MAE 159 Aircraft Design
Final Design Report

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MAE 159

Aircraft Design

FINAL REPORT

I. *Summary of the Airplane Design Study*

This report is a study of the effect of design payload on the cost and performance of a subsonic commercial transport aircraft. Further, this paper will illustrate the reasoning behind the final design as well as present an industry standard drawing of the aircraft. To approach this problem one first consider the design specifications provided as they dictate what the Payload, Range, Takeoff Field Length (TOFL), Cruise Speed, Landing Approach Speed and Initial Cruise Altitude are. It is crucial to first come up with a desired performance before one can tackle this problem as it doesn't leave the design too open ended. This aircraft design was constrained by the following specifications. The Range in still air is 3500 nautical miles, TOFL is 7500 feet, Landing Approach Speed is 135 knots and is to land with the design payload and 75% of its maximum fuel with a cargo weight of 3000 lbs. Further, the Cruise Mach Number is .8 and the Initial Cruise Altitude is 35,000 feet. The aircraft is designed to takeoff and land on a hot day of $84° F$. The design however calls for two different aircrafts, one that carries 150 passengers and another that carries 220 passengers. To obtain an optimized airliner design, one must focus on the design parameters and how they affect the outcome of an optimal airplane. There are numerous combinations that can lead to thousands of different aircraft configurations that satisfy the design specifications. On top of the previous requirements the plane must also satisfy requirements pertaining to center of gravity locations, door locations, landing gear sizing and placement, and interior layout. In any case, the purpose of this report is to find not only the most inexpensive airplane, but to present and justify the final aircraft design after everything is taken into consideration. The goal of this aircraft is to be attractive to airline companies in a business sense as the companies one would sell them too can make or break an aircraft company's future. If the aircraft is too expensive there will be few sold, however one must take into consideration the comfort of the people who are ultimately going to be riding these planes. The more comfortable a plane is the better reputation an airline may become and thus the better relationship an airline and aircraft manufacturing company may have.

The sizing procedure involved a mathematical algorithm that allowed for the variation of independent variables such as Aspect Ratio, Sweep, Number of Engines, Airfoil Type, and Structural Material that altered the final design. In addition to the sizing parameters the interior layout and balancing of the aircraft played a major role in the outcome of this design. For the sizing aspect of the design the analysis becomes fight between aspect ratio, sweepback angle, wing thickness and C_L. Aspect ratio will dictate span and planform area and the more span available the better an airplane can perform in the aspects of lift and drag. However, problems arise when the structure of the wing cannot support itself leading the design to have a thicker wing as it lighter. Wing thickness can also formulate a problem, when an aircraft has a desired cruise speed of .8 times the speed of sound, air around the wing can be accelerated to even higher speeds. Ultimately the design will approach a point where the wing will develop a shockwave at the crest of the airfoil. Shockwaves are undesirable as they lead to an increase in drag. One solution is to give the wing a sweep angle because in doing so the air velocity of interest becomes only a component of the original airspeed. The second solution would be to use a supercritical airfoil designed to avoid shockwave creation or a combination of the two. It can be inferred that this design is driven by a reduction in weight, more specifically the takeoff weight (WTO). The payload and range are essentially fixed will specify a fixed percentage of the total weight. The airframe cost is inevitably the main deciding factor to the direct cost to operate

(DOC) that can be altered. Noted in figure 1, the direct cost to operate was seen to be proportional to the takeoff weight of the aircraft, but one should be careful not to sacrifice performance. The figure shows how the cost changes as the aircraft's wing size changes for the 150 PAX configuration using supercritical airfoils, advanced technology engines and with 6 seats abreast and 1 aisle.

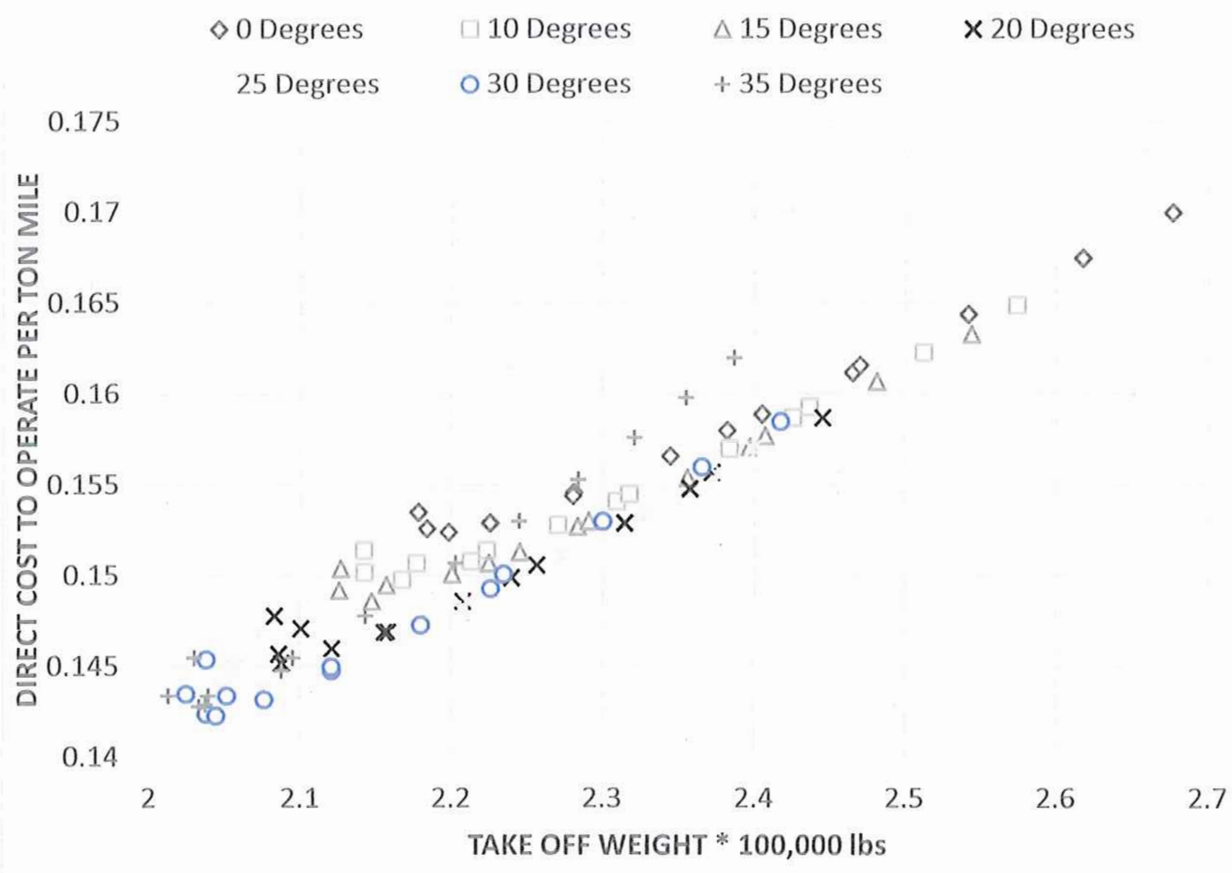


Figure 1: Surpercritical 150 PAX 6 Abreast 1 Aisle + Advanced Technology

Indeed one of the main tasks for this analysis was to reduce the takeoff weight as much as possible. Wing size was a crucial factor as it was dictated by a percentage of the takeoff weight but still had to be large enough to provide the aerodynamic lift and store the majority of the fuel needed to perform its duty. Since the relationship between the DOC and WTO takes a positive linear fashion the relation of both the DOC and the WTO to the aspect ratio can be seen by comparing one of the combinations. As shown in figure 2, it is easy to see that the direct cost to operate finds a minimum cost for a specific sweep back angle and aspect ratio. This was the trend for both PAX sizes.

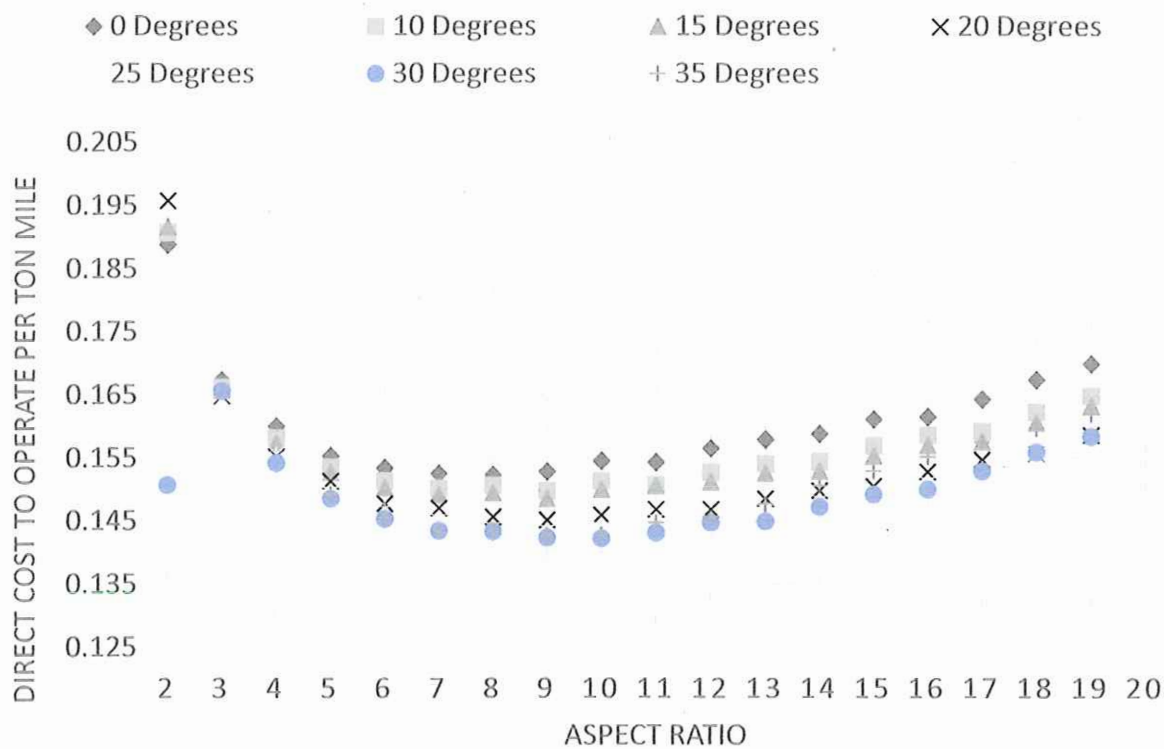


Figure 2: Supercritical 150 PAX 6 Abreast 1 Aisle + Advanced Technology 2 Engines

The Aspect Ratio must be chosen carefully with an appropriate sweep in order to be the most cost effective. After the mathematical analysis the result lead the 150 PAX design to have an aspect ratio of 10 and a sweep of 30 degrees and the 220 PAX design to have an aspect ratio of 8 and a sweep of 30 degrees. Further sizing dimensions and performance parameters can be found in the next section.

The payload-range plot illustrates an aircraft's performance in range as fuel is traded for payload. One must keep the takeoff weight constant for this analysis and at the design WTO. Arbitrarily an extra 2000 lbs is added to the design payload to see the potential range an aircraft has as 2000 lbs extra may be necessary in a real life situation. Indeed the aircraft's range should decrease as the payload is increased. This effects only the initial and final weights used in the Breguet range equation: $Range = \frac{V}{C}\frac{L}{D}\ln\left(\frac{w_o}{w_f}\right)$. Figure 3 is the payload-range plot for both PAX sizes with the payloads annotated.

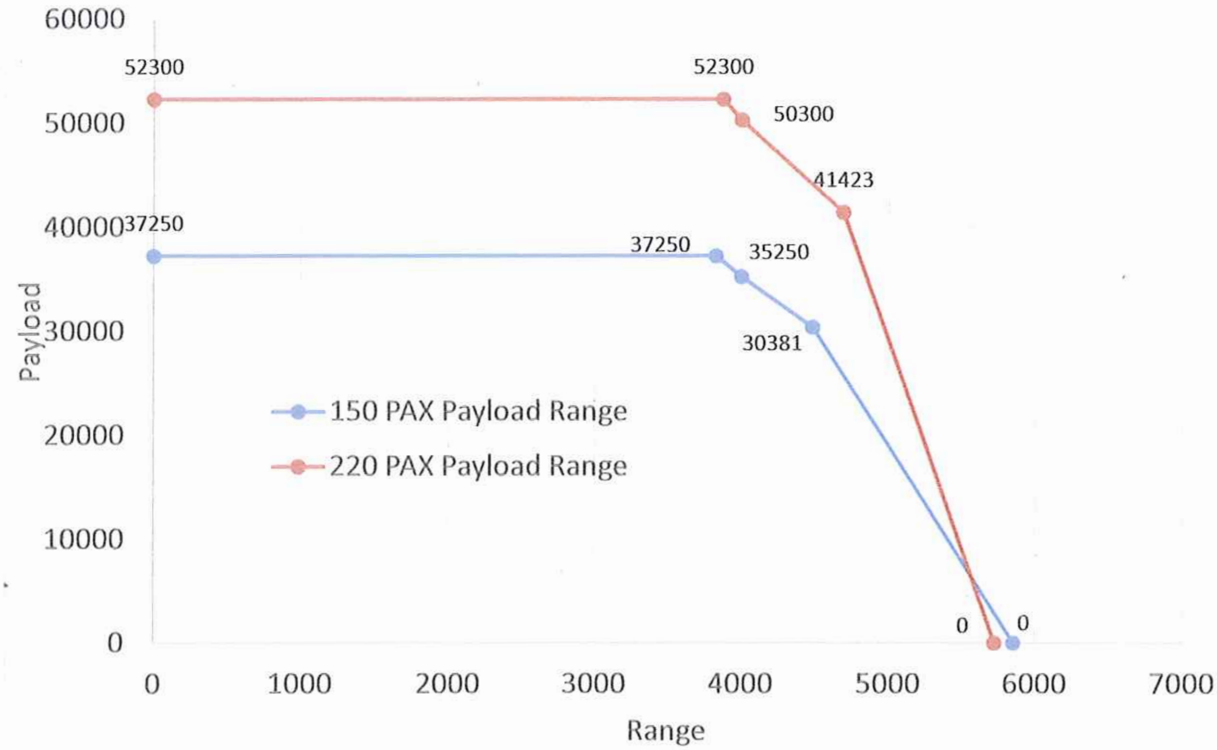


Figure 3: Payload-Range

Both planes have an interesting payload range in which the 220 PAX shows a very desirable maximum payload over the 150 PAX aircraft, however the variation from the payload range tradeoff is much better for the 150 PAX. Both aircraft achieve very equivalent ranges similar to the design range within a wide range of different takeoff weights. This may be very appealing to airlines that look to find planes that are versatile dynamically as far as range and payload are concerned.

The JT8D is the predecessor of the JT9D. The JT9D is guaranteed by Pratt & Whitney to provide more thrust and have a lower fuel consumption. The JT9D was selected as the engine model of choice. The implementation of advanced technology can increase the efficiency of the fuel consumption but does come with its own risks. One notable concern with using advanced technologies is the price for materials. In figure 4 it is shown that using Advanced Technology Engines will decrease the DOC. Advanced technology can be considered what the fan and turbine blades are made of in this case. An engine can be limited by the turbine's material integrity to heat or by the weight of the fan blades and how it related to the turbine's required power output. Any improvement in material can greatly improve the efficiency of the engine.

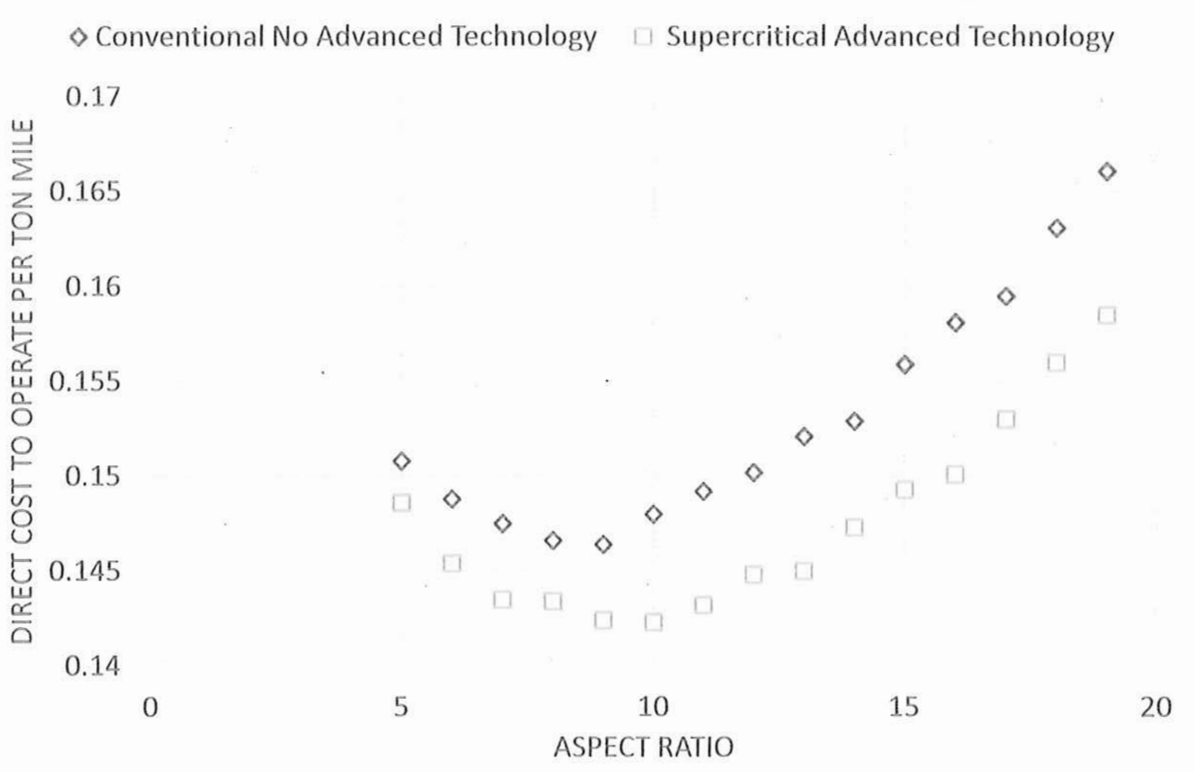


Figure 1: 150 PAX 6 Abreast 1 Aisle 2 Engines

Above the figure shows the power in combining both advanced technology engines with supercritical airfoils. As a warning, the cost of purchasing, manufacturing, maintaining, and replacing these advanced parts can run the risk of costing the company money if anything went wrong. Needless to say advanced technologies will cost more to implement and the cost might not stay fixed due to the industry's fluctuations in prices for these exotic materials. It's hard to stray from conventional materials since methods for production and maintenance have been mostly fleshed out over the years. If a new problem arises with the implementation of these new technologies solving that problem alone can lead a company to bankruptcy. The same can be said for the material chosen for the airframe. Aluminum is easy to work with as it can be welded and is ductile. Today though, weight can be saved by using composites. Composite materials can seem very attractive, as indicated by figure 1 the less takeoff weight the less the aircraft will cost to operate. Unfortunately the cost to produce and maintain airframe structures can be very heavy for newer companies. New procedures must be developed and tested rigorously to build the parts and guarantee quality for a certain lifespan. These new procedures will be costly on their own as new tools will have to be developed in the process. It's a gamble for a company to risk all of the chips on a new aircraft and the return profit could take years to break even. However don't let this be a hindrance to the company, eventually risks must be taken to stay in business, the implementation of composites seems to be the future and that's where a company must head.

II. *Description of the Configuration*

A major consideration for an aircraft design is that the aircraft must be able to make a profit. The faster the aircraft can be loaded unloaded and refueled the more money the airline company can make making it a more desirable aircraft. For both aircraft, the comparison was made between having 2 or 1 aisle. For 150 PAX this seems almost trivial, the more aisles the quicker the passenger can board and leave but this results in a very wide aircraft. There are troubles in drag by surface area and ultimately weight as hull diameter increases dramatically. For 220 PAX having 2 aisles is very desirable as the turn time would be decrease substantially. The cost for building a single aisle airplane for 220 PAX is reduced greatly but the attractiveness for a shorter turn time from airlines is far greater when one considers the extra flights it will have over the useful life. For this reason a twin aisle was chosen.

Another consideration was the comfort a passenger would feel when aboard one of these aircrafts. For the 150 PAX aircraft the seat pitch was 35in with a seat pan of 19in and an aisle width of 22in for coach. For first class a seat pitch of 60in with a seat pan of 21in and an aisle width of 26in were chosen. The 12 seats allocated to first class allows plenty of leg and elbow room possibly a wider seat pitch could have been selected but this in only a preliminary design that should go through many iterations. For coach being on a long flight can be uncomfortable for a flight with a 9 hour block time. Any extra leg room becomes an oasis. The same can be said for the wider seats. The same reasoning for the 220 PAX aircraft can be said again though it is harder to maintain a smaller diameter when one does not want to sacrifice comfort. The seat pitch for the 220 PAX aircraft was 33in with a 19in seat pan and an 18in aisle width and allowed for 20 seats in first class. Both planes had 6 seats abreast to maintain seat pan size. When doing the layout for both aircrafts it was necessary to make the fuselage diameters and lengths larger to avoid sacrificing seat pan and aisle length but also to accommodate the nose and tail section.

One final note about the 220 PAX aircraft regarding the landing gear. It has become apparent that when having 6 seats abreast then fuselage diameter and length become set and cannot change very drastically afterwards. The length of the fuselage becomes problematic. To satisfy a 12°~14° rotation on takeoff the main landing gear must be placed in a location that allows for that, but also it must raise the aircraft up enough to avoid a tail strike. Since the 220 PAX aircraft was very long the main landing gear regrettably ended up being very tall, meaning that it would also be very heavy. This is not desirable and as mentioned before the design would have probably started a new iteration, perhaps using 7 seats abreast.

Table 1: Design Specifications with Adjusted Lengths

Layout and Sizing Specifications					
	150	220		150	220
Interior			Outer Surfaces		
Seat Pitch 1st	60 in	60in	Nose L/D	1.5	1.5
Seat Pitch Co.	35in	33in	Tail L/D	3.1	2.6
Seat Pan 1st	21in	24in	Fuselage L	154.45 ft	178 ft
Seat Pan Co.	19in	19in	Fuselage D	168in	180in
Seats Abreast Co.	6	6	Wing Span	128.61 ft	138.25 ft
Seats Abreast 1st	4	4	Wing Planform	1654 sq ft	2389 sq ft
Seats in 1st	12	20	Wing Sweep	30 deg	30 deg
Seats in Co.	138	200	Wing Aspect Ratio	10	8
Aisles	1	2	Tail Section Sweep	30 deg	30 deg
Aisles Width	22in	20in	Vertical Tail Span	280.32in	332.64in
Lavatories	6	6	Vertical Tail Planform	3143 sq in	4426 sq in
Carts	17	22	Vertical Tail Aspect Ratio	2.5	2.5
Gallies	3.5	3	Horizontal Tail Span	461.16in	557.04
Emergency Exits	6	7	Horizontal Tail Planform	4253.4 sq in	6206 sq in
X, A, B, Doors Used	2, 4, 1	2, 2, 2	Horizontail Tail Aspect Ratio	5	5
Engine: JT9D			Landing Gear & Container		
Inlet Diameter	87.59in	104.1in	Tire Size Main	40in x 14in	46in x 16in
Fan Diameter	78.63in	94.63in	Tire Size Nose	29in x 7.7in	40in x 14in
Thrust Ratio	0.6938	0.98	Strut Length Static	53in	114in
Nacelle Length	202.33in	213.9in	Nose/Main Spacing	632.55in	690in
Dist. From Fuselage	338.64in	361.68in	Container Type	LD-W Double	LD3A Single
Inlet to Leading Edge	195.2in	208.2in	Containers Used	14	11

Table 2: Initial Design Performance Specifications with Original Design Lengths

Size	ADV Tech	Supercritical	Aisles	Abreast	# Engines
150	yes	yes	1	6	2
220	yes	yes	2	6	2
	Takeoff Weight	Span	Planform Area	Fuselage L	Fuselage D
150	204,430 lb	128.61 ft	1654.1 ft^2	127.2 ft	13.08 ft
220	283,850 lb	138.25 ft	2389.3 ft^2	171.07 ft	14.66 ft
	Sweep	t/c	Aspect Ratio	CL_IC	CL_max_TO
150	30 deg	0.1391	10	0.5332	2.408
220	30 deg	0.1391	8	0.5125	2.2779
	CL_max_LDG	W/S_TO	W/S_LDG	M_Div	Delta M_Div
150	3.3115	123.59 lb/ft^2	114.97 lb/ft^2	0.7968	0.0072
220	3.1826	118.80 lb/ft^2	110.50 lb/ft^2	0.7968	0.0072
	Thrust	Thrust/Eng	SFC 35K ft	Fuel Fraction 9D	Thrust/Weight
150	63,132 lb	31,566 lb	0.5956	0.2788	3.2381
220	89,178 lb	44,589 lb	0.5956	0.2794	3.1829
	Drag: f	Efficiency: e	Cf Wing	Cf Fuselage	CDo
150	31.7357	0.7911	0.0031	0.002	0.0192
220	41.2857	0.8333	0.003	0.0019	0.0173
	Range Total	Range All Out	L/D Cruise	Thrust req Scaled	T_req_scale/Eng
150	3996 n mi	4045 n mi	16.1763	15,523 lb	77,613 lb
220	3996 n mi	4045 n mi	16.1269	15,298 lb	76,491 lb
	Climb Range	Fuel Climb	Rate of Climb	SFC 20k ft	Time to Climb
150	118.0482 n mi	3,455 lb	2041.1 ft/min	0.6038	17.14 min
220	120.991 n mi	4,834 lb	2091.9 ft/min	0.6183	16.73 min
	GRAD 1	GRAD 2	GRAD 3	GRAD 4	GRAD 5
GRAD Min 2 Eng	0%	2.40%	1.20%	2.10%	3.20%
150	2.48%	3.63%	3.72%	3.11%	16.43%
220	1.92%	3.01%	3.50%	2.60%	15.88%
	Weight Payload	Weight Airframe	Weight Engine	Cost Airframe	Cost Engine
150	17.625 Tons	91,212 lb	19,398 lb	$10,381,022.10	$1,204,561.70
220	25.15 Tons	124,650 lb	27,401 lb	$13,306,636.90	$1,433,765.80
	Flight Crew	Fuel & Oil	Insurance	Maintenance	Depreciation
150	$0.0248	$0.0500	$0.0039	$0.0318	$0.0315
220	$0.0187	$0.0487	$0.0035	$0.0271	$0.0279
	DOC per Ton Mile		Cost Per Passenger Mile		
150	$0.1423		$0.01671		
220	$0.1261		$0.01441		

Lastly, an interesting case study for a 150 PAX fuselage with a 220 PAX wing was proposed for the sake of commonality and cost in construction. This could be favorable if a company manufactures fuselages and wings separately. Consider the tooling and methods for each of the 4 different parts. The company would be able to save money by using only one wing design for both fuselages.

Table 3: Point Design Wing Comparison

	220 PAX Wing	With 150 PAX Fuselage		AR	8
	Planform Area	2389.3 ft^2		Span	138.25 ft
	WTO	Weight Fuel	Thrust/Eng	DOC	
150 Wing/ 150 Fuse	204,430 lb	55,581 lb	31,566 lb	$0.1423	
220 Wing/ 150 Fuse	207,570 lb	60,672 lb	32,799 lb	$0.1467	

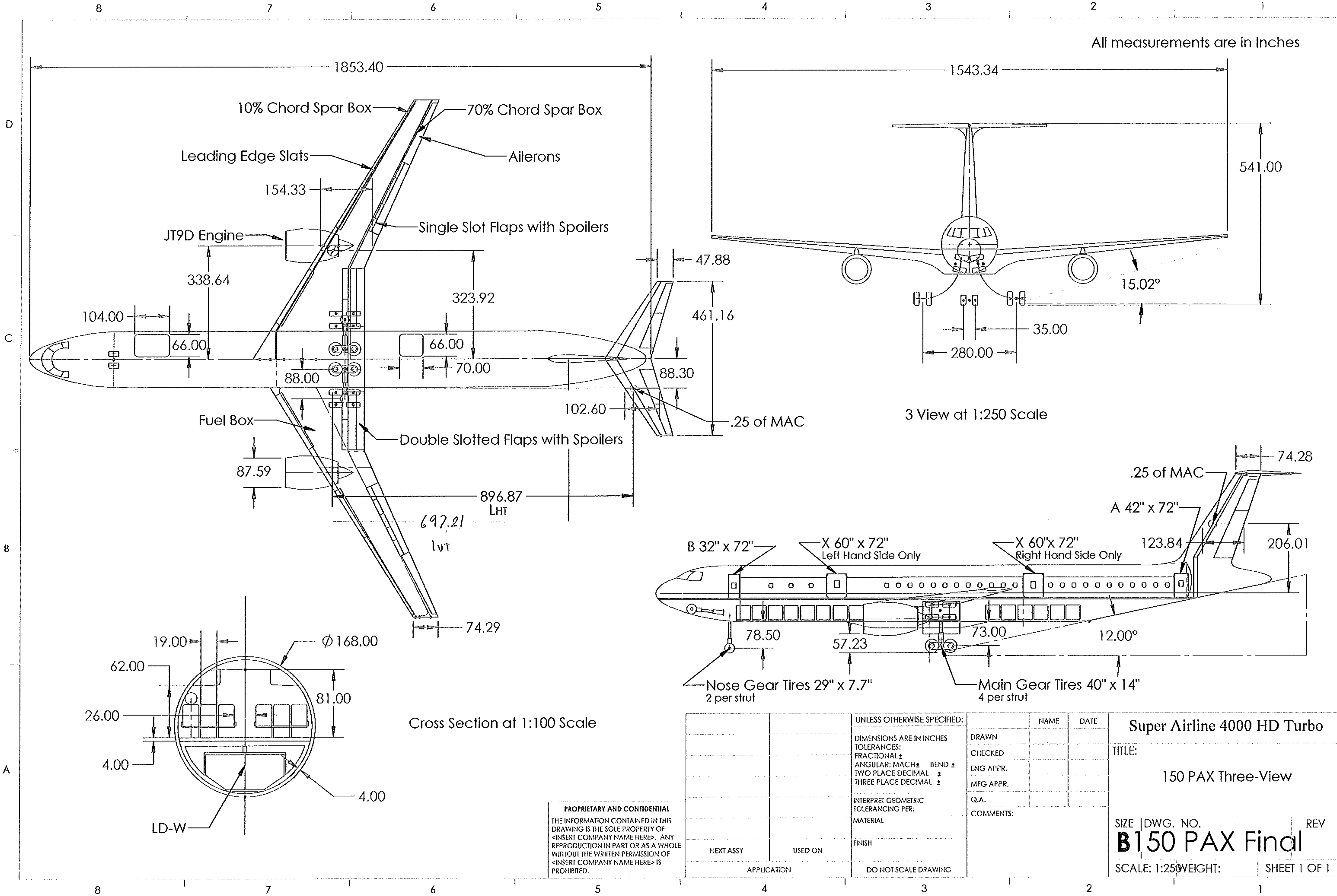
The result is that the cost to produce the 150 PAX aircraft with a wing design for a 220 PAX aircraft contains a 3% difference from an optimized 150 PAX aircraft. If the cost to produce tools and proper spacing for a second area to produce a second wing configuration is taken into account the 3% may seem to be a favorable increase. Not only does having commonality in the wings result in a favorable outcome but also anything else that has commonality will reduce tooling costs, contract costs, and necessary production area. Both noses were designed with the same fineness ratio hence the same efficiency from using the same wing can be applied to the nose section as well.

Upon completing the three-view for the point design aircraft it was interesting to note that the tail volume needed to be altered from .08 to 0.0846 for the vertical tail and 1.1 to 1.2137 for the horizontal tail in order to fit within the allotted fuselage length and selected tail section fineness ratio.

References

Schaufele, Roger D. *The Elements of Aircraft Preliminary Design*. Santa Ana, CA: Aries Publications, 2000. Print.

Shevell, Richard Shepherd. *Fundamentals of Flight*. Englewood Cliffs, NJ: Prentice-Hall, 1983. Print.



All measurements are in Inches
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70% Chord Spar Box
Leading Edge Slats
Ailerons
154.33
JT9D Engine
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338.64
323.92
47.88
461.16
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66.00
66.00
70.00
88.00
88.30
102.60
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Fuel Box
Double Slotted Flaps with Spoilers
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896.87
LHT
697.21
lvt
74.29
1543.34
541.00
15.02°
35.00
280.00
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.25 of MAC
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123.84
206.01
B 32" x 72"
X 60" x 72"
Left Hand Side Only
X 60"x 72"
Right Hand Side Only
78.50
57.23
73.00
12.00°
Nose Gear Tires 29" x 7.7"
2 per strut
Main Gear Tires 40" x 14"
4 per strut
19.00
Ø 168.00
62.00
81.00
26.00
4.00
4.00
LD-W
Cross Section at 1:100 Scale
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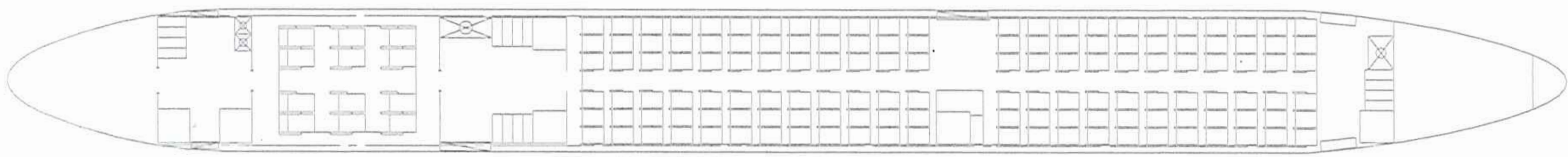
Interior Arrangement
150 Passengers
Mixed Class



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Seat Pitch - 60in
4 Abreast

Economy Class - 138
Seat Pitch - 35in
6 Abreast

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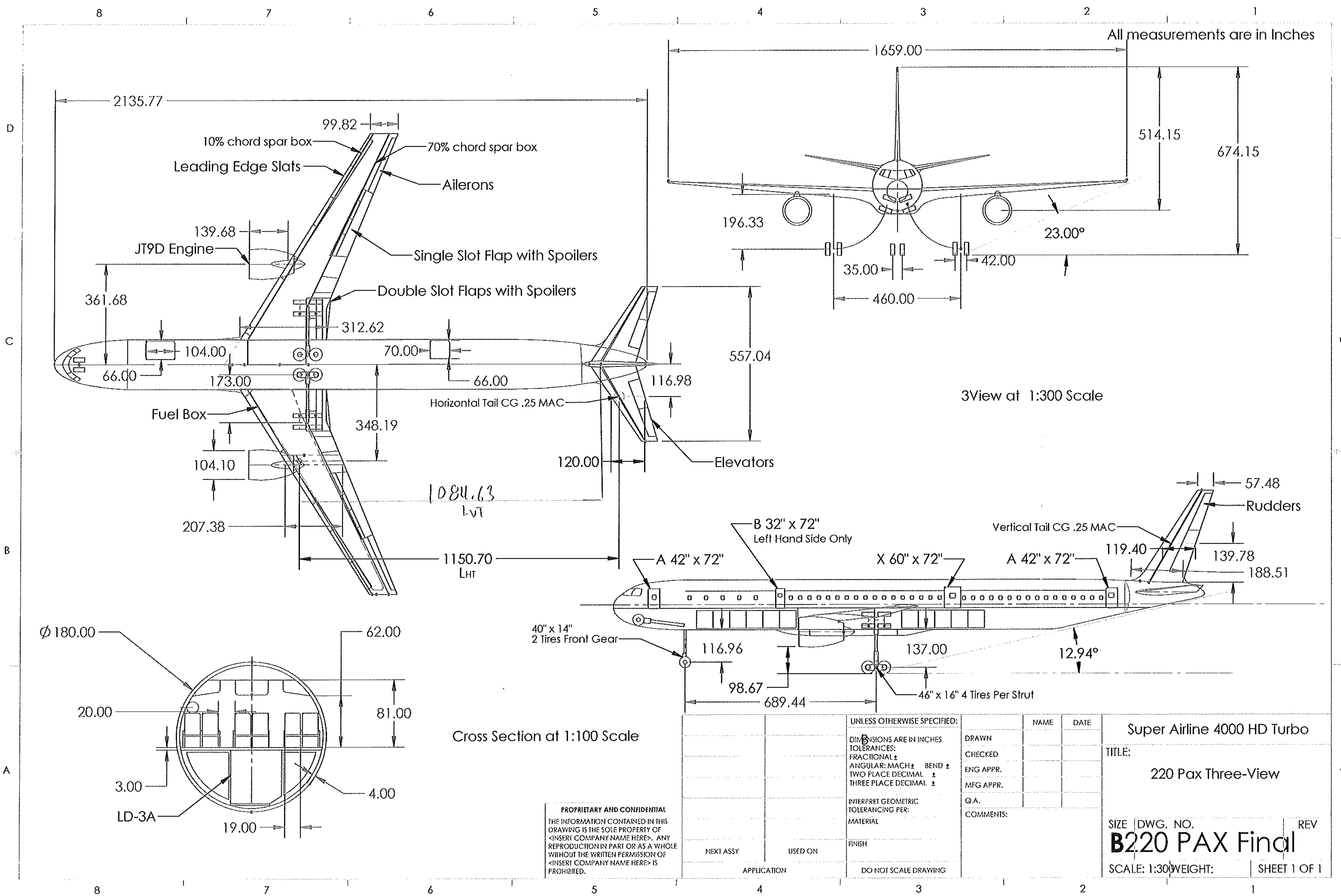
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70% chord spar box
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Ailerons
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JT9D Engine
Single Slot Flap with Spoilers
Double Slot Flaps with Spoilers
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Fuel Box
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Elevators
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23.00°
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3View at 1:300 Scale
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Left Hand Side Only
Vertical Tail CG .25 MAC
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139.78
A 42" x 72"
X 60" x 72"
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TITLE:
220 Pax Three-View
SIZE
DWG. NO.
REV
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220 PAX Final
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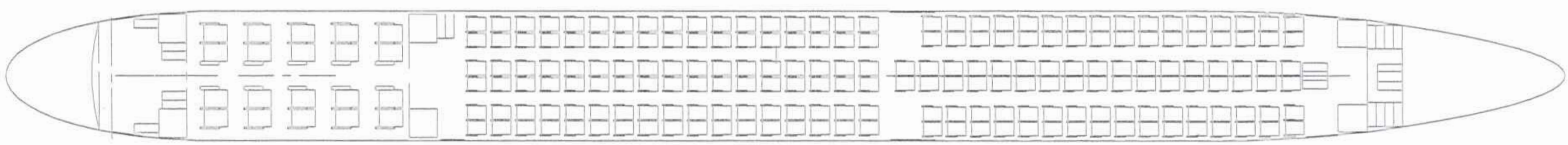
WEIGHT:
SHEET 1 OF 1

Interior Arrangment
220 Passengers
Mixed Class



First Class - 20
Seat Pitch - 60in
4 Abreast

Economy Class - 200
Seat Pitch - 33in
6 Abreast

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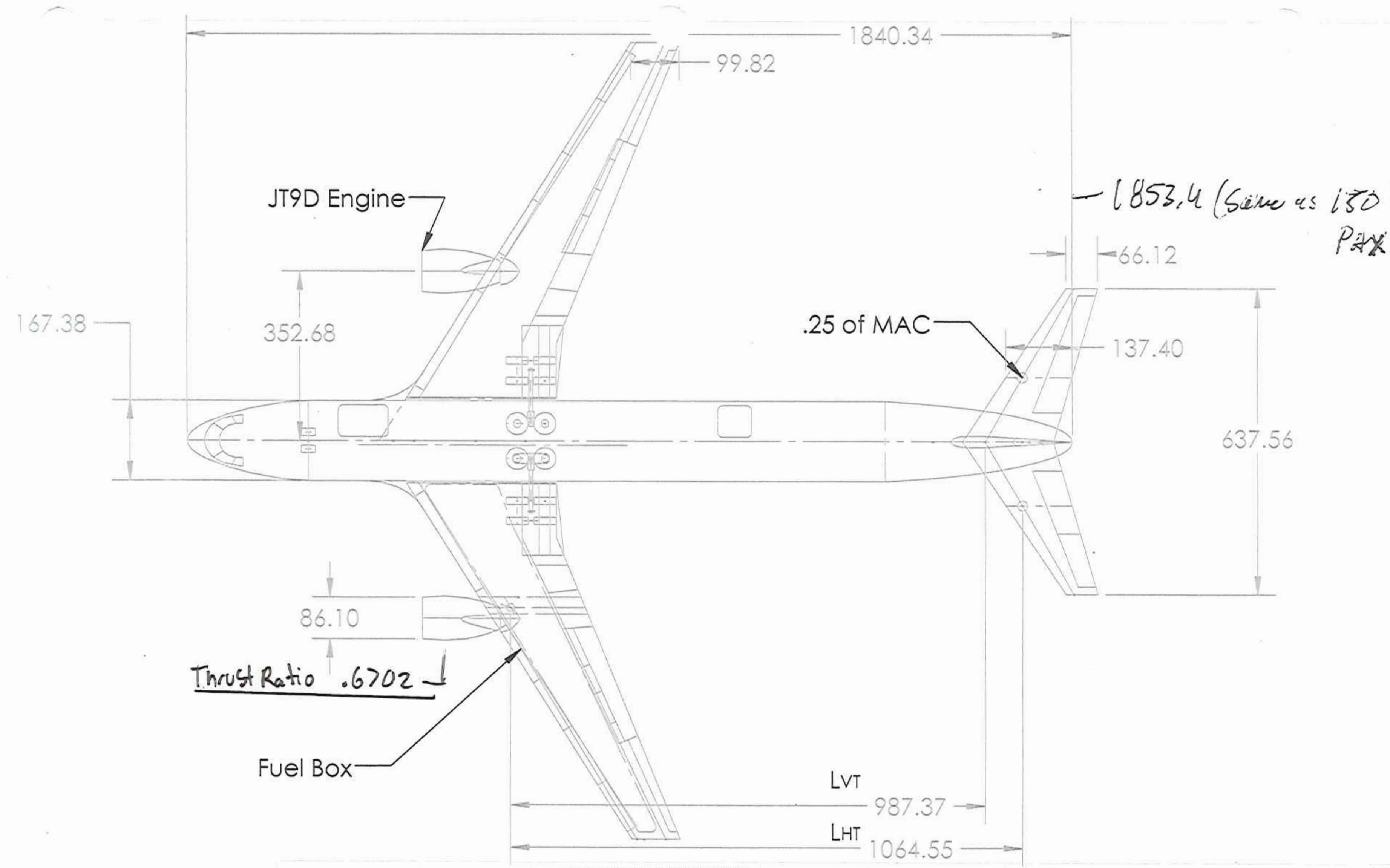

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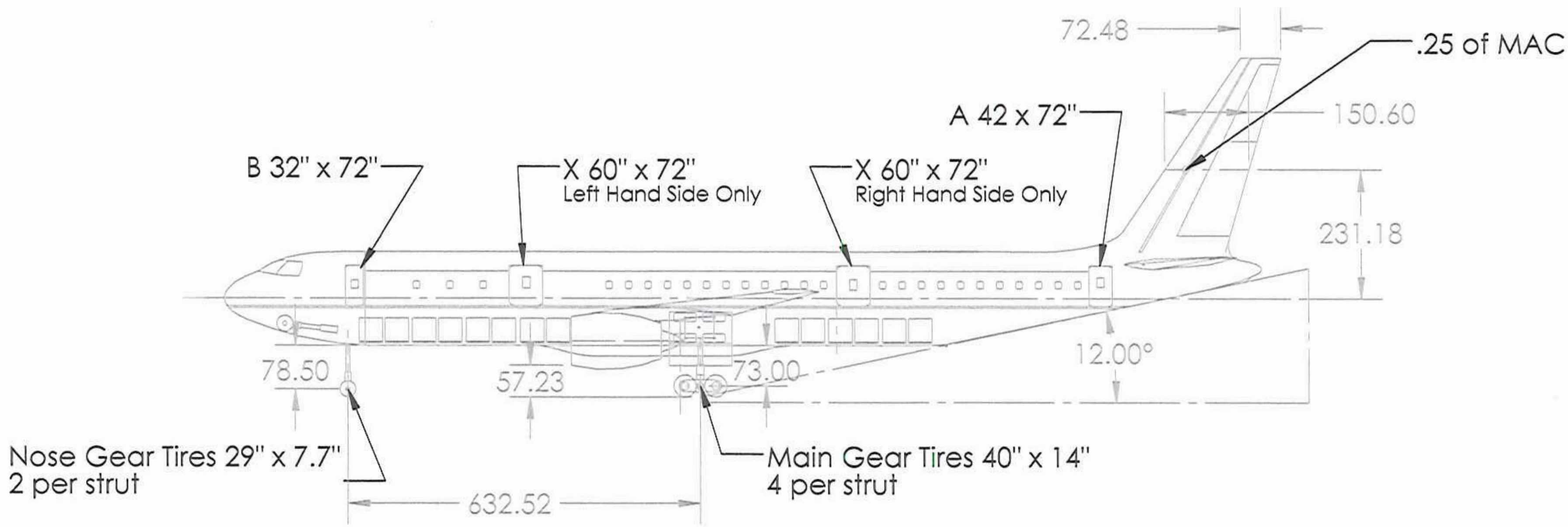

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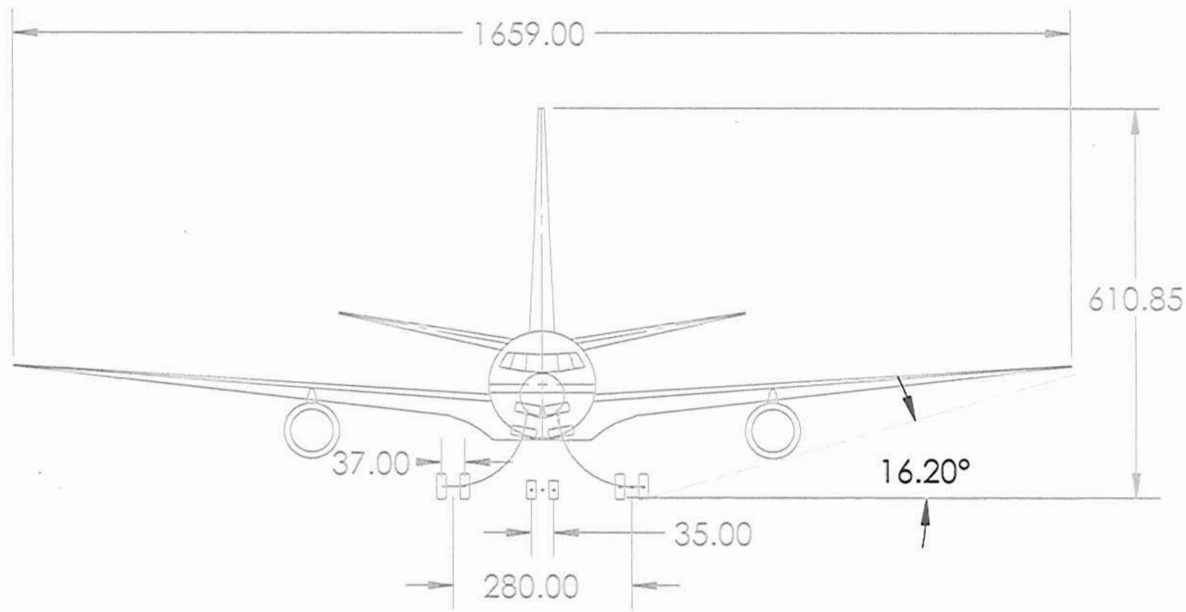
Super Airline 4000 HD Turbo

TITLE:
220 PAX Wing on
150 PAX Fuselage

SIZE A DWG. NO. Side View Point Study REV

SCALE: 1:300 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN		
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

NEXT ASSY	USED ON
APPLICATION	

Super Airline 4000 HD Turbo

TITLE:

220 PAX Wing on
150 PAX Fuselage

SIZE	DWG. NO.	REV
A	Front View Point Study	
SCALE: 1:300	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1

Center of Gravity Locations

CG Locations		
150 PAX	Inches from Nose	% of Fuselage
Full Payload Full Fuel	672	0.44
Full Payload No Fuel	667	0.4371
No Payload Full Fuel	658	0.4312
No Payload No Fuel	639	0.4187

220 PAX	Inches from Nose	% of Fuselage
Full Payload Full Fuel	919	0.4479
Full Payload No Fuel	914	0.4454
No Payload Full Fuel	895	0.4362
No Payload No Fuel	888	0.4327

Point Study 150 PAX	Inches from Nose	% of Fuselage
Full Payload Full Fuel	682	0.4469
Full Payload No Fuel	678	0.4443
No Payload Full Fuel	658	0.4312
No Payload No Fuel	651	0.4266

Payload Range

150	n mi.	220	n mi.
Payload lbs	Range	Payload lbs	Range
37250	0	52300	0
37250	3828	52300	3874
35250	4000	50300	4000
30381	4481.7	41423	4690
0	5854	0	5724