critical Design Report

University of Michigan – Ann Arbor
Sabrewing Inc., Team 5

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List of Acronyms

Angle of Attack (AoA)
Center of Gravity (CG)
Maximum Takeoff Weight (MTOW)
Static Margin (SM)
Direct Operating Cost (DOC)

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1 Executive Summary

This design report contains the critical design of Sabrewing Inc S505 jet transport aircraft. The following sections provide details into the S505's philosophy, design, and expected performance.

1.1 System Overview

The S505 meets all requirements set forth by the project specification. It is designed to carry 220 passengers in a two class configuration, with 16 passengers in Business Class and 204 passengers in Economy Class. The aircraft will be crewed by 2 pilots and 5 flight attendants, and it will accommodate enough payload to carry 60 lbs of luggage for each passenger and crew member. The S505 features a conventional twin engine, narrow-body design that is proven to be reliable for this size of aircraft. The aircraft is powered by two Pratt and Whitney PW1133G-PM geared turbofan engines and is capable of storing enough fuel to travel up to 4,800 nautical miles.

1.2 Discriminating Technologies

To reduce the DOC of the S505 we've employed several technologies that either reduce our structural weight or drag in flight. Each of these technologies, as seen in Figure 1, are described in detail within this report.

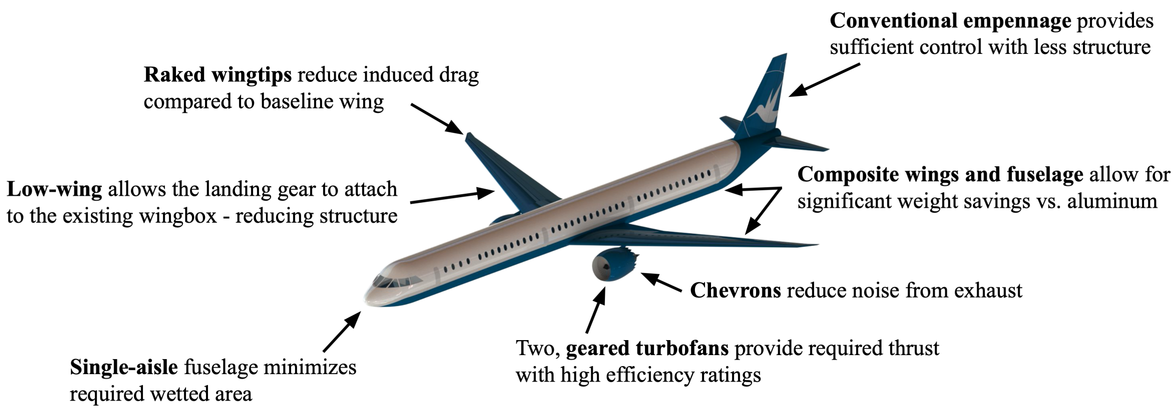
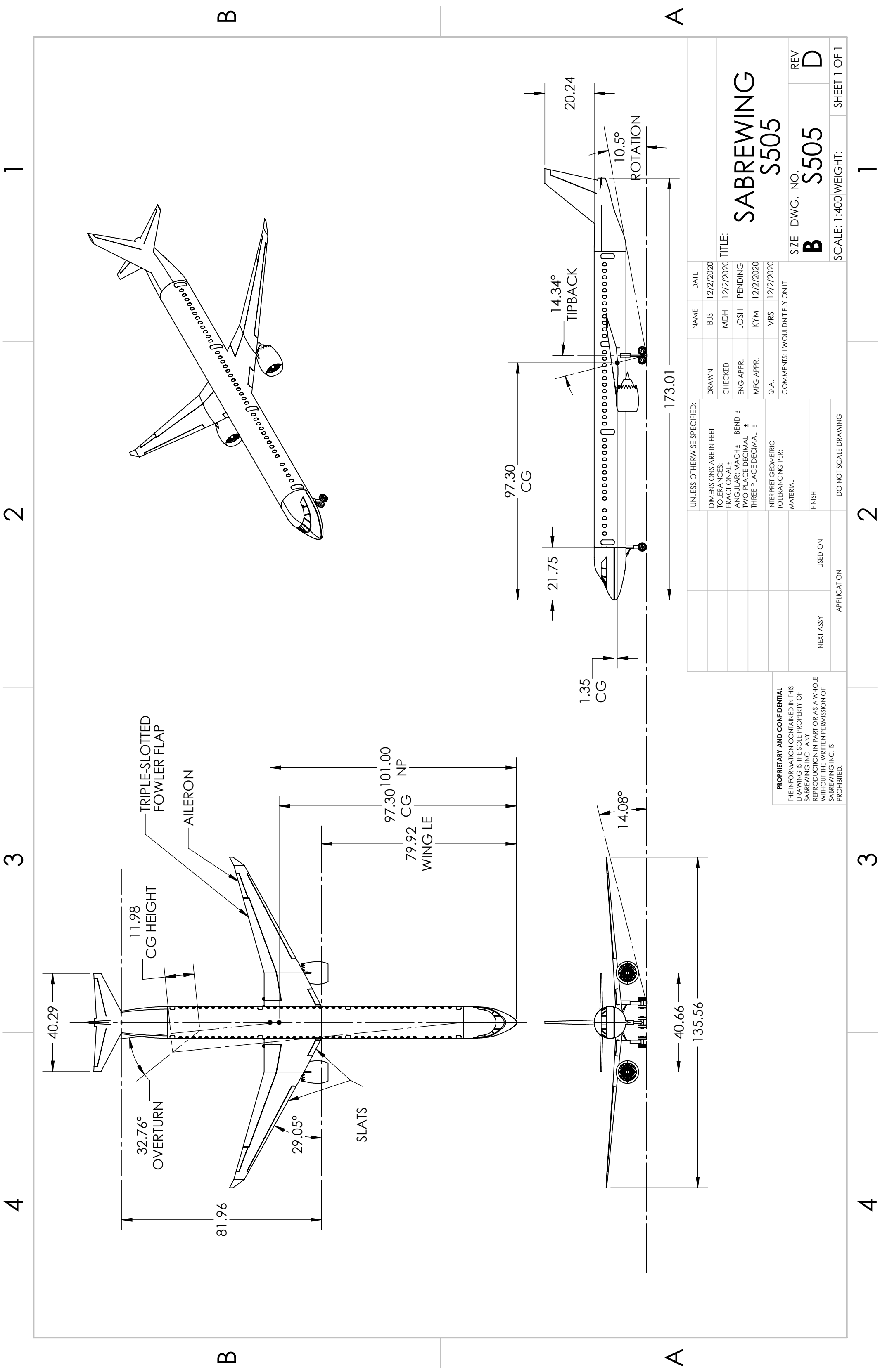


Figure 1: The S505's discriminating technologies work to reduce DOC

Notably, while the S505 features a conventional design that has been the standard for decades, it also utilizes a full composite construction which enable better rigidity and is considerably lighter than traditional manufacturing materials, such as steel or aluminum. The wings, tail, and fuselage will be constructed of composite materials. This inspiration comes from the Boeing 787 Dreamliner series, which uitlizes a single piece composite fuselage, and the Boeing 777X, which incorporates fully composite wings.

2 Dimensioned Three-View Drawing (MTOW Configuration)



3 Key Geometric and Performance Parameters

Parameters	S505	737-900	A320neo	757-200
MTOW (lbs)	228,404	194,700	174,165	255,000
W_e (lbs)	112,878	93,700	93,035	130,440
Payload (lbs)	13,620	20,240	44,974	56,637
$C_{L Cruise}$	0.7	–	–	–
$C_{L Landing}$	3.0	–	–	–
$C_{L Takeoff}$	2.83	–	–	–
T/W	0.28	0.3	0.31	0.32
W/S $\frac{lbs}{ft^2}$	138	142.1	132.2	127.9
Engine Type (x2)	PW1133G-PM	CFM LEAP-1B	CFM LEAP-1A	RB211-535E4B
Max SL Thrust (lbs)	66,220	58,600	54,240	80,200
SFC ($\frac{lb}{lbf\ hr}$)	0.47	0.53	0.53	0.38
Span (ft)	132.6	117.8	117.5	124.8
S (ft^2)	1,750	1,370	1,317.5	1,994
AR	10.50	10.13	10.48	7.81
t/c average	10.8	–	–	–
M_{cruise}	0.801	0.79	0.78	0.8
Max Range (nmi)	4,800	3,550	3,400	3,900
R_{max} Fuel Burn (lbs)	61,046	45,913.5	47,862.4	88,603.8
No. Passengers	220	193	190	200
Static Margin (cruise)	15-19% MAC	–	–	–
Landing Distance (ft)	5,086.9	5,445.1	4,489.7	5,820.2
Takeoff Distance (ft)	8,526.9	9,700	7,645.1	8,799.2

Table 1: Major geometric and performance parameters for the S505 and comparable aircraft.

4 Design Overview

4.1 Mission Introduction

Sabrewing Inc. has been tasked with developing a clean-sheet aircraft to replace Boeing's 737 family in the year 2027. This aircraft is aimed at matching the performance of the Airbus A321XLR while flying with a lower DOC. The new aircraft must transport 220 passengers and 7 crew members. These passengers will be split into a two-class configuration: 16 in business class, and 204 in economy class. Additionally, the aircraft must carry luggage for all 227 people onboard. To compete with the A321XLR, the aircraft must have a maximum range of 4800 nmi and be able to fly between DTW and FCO. The aircraft must comply with Part 25 of the Federal Aviation Regulations (FAR); it must also carry enough fuel to satisfy longest flight and reserve requirements. Finally, we are allowed to use the NextGen initiative mission profile (Appendix E) to take advantage of fuel savings during an optimized climb.

4.2 Configuration

Sabrewing has elected to create a plane that meets all of the design requirements and matches the performance of the Airbus A321XLR. This aircraft has been designated the Sabrewing S505; a brief overview of the aircraft can be seen below in Figure 2. The current configuration of this aircraft is a twin engine, conventional tailed, narrow body composite fuselage, with composite wings.

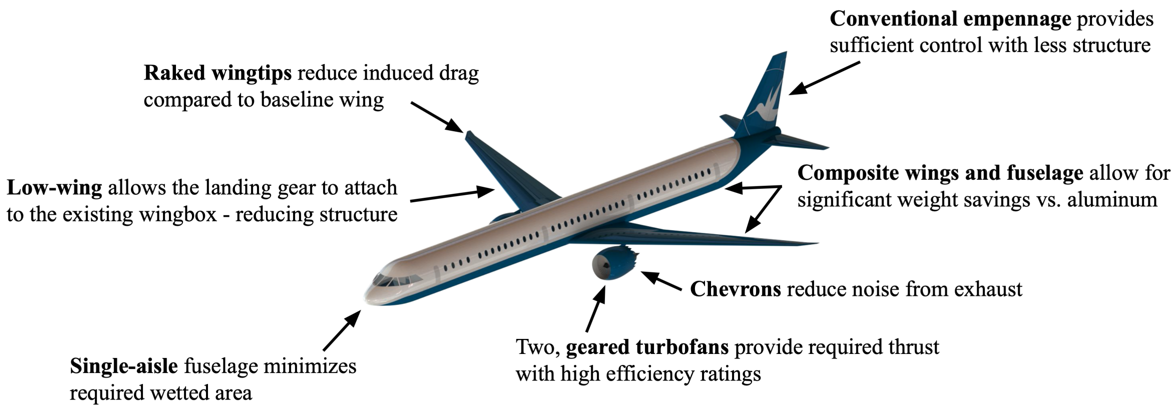


Figure 2: The S505's discriminating technologies work to reduce weight and drag in flight.

Many of the technologies implemented on the S505 were implemented on the basis that they lowered our DOC by either reducing drag or structural weight. We implemented the use of raked wingtips as we found that they lowered our induced drag for our AVL model (Section 6.3). A low-wing configuration allows our landing gear to attach to the existing wing-box structure - reducing the structural requirements to support it. Later discussed in Section 5.2, we chose a single-aisle configuration as we found it yielded a lower wetted area compared to aircraft carrying a similar amount of people. We chose to use geared turbofans to take advantage of their higher efficiency, thus lower fuel weight requirements. Finally, we decided to use a composite structure to comprise our fuselage and wings as these are becoming standard technologies on newer planes such as the Boeing 787, 777X, and Airbus A350. From investigating the uses of composites in Raymer, we found that we were able to apply weight saving "fudge factors" that reduces our structural weight significantly compared to a aluminium structure [2].

5 Detailed Design Description

The following sections provide a detailed description on the design of the S505, and will go over the lifting surface sizing, fuselage design, interior layout, and other major design features.

5.1 Refined Sizing

The following subsections discuss the sizing methods and results that we used to refine the design of the S505.

5.1.1 Estimation of Takeoff Weight

To automate the initial weight estimation process, which is integral to the final sizing calculations, we created a program that uses a weight convergence algorithm to compute the component weight breakdown and fuel fractions for our given mission parameters (passenger/payload requirements, range, etc.). This function calculated all the component weights based on fuselage size, wing area, and thrust to compute an empty weight, and then used the convergence algorithm to calculate weight fractions. The takeoff gross weight calculated using this algorithm is 228,404 lbs. This algorithm is discussed in detail in Section 7.1.

5.1.2 T/W - W/S Plot

Knowing an estimate of our MTOW, we then moved on to determining a range of feasible configurations for a plane of our size. To help make this decision, we chose the following flight constraints that we knew the S505 must satisfy: takeoff, cruise, takeoff climb, transition climb, second climb, enroute climb, all-engines-operative climb, one-engine-inoperative climb, ceiling, and landing. Specifically, by determining the required thrust-to-weight ratios (T/W) for these segments of flight as a function of wing loading (W/S), we can plot them on a single plot. The combinations of (T/W) and (W/S) that lie above the flight segment constraint lines correspond to a feasible combination of thrust-to-weight and wing loading.

The MATLAB script `final_sizing.m` was again used to accomplish this task. Details of its computation can be seen in Section 8. Each flight segment constraint line was calculated using the corresponding formulas for each found in the Chapter 4 of the Aircraft Design Metabook [3]. Figure 3 shows the final T/W vs W/S plot. The light green area corresponds to a feasible design space, where respective combinations of T/W and W/S will satisfy ALL constraints.

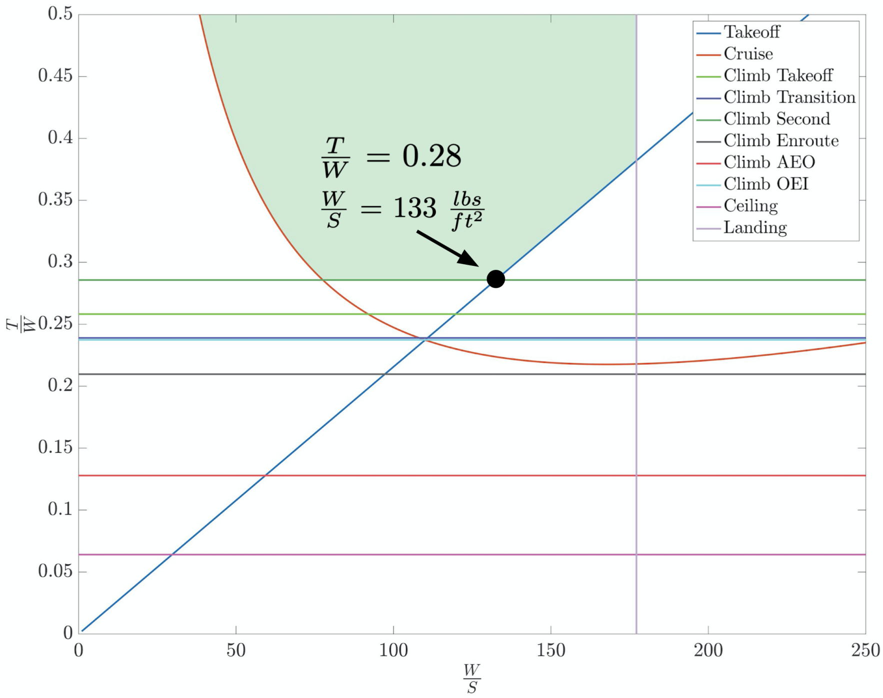


Figure 3: T/W vs W/S plot shows that the S505's design point is within the feasible region

In choosing our design point we decided to maximize our W/S and minimize our T/W. Maximizing our W/S has the benefit of reduced drag, weight, and cost. Minimizing our T/W decreases our engine size, and therefore engine weight. As seen above, our chosen design point corresponded to a T/W $= 0.28$ and a W/S $= 133\frac{lbs}{ft^2}$.

5.1.3 T-S Plot

Similarly to PDR, we transformed our T/W vs W/S plot into a dimensioned T vs S plot. Besides providing more insight into the required thrust and wing area, this approach will allow us to overlay objective functions and choose a design point that is both feasible and optimal for our objective.

To this end, the constraint lines from `final_sizing.m` were modified from T/W constraints to thrust constraints. Chapter 4, Section 12 of the Aircraft Design Metabook [3] provided us with specific equations to properly convert T/W vs W/S constraints into T vs S space. Algorithm 4, seen in Appendix B, provides the outline for converting these constraints and was implemented into `final_sizing.m`. At its core is a refined weight estimation function that takes into account significantly more details compared to the initial weight estimation steps seen in PDR. Specifically, our weight is now comprised of multiple components, such as the engines, wings, fuel, and tail surfaces - dependent on the total wing area. Computational details covering the MATLAB functions and inputs can be found in Section 8. Finally, a contour plot of our objective function of Direct Operating Cost (DOC), details of its computation seen in Section 5.1.4, was overlayed on top of our T vs S plot, seen in Figure 4.

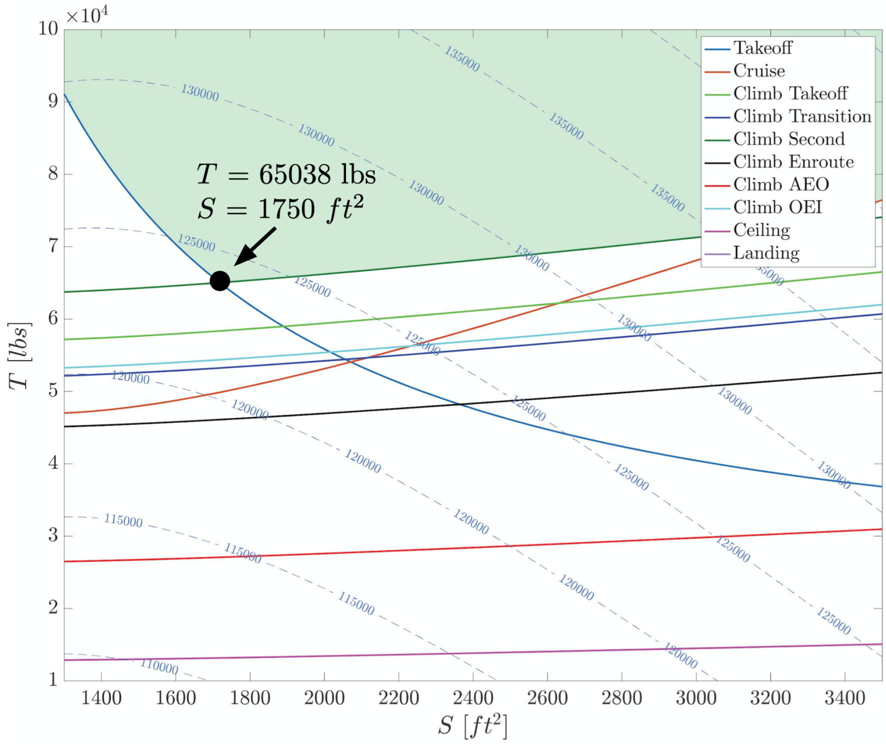


Figure 4: Thrust-Area Constraints and DOC Objective Function Overlay

As seen above, after overlaying our objective function of DOC, we were able to determine a design point for the S505 that had a minimum DOC while remaining feasible. This corresponded to a thrust of T = 65,038 lbs and a wing area of S = 1,750 ft^2. Our DOC is projected to be approximately $123,952, equivalent to 11.73 ¢/ASM.

5.1.4 Objective Function

As mentioned above, we utilized the T vs S plot to identify the design point that fit the goals of the design. We needed an additional objective function to identify where in the feasible T-S our design point should be. Since the objective of the S505 is to replace the Boeing 737 and compete with the Airbus A321XLR, we chose the objective function to be the DOC of the S505 as a function of thrust and wing reference area. This was chosen because it was a holistic value that was computed using aircraft weight, fuel weight, staffing costs, and other key costs that incorporate all aspects of aircraft operation; the DOC provided a single measure that can be compared across different configurations.

As shown in Figure 4 this objective function was superimposed as contours in 2-D space onto the T-S plot and the design point was chosen as the cheapest feasible T-S configuration that fit within the design constraints. The breakdown of the DOC for the chosen design point is shown in Table 2.

It should be noted that the DOC is very sensitive to the weight and weight fractions of the design, so the inputs of the direct operation cost calculation were decided as the estimated takeoff gross weight, the fuel weight, and the flight conditions. The cruise speed was used to compute the block time of the aircraft. Further details about the function used to compute the DOC are described in Section 8.

Component	Cost ($)
Crew	8,999
Attendants	7,279
Fuel	30,623
Oil	833
Landing Fees	1,453
Navigation Fees	768
Airframe Maintenance	24,255
Engine Maintenance	2,206
Insurance	1,378
Financing	8,106
Depreciation	22,160
Registration and Taxes	380
Total	124,290
Total (ASM)	11.73 ¢

Table 2: DOC Breakdown computed using final design point

The DOC is comprised of the cash operating cost and the fixed operating cost, each of which is comprised of subcomponents. The cash operating cost represents costs directly related to flight and the fixed operating cost represents other costs incurred when not flying. The components of the cash operating cost are

- Crew: This is the cost incurred through flight crew staffing expenses and other compensations. This was calculated using Eq 3.11 in the Aircraft Design Metabook [3] with a cost escalation factor based off a base year of 1999.
- Attendants: This is the cost associated with flight attendant staffing fees and is given compensation. This cost was calculated using Equation 3.15 in the metabook [3].
- Fuel: The fuel weight was computed by calculating the fuel fraction using a weight convergence algorithm, and the cost of fuel was computed using Equation 3.16 in the metabook [3].
- Oil: The cost of oil and lubricants is computed based off the weight of oil, which is computed using the weight of the fuel. We used Equation 3.18 and 3.19 in the metabook [3].
- Landing Fees: The landing fees represent the cost of landing at an airport and paying for gate fees and other services. This was computed using Equation 3.21 in the metabook [3].

- Navigation Fees: The navigation fees describe the cost related to flight planning and the use of air traffic control systems. These costs were computed using Equation 3.22 in the metabook [3].
- Airframe Maintenance: This component represents all the costs relevant to the maintenance of the airframe, and is based on the maintenance labor hours, the cost of labor, and material cost. It is a function of airframe cost, which was estimated using the procedure detailed in Section 3.3 of the metabook [3]. The cost of airframe maintenance was calculated using Equations 3.23, 3.24, and 3.26 in the metabook [3].
- Engine Maintenance: The engine maintenance cost is computed in the same way as the airframe maintenance cost, and uses correlations involving the maximum thrust of the engines. The total cost of engine maintenance was computed using Equations 3.27, 3.28. and 3.31 in the metabook [3].

The components of the aircraft's fixed operation costs are

- Insurance: The insurance cost is an annual cost that is expressed in terms of the aircraft initial cost. The annual insurance cost was computed using Equations 3.35 and 3.36 in the Aircraft Design Metabook [3].
- Financing: This is the interest applied on the initial loan used to buy the aircraft. As stated in the metabook, the annual cost of financing was approximated as 7% of the total DOCs discounting the financing cost [3].
- Depreciation: The depreciation cost is an allocation of the purchase price over the life of the aircraft and is computed using Equation 3.37 in the metabook [3].
- Registration and Taxes: This is the tax paid by the airline operator to register the aircraft, and is expressed as a fixed percentage of the MTOW. This was calculated using Equation 3.38 in the metabook [3].

5.1.5 Method Validation

To validate that our sizing code was working correctly and was trustworthy, we re-ran a separate final sizing sizing case against a known aircraft. We chose to use a Boeing 737-800 as our test case - parameters of which can be seen in Appendix A.

After modifying our sizing code to conform to these airplane characteristics, we again created T-S plots of the different flight constraints the aircraft would have to meet. If our code predicted a feasible region that did not contain the real-life 737, we would know that our final sizing results could not be trusted. Figure 5 below shows the results of our sizing code against the 737-800.

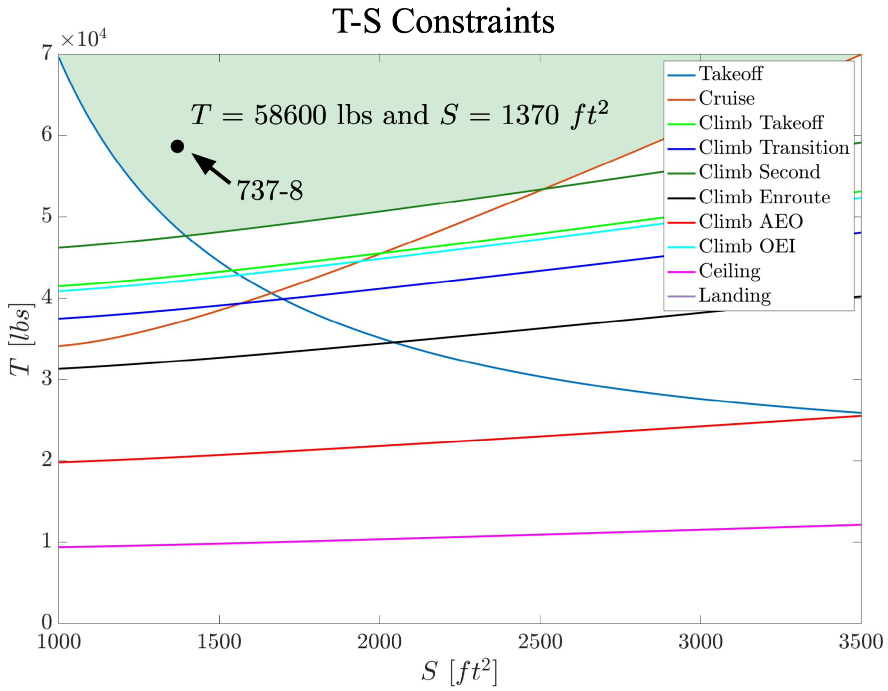


Figure 5: The Boeing 737-800 is shown to exist within the feasible region created by our sizing code.

As seen above, with a known thrust of 58,600 lbs and a reference area of 1,370 square-feet, the 737 is verified to meet all of the flight requirements and fits comfortably within the feasible region of our sizing code. Going further, we compared the output of our improved weight estimation function (discussed in Section 7.1) to the known MTOW of the 737-800. With the given thrust and wing area values of the 737, our weight estimation code predicted a final MTOW of 170,380 lbs - only 6% off from the actual MTOW of 181,200 lbs. These two results support our implementation used to size the S505, and it is within reason and can be trusted to result in a sensible aircraft.

5.2 Fuselage

The Sabrewing S505's fuselage comprises of a single aisle layout with features that take advantage of a composite construction. The design was driven by the safety requirements outlined in Part 25 of FAR, the number of passengers, and the amount of cargo that must be transported.

5.2.1 Sizing

We started the final sizing process by reviewing the number of aisles required to seat all 220 passengers in reasonable space. By maintaining our seat size from PDR, we were able to roughly model twin aisle configurations of our aircraft and determine their wetted and frontal areas. We compared the new values to our single aisle configuration shown in Table 3 below. Using this information, we decided to continue developing the single aisle configuration due to the lower frontal and wetted areas. This decision was made to minimize the drag of the aircraft resulting in a lower DOC as discussed in Section 5.1.4.

Configuration	7-abreast	8-abreast	9-abreast	S505 (6-abreast)
Aisles	2	2	2	1
Fuselage S_{wet} (ft^2)	8022.9	7885.3	7885.3	7065.9
Fuselage $S_{frontal}$ (ft^2)	218.2	264.0	314.2	132.7
Fuselage Length (ft)	153.2	136.9	127.8	173.0

Table 3: Twin aisle variants of the S505 have higher approximate wetted and frontal fuselage areas with a two class configuration than with a standard single aisle

Once we decided on continuing development on our single aisle, we redesigned the seats for our business and economy classes. The seats' footprints were averaged from Chapter 5 of Civil Jet Aircraft Design [4], but we added a 15° recline to increase our passenger's comfort level. The new designs of our seats are shown in Figure 6.

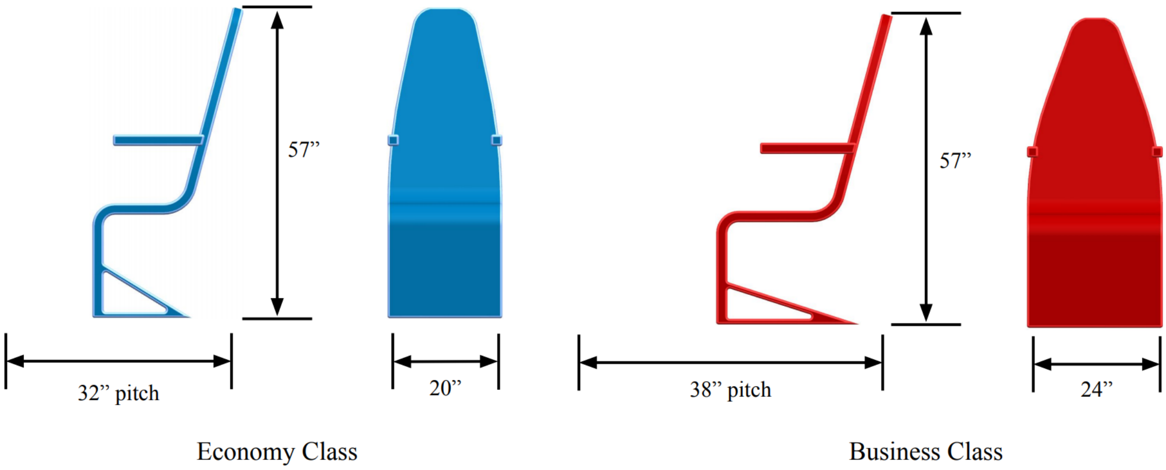
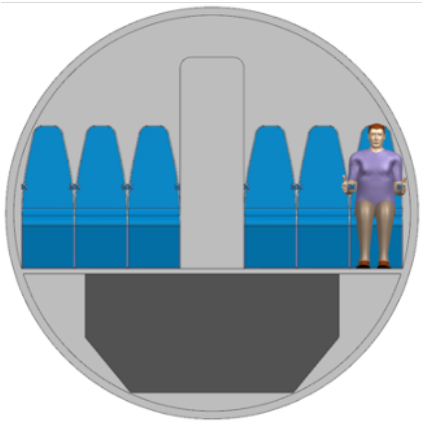
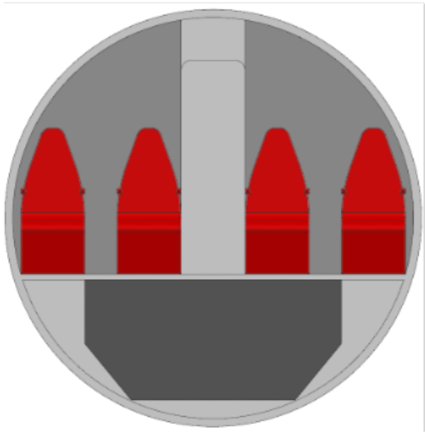


Figure 6: Fuselage length is greatly influenced by the pitch of the economy seats

Our economy class configuration can be seen in Figure 7a below. This configuration is standard for a single aisle aircraft of similar size. In order to reduce the size of our cross-sectional area to increase our aerodynamic efficiency, our team sized the fuselage as close as possible to our passengers while maintaining a level of comfort. We used a 95% human male model to account for the majority of our passengers (this encompasses a 99% female passenger as well), and we determined that there is enough headroom for people to comfortably sit in the window seats. Since the business class requires more room, and our customers are paying for more space, we used a 2-2 abreast configuration shown in Figure 7b.



(a) Economy class 3-3 abreast configuration shared with A321XLR and B737-800



(b) Business class 2-2 abreast configuration occupies same space as economy aisle

Figure 7: Cross sectional views of the economy and business classes

Our aircraft has a single 2 ft aisle to comply with regulations outlined in FAR [5]. The complete dimensioned cross-section can be seen in Figure 8.

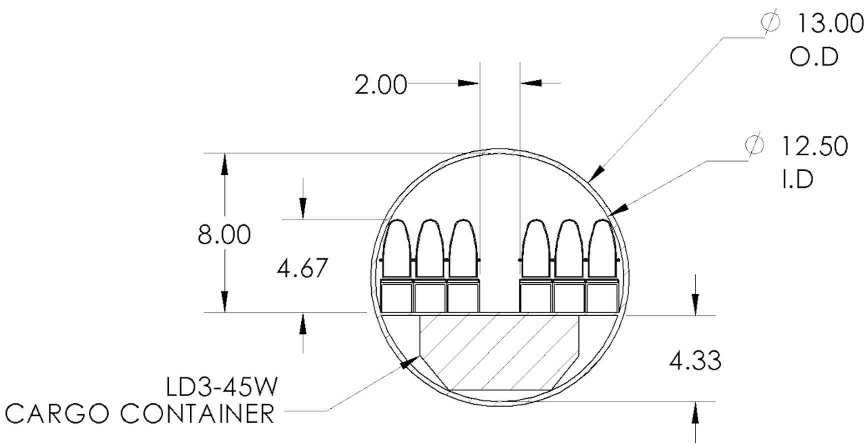


Figure 8: Aircraft has a circular cross section with a 13 foot outer diameter (Dimensions shown in ft)

In order to remain competitive with the A321XLR, we are using the LD3-45W cargo container for our storage system below the cabin. This container was chosen to best fit our fuselage dimensions and is shared with the A321XLR [6]. Once the cross-section was finalized, we split the passengers into four distinct groups. The first section is the business class compartment which holds the required 16 passengers in 4 rows. This section is separated from the next group by two lavatories. The remainder of the aircraft is dedicated to the economy class split into three sections for a total of 34 rows meeting the 204 economy passenger requirement. The current arrangement can be seen in Figure 9. It should be noted that two additional lavatories are contained in the rear of the aircraft, and there is a galley in the crew cabin.

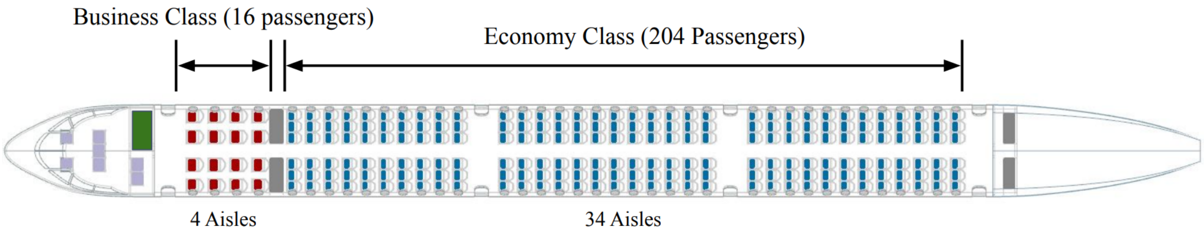


Figure 9: Passengers are organized across the entire fuselage

5.2.2 Safety

Our fuselage design meets all safety requirements outlined in FAR Part 25. There are 8 Type I exits distributed evenly along each side of the plane; this is similar to the A321XLR. Figure 10 displays that there are more than enough emergency exits to support the 45 passenger maximum per Type I emergency exit.

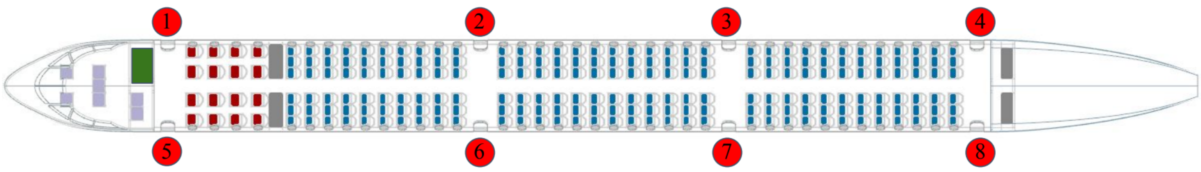


Figure 10: Exits are spaced uniformly along each side of the aircraft

The final safety measure we investigated was crew visibility during operation. We took advantage of our composite construction to create large windows that give the pilots a large field of view and line of site as seen in Figure 11. Additionally, the pilots horizontal line of sight can be seen in Figure 12. The S505's large window construction is made possible with the technology used in the composite fuselage of the B787 Dreamliner [7].

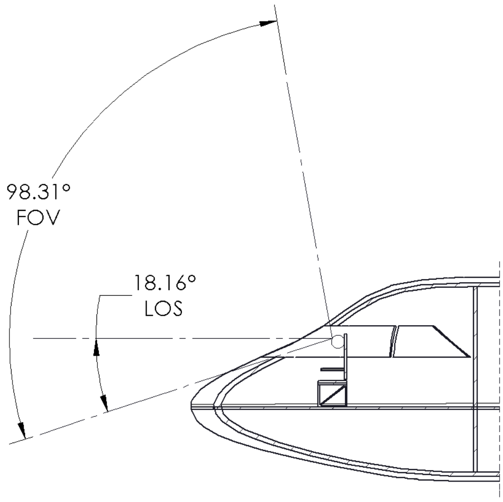


Figure 11: Pilot is able to see the runway clearly with a 18° line of sight

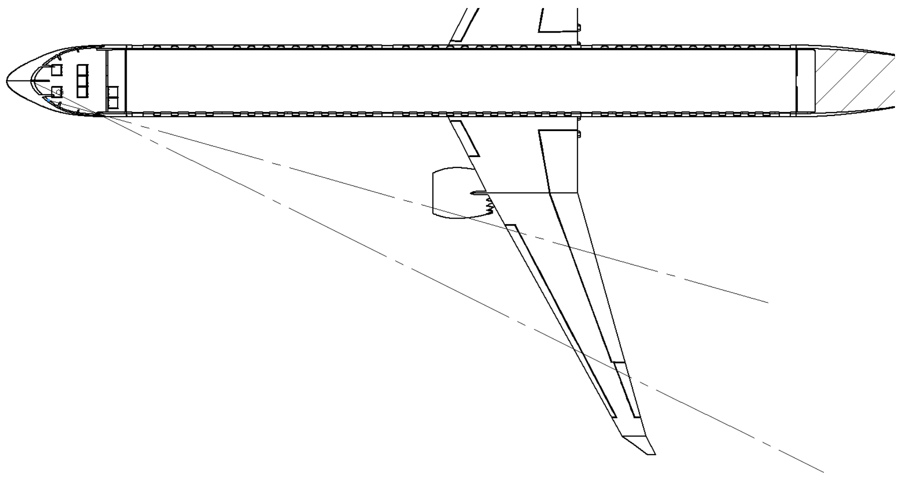


Figure 12: The pilots are able to see the engines from the cockpit and wingtips from their seats

5.2.3 Storage

Due to the length of our fuselage we have space to comfortably fit 18 LD3-45W containers. This can be seen in Figure 13 below. The empty space between the forward and aft cargoholds house our carrythough wing structure and fuel.

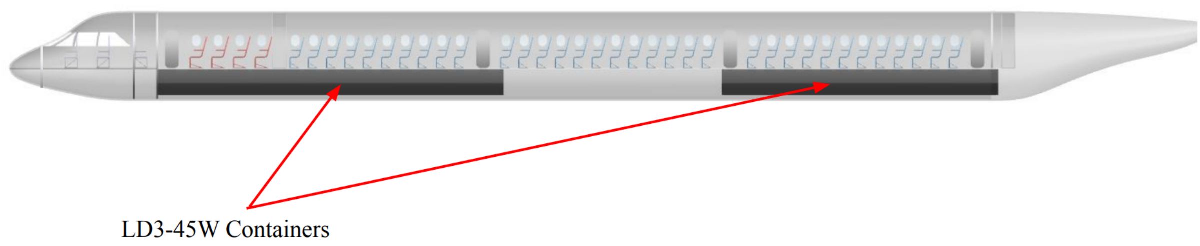


Figure 13: 18 LD3-45W containers are organized into two sections underneath the passenger compartment

5.2.4 Geometry

When designing the tail of the fuselage, Table 4.1 from Roskam was used to find a general length that is standard for jet transports [1]. The nose of our aircraft was modeled after a typical jet transport with enough space to fit the crew sitting in modified business class seats. These final additions left us with a fuselage that was 173.01 ft. This is fairly long compared to our competitors; however, our aircraft carries more passengers in a two class configuration than any other aircraft in its class. The closest aircraft is the A321XLR which carries 220 people in a single class configuration [8]. The complete S505 fuselage which can carry the required 220 passengers in a two class configuration can be seen below in Figure 14.

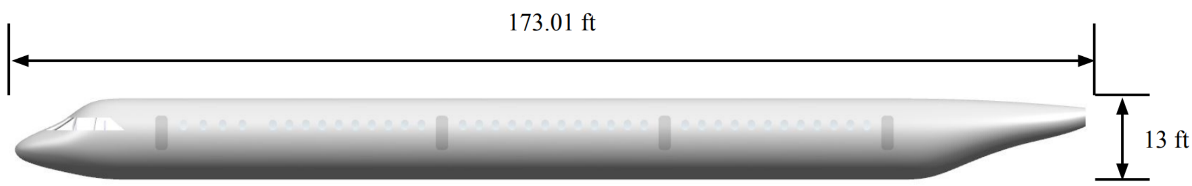


Figure 14: S505 fuselage mimics traditional aircraft

5.3 Aerodynamics

This section explains the design of the main wing and the justifications for our design. We iterated our wing design from PDR to minimize our total induced and wave drag, while also adapting our wing to achieve the high lift required at landing. Additionally, we determined we needed to increase our wing area to 1,750 ft^2 to minimize our operating cost and takeoff thrust. Further explanation of our sizing method can be seen in Subsection 5.1.

5.3.1 Airfoil Selection

We started by revising the main airfoil for our wing. We needed to decide on a new supercritical airfoil with a high C_l so we could achieve our C_L max of 3.0. However, we did not want to drastically increase our chord thickness since it would increase our sweep and, therefore, our structural weight. As a result, we determined that the C5e-il (Figure 15) would be a good option since it has a chord thickness of 10.8% which is only 0.2% higher than our old airfoil. This allowed us to achieve a maximum C_l of 1.7 which made our planform C_L high enough that we would be able to achieve our lift for landing with flaps and slats.

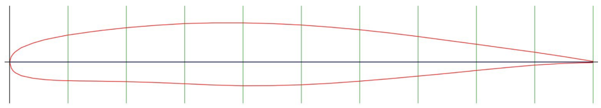


Figure 15: 2D plot of the c5e-il airfoil. It has a $C_{L,max}$ of 1.7 which meets the required C_L for cruise

5.3.2 Drag Polar

To refine our aircraft, we built a drag polar shown in Figure 16 that was used to iterate our total drag in cruise flight and calculate our fuel weight. To generate our lift vs induced drag curve, we used our analysis from AVL which incorporates our wing, tail, and control surfaces. We determined our parasitic drag using a component build-up method. To implement this method, we created a function that takes input for the component type as well as associated sizes and measurements; we use this information to determine each component's skin friction, form factor, and interference factor. Next, a new function calculates the "missing" drag for a few select components. Finally, we assemble all of this information together in a matrix to calculate the leakage and protuberance drag to determine the full parasitic drag [9].

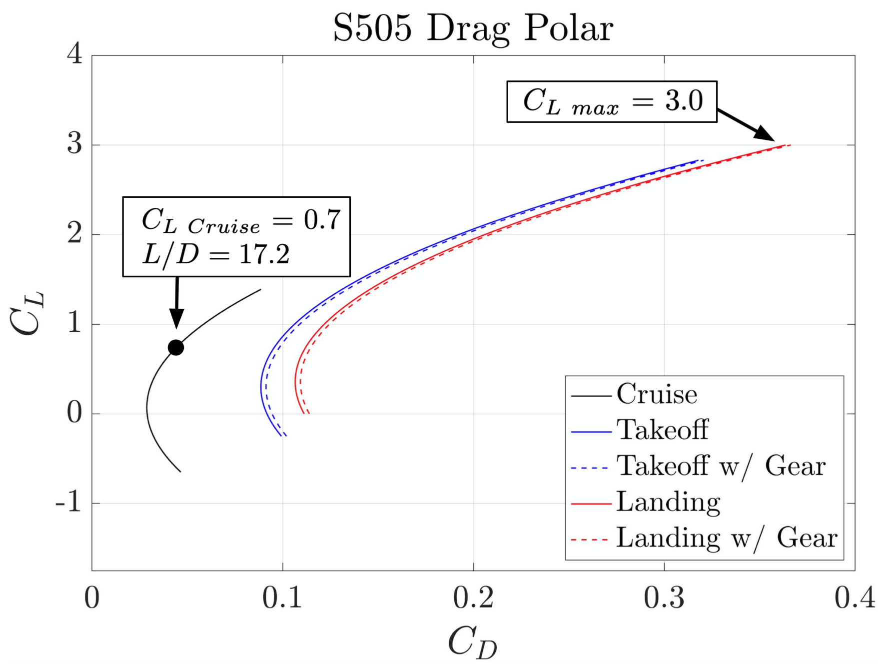


Figure 16: Using this plot, we were able to determine the maximum L/D which is used to estimate our cruise fuel burn and revise the weight of our craft

5.3.3 Wave Drag

To determine the layout of the wing, shown in Figure 18, we used the Korn Mach Divergence equation (Equation 1) with inputs of a cruise Mach of 0.8 (Section 6.1) and a cruise C_L of 0.7. By plotting the Korn equation on a thickness-sweep plot with contours of constant Mach divergence, we were able to identify our quarter-chord sweep of 23.8°. We based this on the thickness of our airfoil and a mach divergence of 0.82 which should be slightly higher than our cruise Mach to minimize wave drag.

$$M_{DD} = \frac{\kappa}{cos(\gamma)} - \frac{t/c}{cos^2(\gamma)} - \frac{C_L}{10cos^3(\gamma)} \tag{1}$$

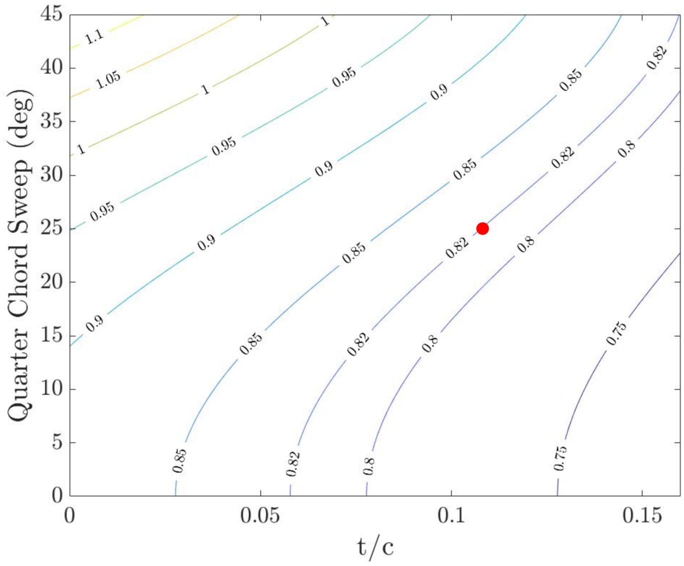


Figure 17: Our design point is labeled by the red dot on the 0.82 Mach line at a thickness of 10.8 and a sweep of 23.8°

5.3.4 Wing Planform

With our airfoil, quarter-chord sweep, and wing area selected, we just were able to generate our wing planform shown in Figure 18. We decided on a taper ratio of 0.2 since it is normal for a lot of aircraft with our sweep and in decreases our wing weight.

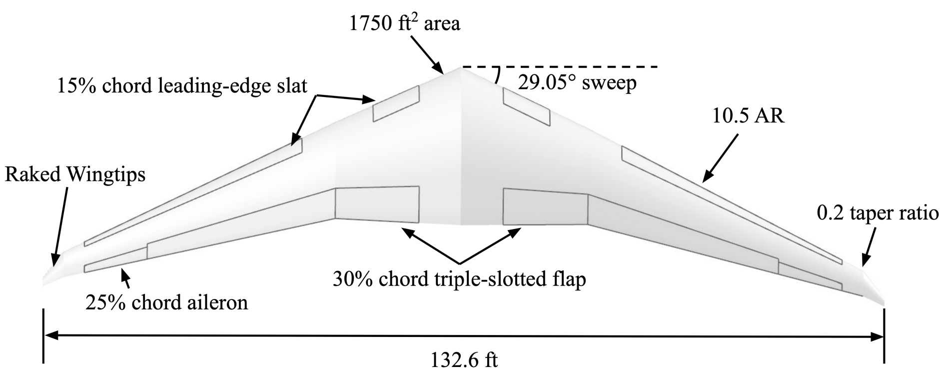


Figure 18: Layout and geometry of the main wing with relevant dimensions

5.3.5 High-Lifting Surfaces

To determine the size of our high lifting surfaces, we used approximations from section 12 of Raymer based on the geometry of our wing to calculate the planform lift of our wing [2]. In this analysis, we determined our clean configuration with no high-lifting surfaces deployed has a C_L of 1.4, which we validated in AVL. Next, through a series of iterations, we determined that we would need triple-slotted flaps with a stowed chord length of 30% and extend the total chord of the wing to 125% when deployed. The flaps extend from 12% span to 75% span to allow spacing for the landing gear inside and ailerons at the wing tips. With the flaps fully deployed, we can achieve a $C_{L,max}$ of 2.8. To achieve our $C_{L,max}$ of 3.0 and reduce stall tendencies at a high AoA, we added 15% chord slats in the front of the wing along 10% to 21% and 38% to 90% span to not interfere with flow to the engine.

The resulting wing provides us with a takeoff stall speed of 117.8 knots based on a $C_{L,max}$ of 2.8 without slats deployed and our MTOW. Our landing stall speed is 113.1 knots based on a $C_{L,max}$ of 3.0 with all flaps and slats fully deployed. Finally, our cruise stall speed is 167.9 knots, but this is unlikely to occur in normal operations of the aircraft.

5.3.6 Empennage Sizing

To size our tail, we used the volume coefficient method as described in Raymer to obtain reference areas (S_{HT} S_{VT}) for the horizontal and vertical stabilizer [2]. The volume coefficient equations can be seen below in Equation 2.

$$c_{HT} = \frac{L_{HT} S_{HT}}{\bar{c}_W S_W} \qquad c_{VT} = \frac{L_{VT} S_{VT}}{\bar{c}_W S_W} \tag{2}$$

From our wing design, we obtained values for our reference chord and wing area to be equal to $\bar{c}_W = 18.26$ ft and $S_W = 1750\ ft^2$. For our refined design, we measured L_{HT} and L_{VT} from our CAD to be 45.6% of the fuselage length; which is still in accordance with Roskam [1]. Finally, we used tail volume coefficients of the Boeing 757-200, yielding us values of $c_{HT} = 0.549$ and $c_{VT} = 0.038$. Solving for the wing are of the tail, we obtained our final values $S_{HT} = 312.6 ft^2$ and $S_{VT} = 275.12 ft^2$. Seen below in Figures 19 and 20 are images of the final horizontal and vertical tail.

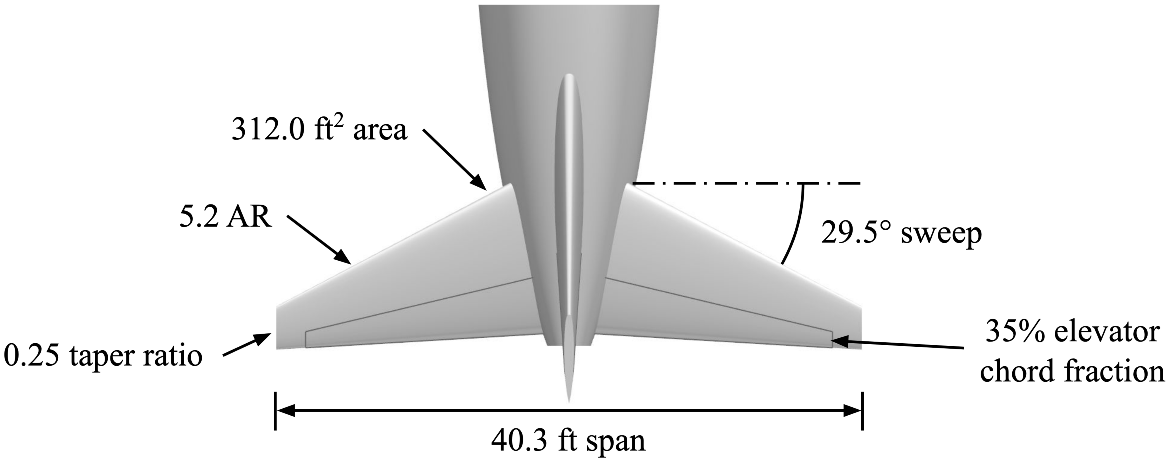


Figure 19: Layout and geometry of the horizontal tail with relevant dimensions

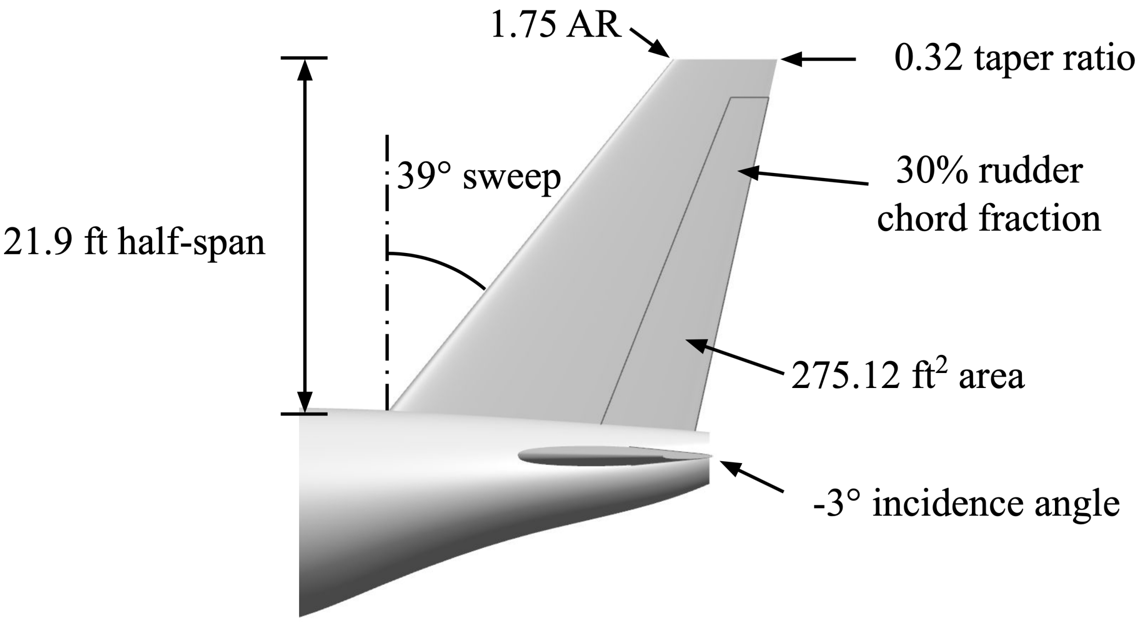
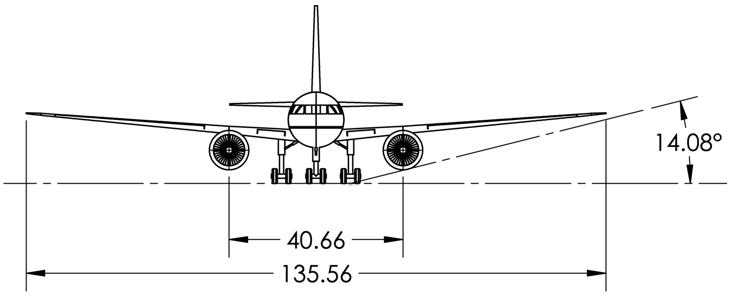


Figure 20: Layout and geometry of the vertical tail with relevant dimensions

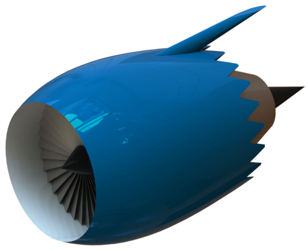
Finally, we performed a trade study to determine an adequate incidence angle at which to mount the horizontal stabilizer. As described in Section 7.2, we determined that an incidence of $-3°$ resulted in a minimal elevator deflection, and thus, lower control surface drag at cruise.

5.4 Propulsion

Based on our final T/S plot, we determined that a total takeoff thrust of 65,038 lbf was required for the S505. From PDR, our choice of Pratt and Whitney PW1133G-PM Geared Turbofans were found to be sufficient as two engines our thrust criteria by providing a maximum sea level thrust of 66220 lbf. Additionally, Pratt and Whitney's Geared Turbofan Technology is the cutting edge of current turbofan technologies - providing industry leading efficiencies and fuel-consumption values [10]. This is instrumental in decreasing the amount of fuel that the S505 is required to carry, and thus, it's weight. The engines are placed at 30% span, as shown in Figure 21a, and slightly in front of the wing. This placement reduce the aerodynamic interference between the intake and the front of the wing so the engine can perform as close to full efficiency as possible. Finally, trailing edge chevrons were added near the back of the engine nacelle to enable quieter operation during flight.



(a) The placement of the engines allow for a ground clearance and a rollover angle of 14.08°



(b) Trailing edge of the nacelle have chevrons to reduce noise during operation.

5.5 Structures

The S505's internal structure supports the applied loads of the aircraft. We chose to use a carbon fiber monocoque with a carrythrough composite wingbox. These choices allow us to minimize the number of bulkheads we use and provide our aircraft with mounting area for the largest components.

5.5.1 Mounting Points

As shown in Figure 22, the S505's mounting points are concentrated along its carrythrough wingbox and two forward bulkheads. The forward bulkheads are necessary despite our carbon fiber construction because the force of the nose landing gear is concentrated in one area, and the 100% carbon fuselage is optimized for tension forces and not bending. These bulkheads can be seen in more detail in Section 5.5.3. The rest of the fuselage will be constructed using a prepreg carbon fiber composite method shared with the Boeing B787 Dreamliner [11].

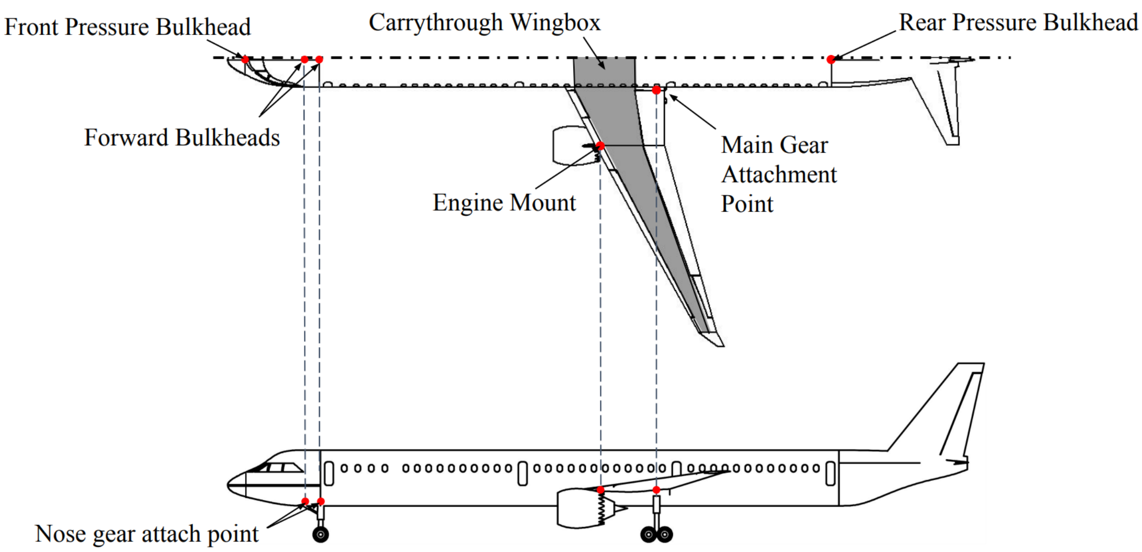


Figure 22: main structural arrangement supports all components

Both engines and main gear are attached to the composite carrythrough wingbox. This section of the aircraft is constructed out of an extremely thick prepreg carbon fiber composite construction like the B777X to withstand the bending moments generated by the weight of the engines, the force of the main landing gear under load, and the lift generated by the wings [12]. Finally, the front and rear pressure bulkheads allow us to easily pressurize the fuselage for high altitude flights.

5.5.2 Fuel

The fuel tanks for the aircraft can be seen in Figure 23. We determined the volume of our fuel tanks by calculating how much fuel we needed to safely satisfy our flight requirements. We then used the known density and mass of Jet-A to find the total required volume of 1218 cubic-feet. Our fuel is stored inside the carrythrough wingbox to ensure that the CG moves minimally during a full-length flight and to take advantage of the space and structure provided by the wingbox.

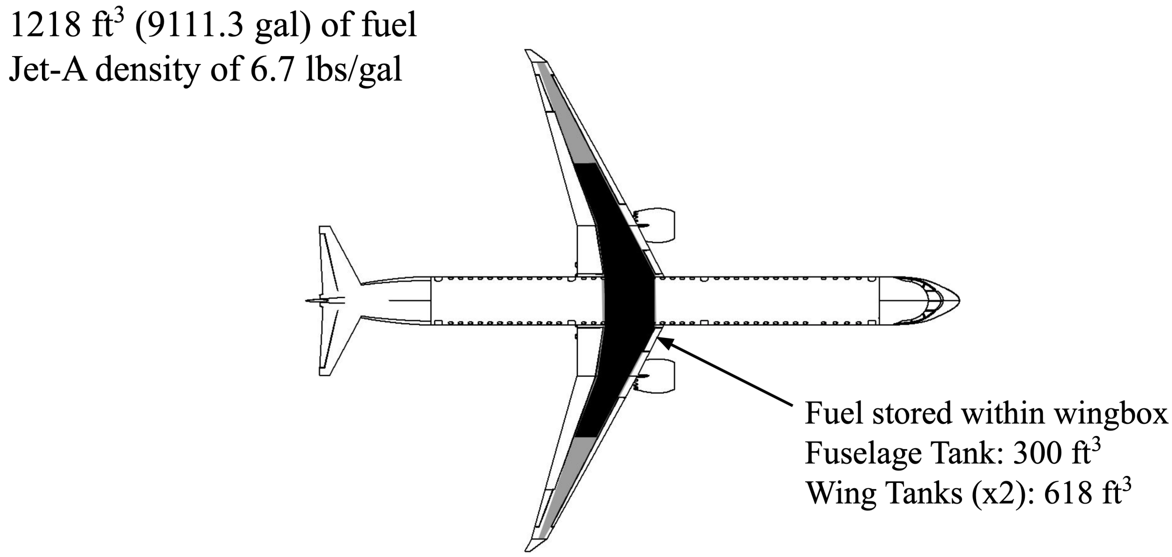


Figure 23: S505 carries enough fuel to satisfy its maximum range as well as reserves

5.5.3 Landing Gear

To size our landing gear, we started with the decision to use a traditional tricycle landing configuration. We based this on the fact that it is one of the more stable configurations and the most common for transport aircraft. We positioned the main landing gear to provide us with a 10.5° rotation angle and a 14° tipback angle. To size the number of wheels we need for each bogey, we used estimates from Raymer to calculate the maximum loads on the main landing gear based on where they were located on the aircraft [2]. We found that the main gear will be required to support 235,000 lbs, which based on estimates from Raymer, requires a 4-wheel bogey as shown in figure 24b [2]. With this decided, we calculated the load on each individual wheel to determine the size of tires. Based on a regression of historical data, we took the load on each wheel and determined that each tire would need to be 41.6 inches in diameter and 14.5 inches. We then placed our nose gear so it would support roughly 5% of the load of the aircraft and so it could be mounted to the nose bulkhead of our fuselage. We gave it a 2-wheel bogey in the nose, as shown in Figure 24a, so it could still be safe to land even if one of the tires is damaged.

(a) Nose landing gear uses a two-wheel bogey to support the weight of the front of the aircraft

(b) Main landing gear uses two four-wheel bogey to support the weight of the aircraft under heavy load

Figure 24: The S505 is equipped with a tricycle style landing gear configuration

Once we sized our landing gear, we determined how we would stow them during flight. Our nose gear folds forward up into the nose of the plane, beneath the cockpit as shown in figure 25. We decided to have it fold forward so it would remain safe in the event of a mechanical failure since. Our main gear folds inwards toward each other underneath the cabin of the aircraft to limit the change in CG when stowed. Since the main gear will be much heavier than the nose gear, it was more important to avoid moving the CG of the landing gear and affect the CG of the entire aircraft.

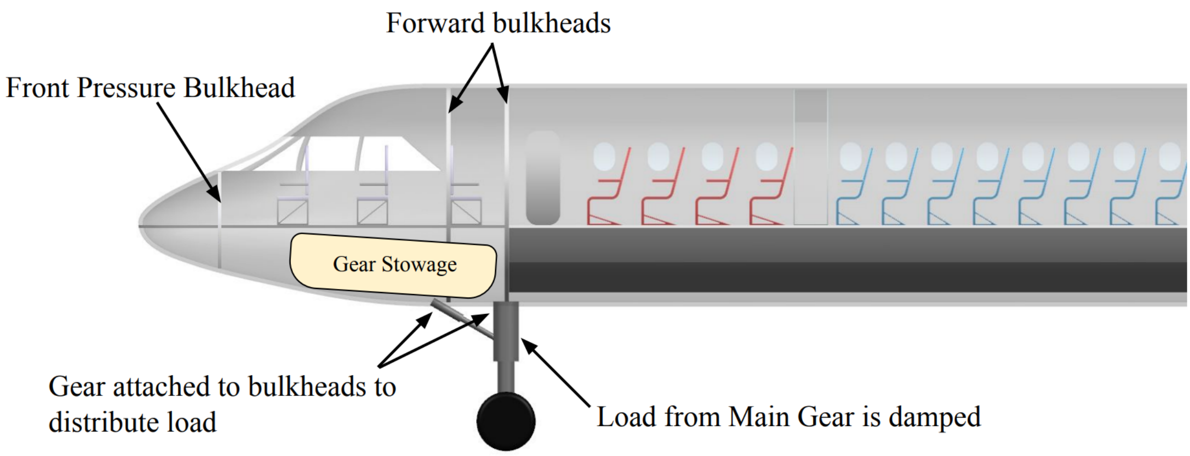


Figure 25: The front landing gear folds forward to be stowed underneath the crew cabin

5.5.4 V-n Diagrams

To determine the flight envelope of the S505, a V-n diagram was created to visualize the critical load points within our flight. This plot shows the load factors expected during flight, including at stall, max cruising speed, and maneuvering speed. Figures 26 and 27 below show complete

V-n diagrams at both minimum and maximum loading conditions.

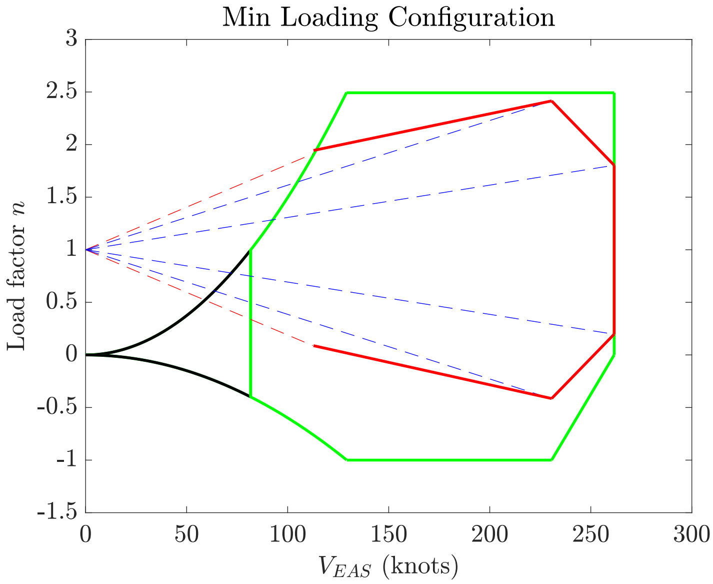


Figure 26: S505 V-n diagram at a minimum loading configuration (flight envelope is highlighted in green).

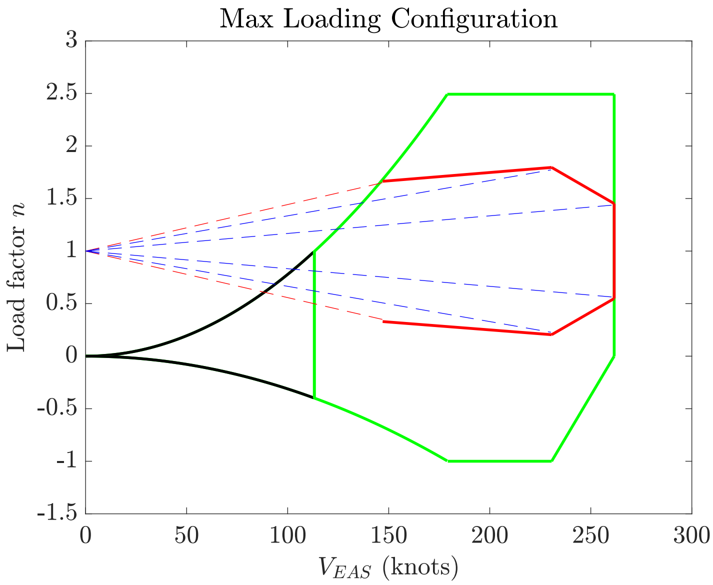


Figure 27: S505 V-n diagram at a maximum loading configuration (flight envelope is highlighted in green).

As seen above, our gust loads are predicted to stay within our maneuvering envelope in both our maximum and minimum weight configurations.

6 Trade Studies

To further refine the design of the S505 from PDR, we performed several trade studies with the goal of reducing our DOC. The following sections discuss these trades in detail.

6.1 Mach - Altitude

To lower of DOC further, we decided to perform a trade study to determine the optimal starting altitude and Mach number for our flight. To do this, we created a MATLAB function, `mach_alt_trade.m`, that iterates through multiple different combinations of altitudes and calculates the corresponding minimum DOC for a given planform design.

For each combination of altitude and Mach number, our code computes the corresponding flight conditions the aircraft will experience - notably it's Reynolds number and wave drag. Additionally, the corresponding structural and fuel weights are calculated. Using these values, our code computes the DOC. It should be noted that for this trade study we ensured that both specific fuel consumption and block time were functions of the altitude and Mach number respectively. A 2D contour map of the resultant design space can be seen below in Figure 28.

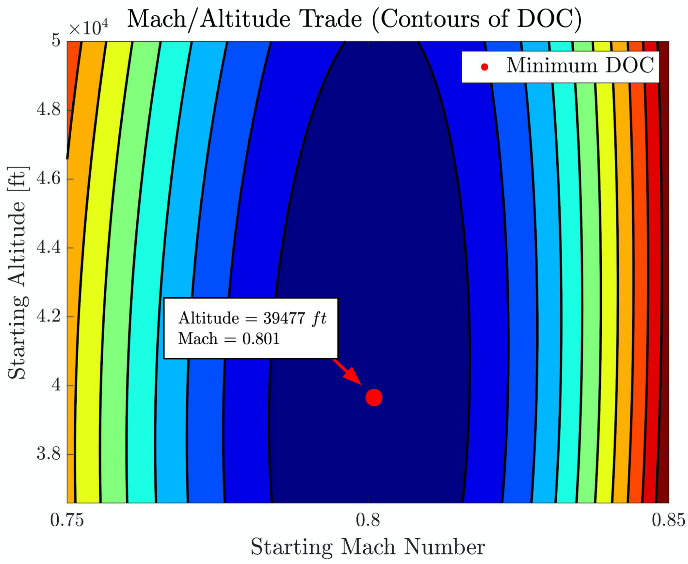


Figure 28: The S505 has it's lowest DOC at an altitude of 39,477 ft and a Mach of 0.801

As seen above, the results of our trade indicate a specific altitude and Mach number at which our DOC is minimized. We see expected behavior in which DOC increases with high Mach numbers due to increased wave drag, and DOC increasing with low Mach numbers due to the weight of extra fuel. Additionally as these values are close to the values seen in conventional aircraft, such as the Boeing 737-8, we believe that they are within reason to be trusted.

6.2 Wing Twist

To ensure that the wing will be able to achieve the our $C_{L,max}$ at landing, we performed an AVL analysis on our wings to determine what the twist of our wing would need to be to prevent tip stall. Through a series of tests, we determined that our wing would need the twist shown in

Figure 29. This arrangement allows the entire wing to stall at the same time and retain control at a high AoA without a sudden loss of lift as the wingtip stalls.

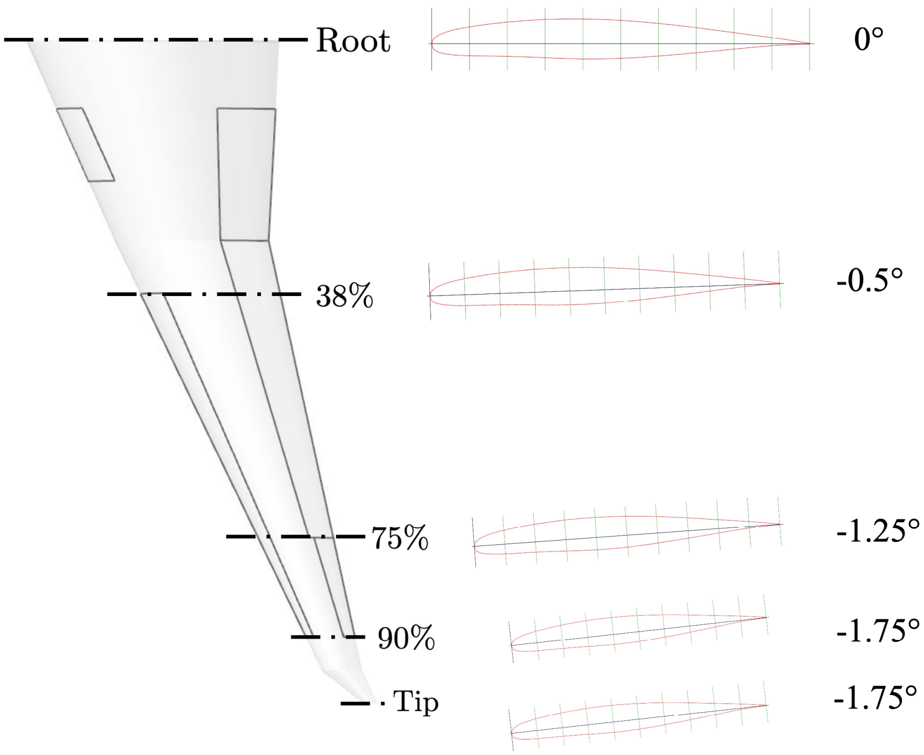


Figure 29: The twist of the main wing varies from 0° at the root up to -1.75° at the tip

6.3 Raked Wingtips

We also added raked wingtips to our wing since we found in our AVL model that this would slightly reduce our overall $C_{D,i}$ as shown in figure 30. We were able to justify the addition of them since as opposed to adding more span or mass to our wing, we trimmed the chord of the last 5% of our reference span and swept back the wing tips. This provided the benefit of raked wingtips while reducing the mass slightly. Additionally, we found that this minimally impacts our total lift since the tip of the wing already generates very little lift compared to the rest of the wing as a result of its small chord and the vortices generated by the rest of the wing.

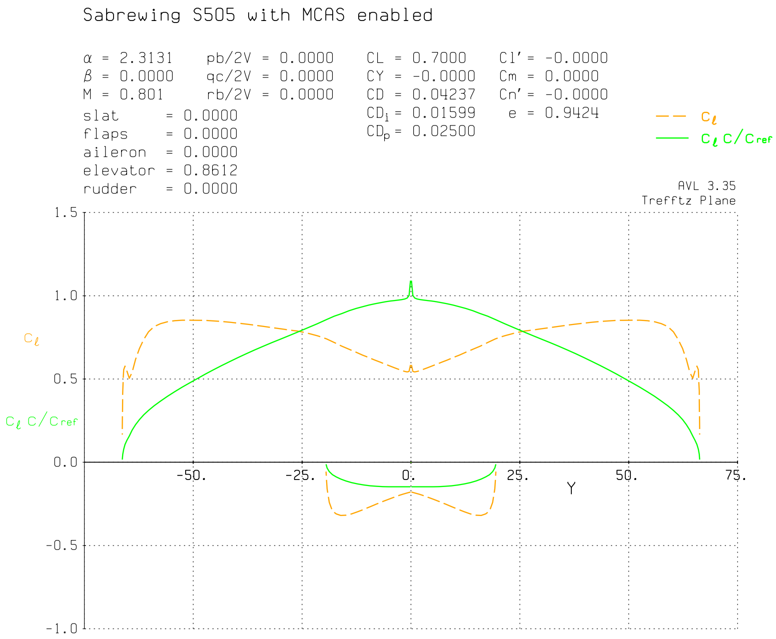


Figure 30: The S505 with raked wingtips has a C_{Di} of 0.01599.

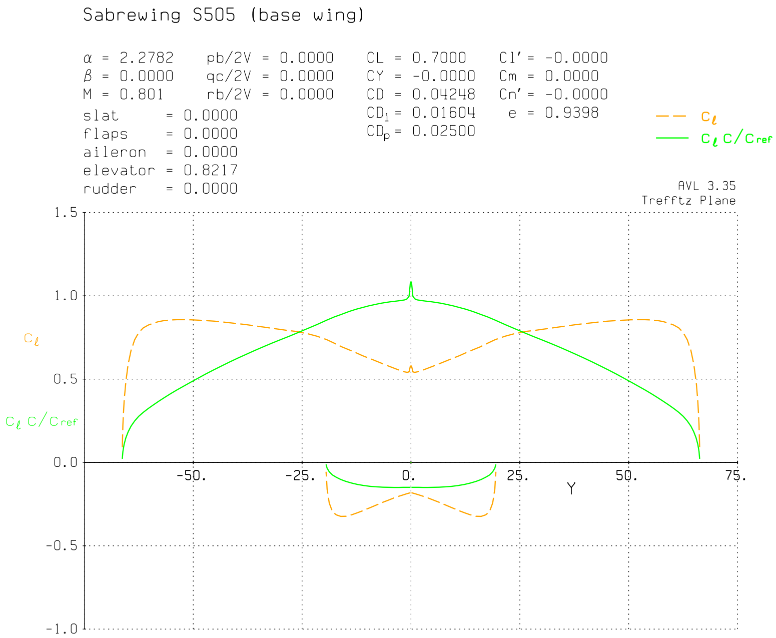


Figure 31: The S505 without raked wingtips has a C_{Di} of 0.01604.

We recognize that the changes between the configurations are minimal - this is mostly due to the resolution of the tools available to us. However, the benefits of raked wingtips have been verified in similar planes, such as the Boeing 787 and 777X [13]. For this reason, we believe that although we can not fully resolve their effects at the moment, there will be a benefit to the fuel consumption of the S505.

7 Design Analysis

The following sections describe the methods used to complete the final weight, control and stability analysis of the S505.

7.1 Final Design Weight Calculation and Breakdown

We calculated the component weights using the Raymer weight buildup method, with our refined sizing measurements to compute a more accurate estimate of the total weight of the aircraft [2]. The Raymer method uses historical trends in aircraft weights to generate scaling factors that depend on the planform size, takeoff weight, MTOW and other key performance parameters [2]. The scaling factors that we used were from Table 7.1 in the metabook [3]. The breakdown of individual component weights calculated using this method is shown in Table 4. We accounted for composite structures by utilizing scaling factors provided in the Raymer textbook [2].

We utilized an updated weight convergence algorithm to compute the weights of components and the weight fractions for each stage of flight. This algorithm used functions to calculate wing and tail design parameters based off wing area and the fuselage design, and also parasitic drag coefficients. These design parameters were then used in Raymer component weight estimations to compute higher-accuracy component weights [2]. Once component weights were calculated, they were used to established an empty weight, and the weight convergence algorithm was used to computed the fuel weight. The breakdown of individual component weights computed from this algorithm is shown in Table 4. The fuel weight was computed using the weight convergence algorithm integrated into `final_sizing.m`. The psuedocode of this algorithm is shown in Appendix C.

Component	Weight (lbs)
Wing	21,832
Horizontal Tail	1,429
Vertical Tail	1,256
Fuselage	25,584
Nose Landing Gear	1,555
Main Landing Gear	7,775
Installed Engine (x2)	14,618
All-else Empty	38,829
Empty Weight	112,878
Crew	40,860
Fuel	61,046
Payload	13,620
TOGW	228,404

Table 4: S505 Weight Breakdown by components

7.2 AVL Model at a Trimmed Cruise Condition

To analyze the cruise conditions of our aircraft, we created a model of the S505 in AVL [14]. A picture of our model can be seen below in Figure 32.

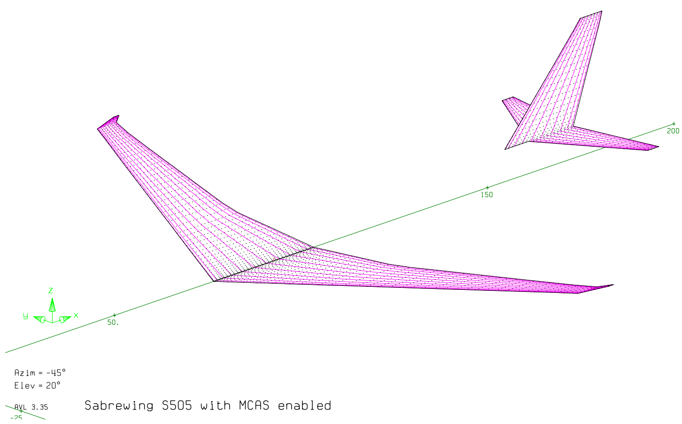


Figure 32: AVL model of S505 lifting surfaces

In this model, we have implemented both high-lift surfaces, such as the slats and flaps, as well as all our control surfaces (ailerons, elevator, rudder). With this, a trimmed flight condition can be specified in AVL - giving us the required elevator deflection for cruise. One study we performed was varying the incidence angles of both the wing and the H-tail in order to minimize the required elevator deflection δ_e. We found that a wing incidence of 3° and a H-tail incidence of $-3°$ resulted in a minimal required δ_e of 0.86°. An AVL Trefftz plot at trimmed cruise can be seen below in Figure 33.

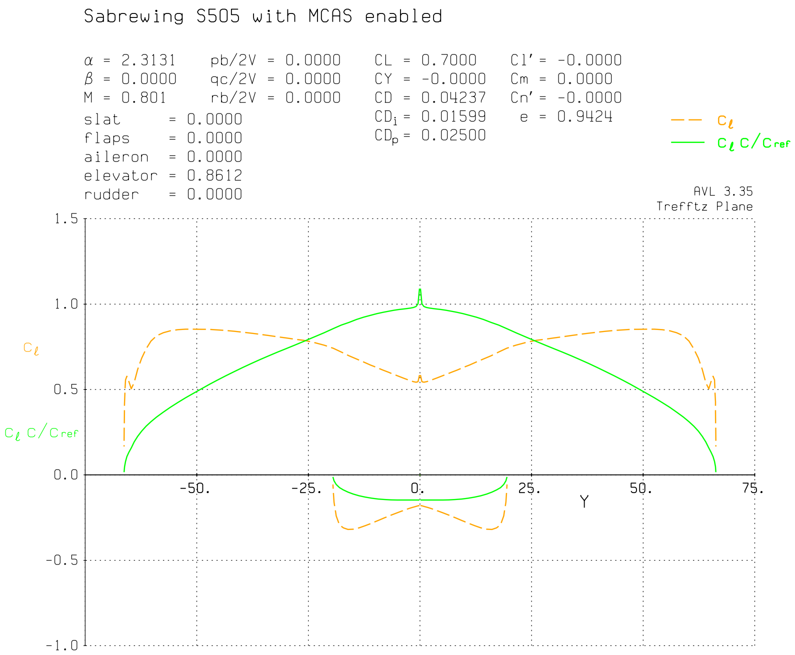


Figure 33: S505 in a trimmed condition with $C_{L\ cruise} = 0.7$. Cruise requires an elevator deflection of 0.87°.

7.3 Stability

The stability of the aircraft is determined by the location of the CG in relation to the neutral point. We calculated the neutral point by modeling the lifting surfaces and the rudimentary fuselage of the S505 in AVL and executing a stability analysis to output the location of the neutral point with respect to the root leading edge of the wing. The neutral point calculated in AVL from from the nose of the aircraft is

$$x_{np} = 101\ ft$$

The fully loaded CG in the longitudinal direction from the nose of the aircraft, as calculated in Section 7.4 is $X_{cg,TOGW} = 97.29\ ft$. This gives a SM (in the fully loaded configuration) of

$$Static\ Margin = 14.5\%\ MAC$$

7.4 Refined Center of Gravity

Once all component weights were calculated, the Raymer CG estimation was used to compute the global CG of the fully loaded aircraft [2]. This method approximates each component as a point mass along the fuselage, and these locations and weights are used to compute the longitudinal CG. Table 5 shows the approximate CG location of each component from the nose of the aircraft.

Component	Approx C.G. Location from Nose (ft)
Wing	96
Horizontal Tail	170
Vertical Tail	170
Fuselage	89
Nose Landing Gear	31
Main Landing Gear	100
Installed Engine	90
All-else Empty	99
Crew	90
Fuel	100
Payload	121

Table 5: S505 Component x_{CG} locations

Empty Center of Gravity: The empty CG was computed using only the component weights and locations and did not include the weights of fuel, crew or payload. The empty CG from the nose of the S505 was calculated to be

$$x_{cg,empty} = 95.58\ ft$$

Fully Loaded Center of Gravity: The fully loaded CG, which includes crew, fuel, and payload, from the nose was calculated to be

$$x_{cg,loaded} = 97.33\ ft$$

7.5 Static Margin Excursion

Based on the SM excursion figure, shown in Figure 34, the S505 will remain safely stable in all reasonable loading configurations. The SM excursion was calculated by computing the SM at each loading configuration, and plotting these values against the weight at these configuration. The stages at which the CG was computed are itemized below:

- Fully Loaded Takeoff
- Loaded Configuration at the beginning of cruise with the landing gear stored
- Loaded End of cruise once the cruise fuel is used
- Loaded configuration during landing with the landing gear extended
- Loaded with passengers and payload with no fuel
- Fully empty

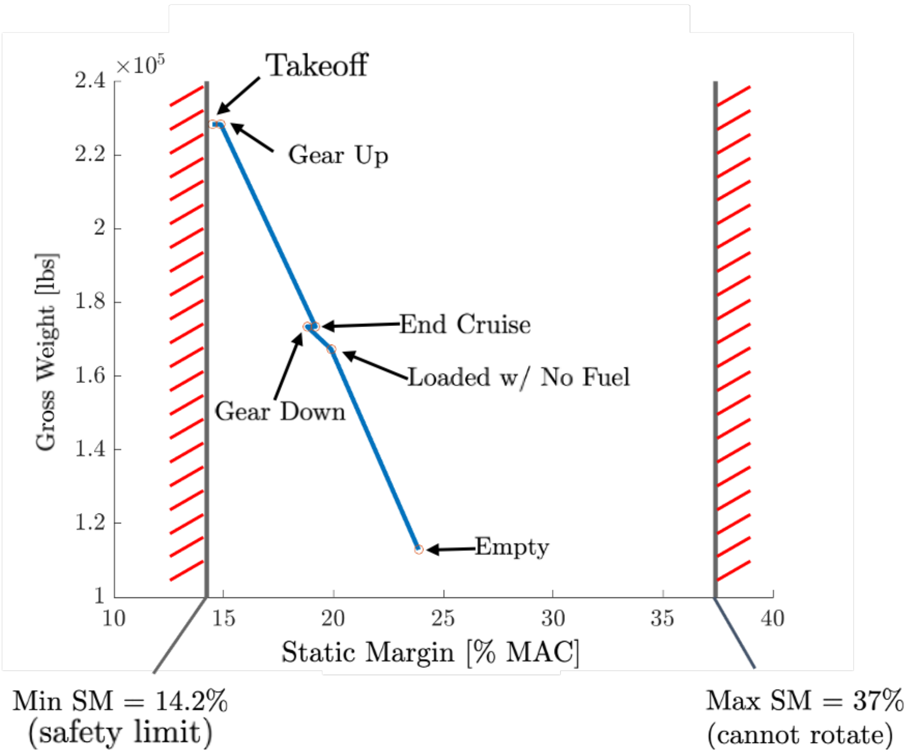


Figure 34: CG remains in a stable and feasible configuration during flight

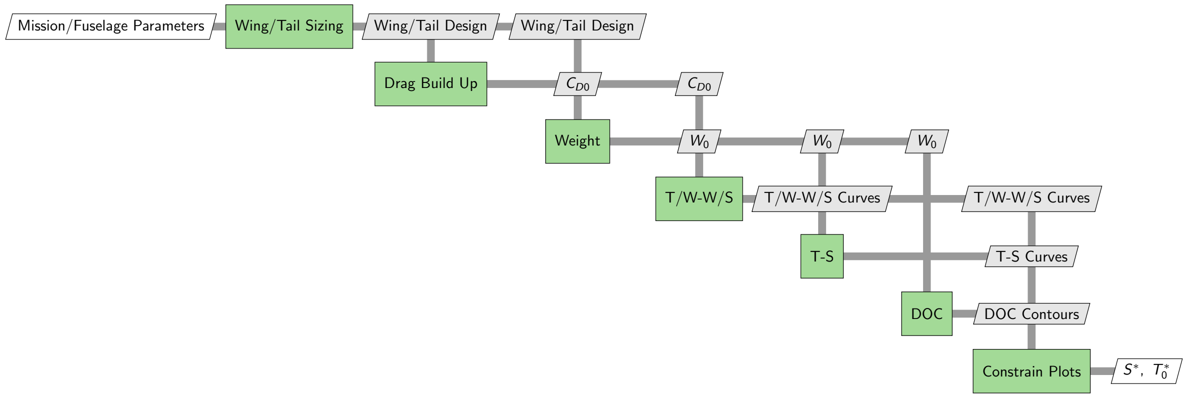
8 Computational Procedure and Software Structure

The following sections detail the inputs, structure, and outputs of our computational scripts.

8.1 Final Sizing Design Procedure

The design point of the S505 was chosen using a computational procedure that calculates the T/W - W/S and the T-S-DOC plot. A visual representation of the flow of information for this algorithm is shown as an XDSM figure in Figure 35. The inputs of this function are a range of T/W and W/S values are used to compute the constraint functions for each flight mode. These are then used to compute the T-S constraint functions, which are then fed to a function that computes the DOC of all possible T-S combinations. All this computed information is then plotted on respective graphs, and visually analyzed to identify the design point. The structure of the software used to generate these graphs will be discussed in Section 8.2. One feature of our software is that we utilize functions that compute wing and tail sizes based on the wing reference area, and these values are then used to compute the parasitic drag and accurate weight estimations.

Figure 35: Main Computation Procedure



8.2 Software Structure

We created the script `final_sizing.m` to compute the $T/W - W/S$ and $T - S$ plot with objective function. This script was organized using functions that computed individual outputs to equations and return corresponding vectors. We utilized structures of variables to keep track of many variable that fell into the same category. The description of the script is below:

- Initial Variables: Drag Polar Structure, Vector of W/S, Vectors of T an S, Fuselage Parameters, Chosen Flight Conditions

- Flight Condition Subfunctions: Each T/W constraint equation that is based on W/S was given a dedicated function with the input as a vector of W/S and the output as the respective T/W for the flight configuration. The equations used to compute the T/W for a given W/S for each flight condition are used defined in Section 4.1 through Section 4.11 in the metabook [3].

- Subfunction `T_convert.m`: The functions that defined the T/W constraints given W/S and a vector of wing reference areas are passed to this function, which implements the weight convergence algorithm implemented in `weight2.m` to calculate the thrust value needed for a constraint at a certain reference area. The $T - S$ contours for each flight condition were computed using this function.

- Subfunction `S_convert.m`: This function operates in a similar manner to `T_convert.m`, but instead requires a vector of thrusts as an input. This function was used to compute the landing $T - S$ constraint.

- Subfunction `weight3.m`: This function implemented a more accurate weight convergence algorithm that is described in Algorithm 5 [3] of the metabook. The psuedocode for this algorithms are shown in Appendix C. The input of this function is a pairing of a thrust and reference area value and cruise flight conditions, and the output is the weight fractions, the converged takeoff gross weight, and the fuel weight.

- Subfunction `cost_analysis.m`: The inputs of this function are the fuel weight and converged takeoff gross weight computed at a (S,T) coordinate using `weight3.m`. This function calculates the total DOC breakdown for the input parameters, and the output represents the DOC of an aircraft that is designed around the (S,T) point that was used to compute the weights. The equations for computing the components of direct operation costs are from Metabook Section 3.4 [3].
- Subfunction `f_tailsizing.m`: This function calculated structures that held critical design variables, such as root chord length, tip cord length, aspect ratio, etc., that were required for weight and drag calculation on the horizontal stabilizer and vertical tail. The design parameters of the two components are calculated using the volume coefficient method. The inputs of this function are a wing reference area, and the outputs are structures containing relevant design parameters for the horizontal and vertical tails.
- Subfunction `f_clean.m`: This function calculates the clean parasitic drag coefficient of the aircraft based on the design of the wing and tail. This is done using the Raymer drag build-up method [2]. The inputs of this function are structures containing the wing and tail design parameters and the output is a parasitic drag coefficient, which is used in the `weight3.m` function.

The functions listed above are implemenyed in the script and the returned vectors are then used to generate the $T/W - W/S$ and $T - S - DOC$ plots.

9 Conclusion

Since our PDR, Sabrewing Inc. has refined our clean-sheet replacement for the Boeing 737 with technologies to further decrease our DOC. To do this, we have implemented raked wing-tips, a low-wing configuration, a single-aisle fuselage, geared turbofans, and an advanced composite structure for the wings and fuselage. We chose these technologies as they are not only widely adopted today, but remained grounded in proven configurations that are effective. Additionally, we performed multiple design refinement studies to again ensure that our DOC could be lowered further from its value at PDR. Specifically, we have implemented a more advanced wing design, with both high-lifting surfaces and twist, as well as placed constraints upon our cruise conditions - particularly the cruising altitude and speed of the S505. With this design, the S505 passes all of it's requirements, in particular it's required range and passenger count, and is working its way towards out-competing the A321XLR.

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[14] Mark Drela Harold Youngren. AVL. `http://web.mit.edu/drela/Public/web/avl/`.

A 737-800 MAX Parameters

Parameters	Boeing 737 MAX-8	Units
Maximum number of passengers	166 Economy & 12 Business	
Number of pilots	2	
Number of passengers for specified range		
Range	3,550	nmi
Cruise Mach number	0.785	
Maximum L/D	16	
Maximum Take-Off Thrust per engine	130.41	kN
Wing aspect ratio	10.	
MTOW	181,200	lbs
Wing reference area	127	m^2
Wing span	35.92	m
$C_{L_{\mathrm{max,takeoff}}}$	2.0	
$C_{L_{\mathrm{max,landing}}}$	2.7	

B Algorithm 4

Algorithm 4 T/W constraint curves for T–S plot

$S = S_{\text{begin}} : \Delta S : S_{\text{end}}$
for $i = 1 : \text{length}(S)$ **do**
    $S_0 = S(i)$ ▷ Prescribe wing area
    $T(i) = T_{\text{guess}}$ ▷ Initial thrust guess
    tolerance $\leftarrow 0.1$ ▷ Convergence tolerance
    converged $\leftarrow$ False
    while converged = False **do**
        $W = W(S_0, T(i))$ ▷ Compute TOGW
        Compute W/S_0 ▷ Compute wing loading
        $(T/W)_{\text{new}} = f(W/S_0)$ ▷ Compute T/W from constraint equation
        $T_{\text{new}} = (T/W)_{\text{new}} \times W$ ▷ Compute new total thrust
        if $|T_{\text{new}} - T(i)| <= \text{tolerance}$ **then** ▷ Check for convergence
            converged = True
        end if
        $T(i) = T_{\text{new}}$ ▷ Uptade thrust value
    end while
end for

C Algorithm 5

Algorithm 5 A more detailed weight estimate

▷ **All values are assumed to be in English units.**

$W_0 \leftarrow W_{\text{guess}}$ ▷ Initial guess
tolerance $\leftarrow 0.1$ ▷ Convergence tolerance
$W_{\text{eng dry}} = 0.521(T_0)^{0.9}$ ▷ Compute engine dry weight
$W_{\text{eng oil}} = 0.082(T_0)^{0.65}$ ▷ Compute engine oil weight
$W_{\text{eng rev}} = 0.034(T_0)$ ▷ Compute engine thrust reverser weight
$W_{\text{eng control}} = 0.26(T_0)^{0.5}$ ▷ Compute engine control weight
$W_{\text{eng start}} = 9.33\left(\frac{W_{\text{eng dry}}}{1000}\right)^{1.078}$ ▷ Compute engine start weight
$W_{\text{engine}} = W_{\text{eng dry}} + W_{\text{eng oil}} + W_{\text{eng rev}} + W_{\text{eng control}} + W_{\text{eng start}}$ ▷ Compute engine weight
$W_{\text{fuse}} = 5S_{\text{fuse}}$ ▷ Compute fuselage weight
$W_{\text{ht}} = 5.5S_{\text{ht}}$ ▷ Compute horizontal tail weight
$W_{\text{wing}} = 10S_{\text{wing}}$ ▷ Compute Wing weight
$W_{\text{vt}} = 5.5S_{\text{vt}}$ ▷ Compute vertical tail weight
converged $\leftarrow$ False
while converged = False **do**
  Compute $\frac{W_f}{W_0}$ ▷ Compute fuel fraction
  $W_{\text{f}} = \frac{W_f}{W_0} \times W_0$ ▷ Compute fuel weight
  $W_{\text{lg}} = 0.043W_0$ ▷ Compute landing gear weight
  $W_{\text{xtra}} = 0.17W_0$ ▷ Compute extra weight
  $W_{0_{\text{new}}} = n_{\text{engine}}W_{\text{engine}} + W_{\text{Wing}} + W_{\text{ht}} + W_{\text{vt}} + W_{\text{fuse}} + W_{\text{xtra}} + W_{\text{lg}} + W_{\text{f}} + W_{\text{payload}} + W_{\text{crew}}$
▷ Compute the new MTOW
  if $|W_{0_{new}} - W_0| <=$ tolerance **then** ▷ Check for convergence
    converged = True
  end if
  $W_0 = W_{0_{\text{new}}}$ ▷ Update MTOW value
end while

D Roskam Horizontal and Vertical Tail Parameters

The following figures showing the parameters used to calculate the sizing of the empennage are taken from Roskam [1].

Table 8.13 Planform Design Parameters for Horizontal Tails

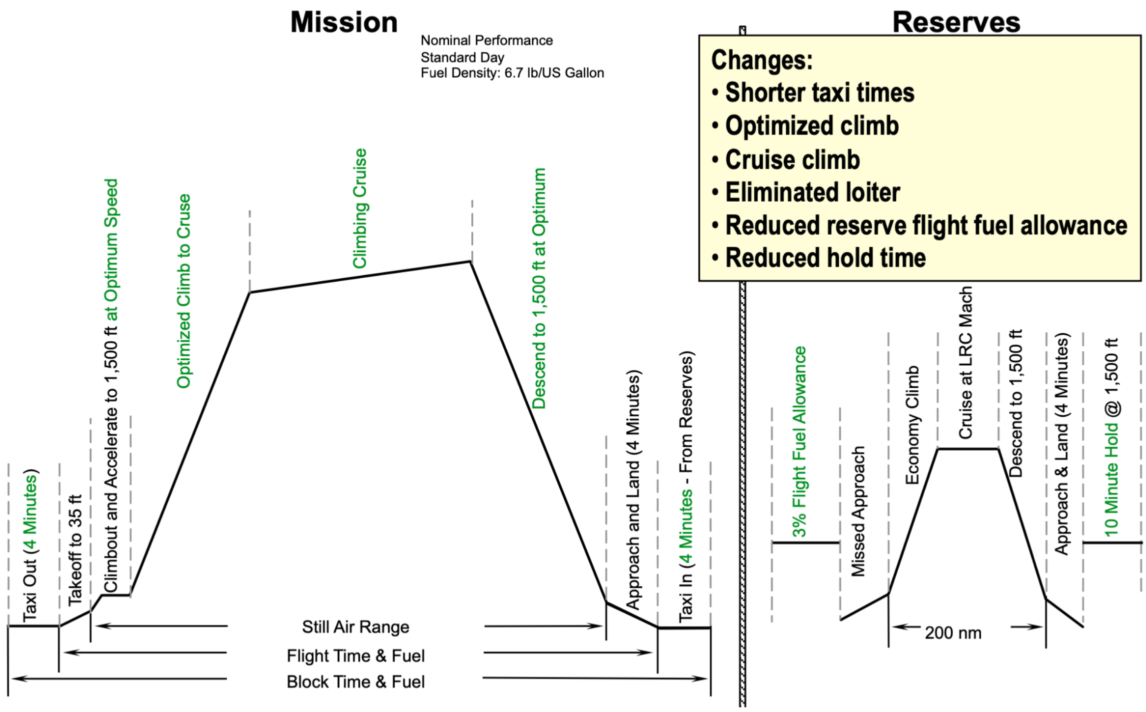
Type	Dihedral Angle, Γ_h deg.	Incidence Angle, i_h deg.	Aspect Ratio, A_h	Sweep Angle, $\Lambda_{c/4_h}$ deg.	Taper Ratio, λ_h
Homebuilts	+5 - -10	0 fixed to variable	1.8 - 4.5	0 - 20	0.29 - 1.0
Single Engine Prop. Driven	0	-5 - 0 or variable	4.0 - 6.3	0 - 10	0.45 - 1.0
Twin Engine Prop Driven	0 - +12	0 fixed to variable	3.7 - 7.7	0 - 17	0.48 - 1.0
Agricultural	0 - +3	0	2.7 - 5.4	0 - 10	0.59 - 1.0
Business Jets	-4 - +9	-3.5 fixed	3.2 - 6.3	0 - 35	0.32 - 0.57
Regional Turbo-Props.	0 - +12	0 - 3 fixed to variable	3.4 - 7.7	0 - 35	0.39 - 1.0
Jet Transports	0 - +11	variable	3.4 - 6.1	18 - 37	0.27 - 0.62
Military Trainers	-11 - +6	0 fixed to	3.0 - 5.1	0 - 30	0.36 - 1.0
Fighters	-23 - +5	0 fixed to variable	2.3 - 5.8	0 - 55	0.16 - 1.0
Mil. Patrol, Bomb and Transports	-5 - +11	0 fixed to variable	1.3 - 6.9	5 - 35	0.31 - 0.8
Flying Boats, Amph. and Float Airplanes	0 - +25	0 fixed	2.2 - 5.1	0 - 17	0.33 - 1.0
Supersonic Cruise Airplanes	-15 - 0	0 fixed to variable	1.8 - 2.6	32 - 60	0.14 - 0.39

Table 8.14 Planform Design Parameters for Vertical Tails

Type	Dihedral Angle, Γ_v deg.	Incidence Angle, i_v deg.	Aspect Ratio, A_v	Sweep Angle, $\Lambda_{c/4_v}$ deg.	Taper Ratio, λ_v
Homebuilts	90	0	0.4 - 1.4	0 - 47	0.26 - 0.71
Single Engine Prop. Driven	90	0	0.9 - 2.2	12 - 42	0.32 - 0.58
Twin Engine Prop Driven	90	0	0.7 - 1.8	18 - 45	0.33 - 0.74
Agricultural	90	0	0.6 - 1.4	0 - 32	0.43 - 0.74
Business Jets	90	0	0.8 - 1.6	28 - 55	0.30 - 0.74
Regional Turbo-Props.	90	0	0.8 - 1.7	0 - 45	0.32 - 1.0
Jet Transports	90	0	0.7 - 2.0	33 - 53	0.26 - 0.73
Military Trainers	90	0	1.0 - 2.9	0 - 45	0.32 - 0.74
Fighters	75 - 90	0	0.4 - 2.0	9 - 60	0.19 - 0.57
Mil. Patrol, Bomb and Transports	90	0	0.9 - 1.9	0 - 37	0.28 - 1.0
Flying Boats, Amph. and Float Airplanes	90	0	1.2 - 2.4	0 - 32	0.37 - 1.0
Supersonic Cruise Airplanes	75 - 90	0	0.5 - 1.8	37 - 65	0.20 - 0.43

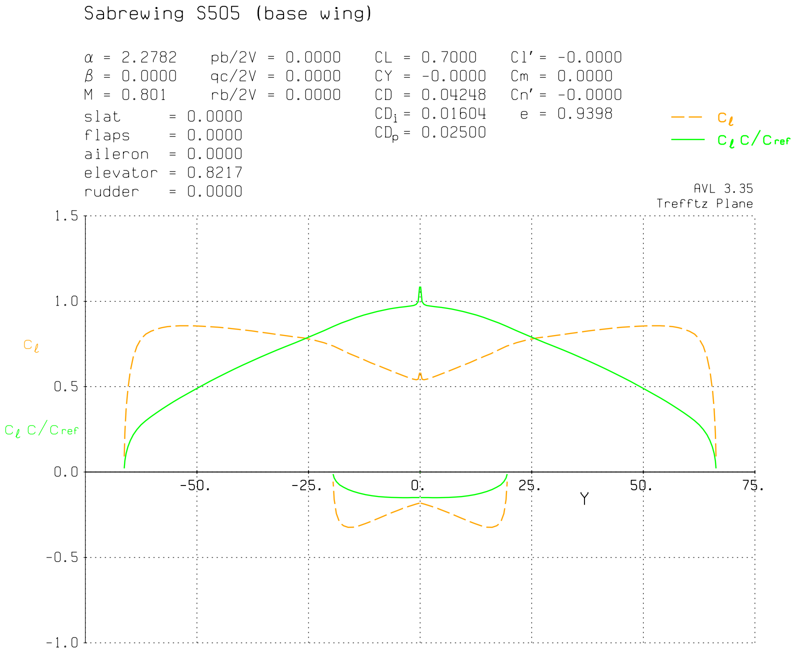
E NextGen Flight Path

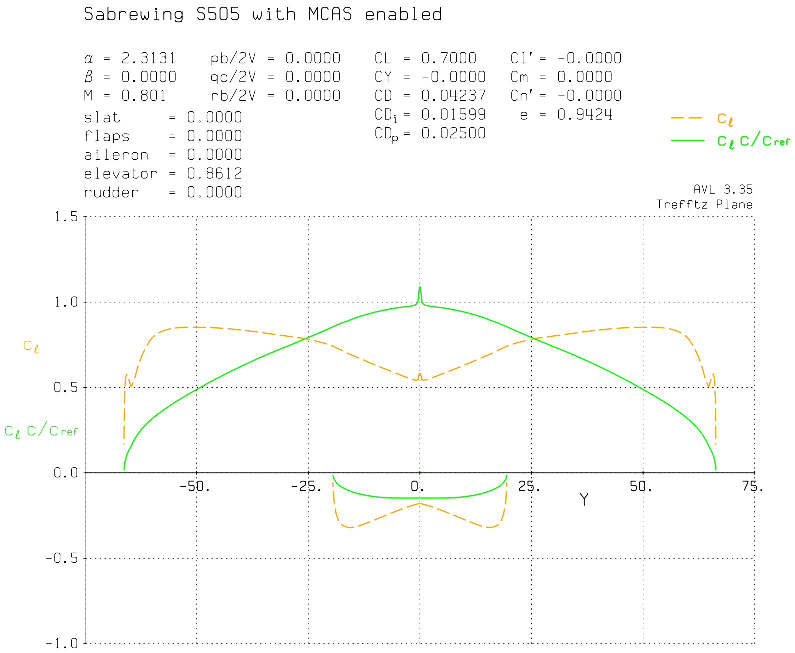
The flight path of our aircraft follows the NextGen Flight path taken out of the Metabook [3]



F AVL Raked Winglet Study

Below are trimmed Trefftz plots for our wing with no winglets (top) and with raked wingtips (bottom).





G Preliminary Weight Estimation of Takeoff Weight

To begin our preliminary sizing process, we started by researching the performance parameters, notably, the empty and loaded weights of similarly sized aircraft such as the A321XLR, A320neo, B737-MAX 9, B757-200, and B767-200. By performing a regression analysis on the MTOW of each plane as a function of their empty weight, we obtained a logarithmic relationship that could be used to estimate the ratio of MTOW to empty weight in the form of $\frac{W_E}{W_0} = AW0^C$. Next, using data from Roskam, we obtained feasible fuel fractions for a typical flight, including, details of which can be seen below in Table 6 [1].

Weight Fraction	Value	Segment
W_1/W_0	0.992	Warmup
W_2/W_1	0.996	Taxi
W_3/W_2	0.996	Takeoff
W_4/W_3	0.99	Climb
W_5/W_4	–	Cruise
W_6/W_5	0.992	Descent
W_7/W_6	0.992	Landing

Table 6: Weight fractions for a typical flight, taken from Roskam [1]

To obtain W5/W4, we use the following relation stemming from the Breguet Range equation.

$$\frac{W_5}{W_4} = exp(\frac{-Rc}{V(L/D)}) \tag{3}$$

Knowing this, the empty weight to MTOW ratio can be calculated according to equation 4.

$$\frac{W_f}{W_0} = 1 - \frac{W_7}{W_6}\frac{W_6}{W_5}\frac{W_5}{W_4}\frac{W_4}{W_3}\frac{W_3}{W_2}\frac{W_2}{W_1}\frac{W_1}{W_0} \tag{4}$$

Finally, we now can solve for a final MTOW value using equation 5 below.

$$W_0 = \frac{W_{crew} + W_{payload}}{1 - \frac{W_f}{W_0} - \frac{W_e}{W_0}} \tag{5}$$

To automate the initial weight estimation process, the function `prelim_weight_v2.m` was created in MATLAB - details of which can be seen in Section **??**. Given an initial guess for W0, the code repeatedly solves for a new W0 according to the process explained above and until a converged value is found. Pseudocode of the algorithm can be found in Appendix **??**. Using an initial guess of 240000 lbs, `prelim_weight_v2.m`. yielded a MTOW estimate of 245880 lbs for the S505.