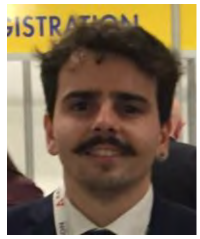
# Desprüngdarcost Aerospace Presents: The Tachion Business Jet Series

AIAA Graduate Team Aircraft Design Competition 2016-2017


Marwan Dessouki


Italo Costa


Drew Darrah

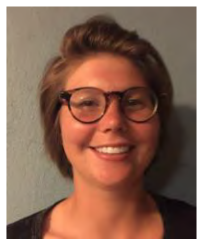

Martin Mendoza


Riley Sprunger


Michael Moschetti


Taylor George


Kyle Herda


Megan Burns


Yizi Zhou

| Team Member | AIAA Number | University/Major | Signature |
|---|---|---|---|
| Marwan Dessouki | 567529 | Team Lead - KU Aerospace Enginering | [illegible] |
| Italo Costa | 578953 | KU Aerospace Engineering | Italo Costa |
| Drew Darrah | 517105 | KU Aerospace Engineering | [illegible] |
| Martin Mendoza | 531334 | KU Aerospace Engineering | [illegible] |
| Riley Sprunger | 464117 | KU Aerospace Engineering | [illegible] |
| Michael Moschetti | 822280 | RMIT Aerospace Engineering | [illegible] |
| Taylor George | 665629 | KU Aerospace Engineering | Taylor George |
| Kyle Herda | 808574 | KU Aerospace Engineering | [illegible] |
| Megan Burns | 808702 | KU Arcitecture | Megan Burns |
| Yivi Zhou | 820082 | KU Architecture | [illegible] |
| **Team Advisors** | **AIAA Number** | | **Signature** |
| Dr. Ron Barrett | 022393 | KU | Ron Barrett |
| Dr. Cees Bil | 077937 | RMIT | [illegible] |

**TABLE OF CONTENTS** **PAGE NO.**

# LIST OF SYMBOLS

| Symbol | Description | Units |
|---|---|---|
| $a_{lat}$ | Lateral Acceleration | g |
| AR | Aspect Ratio | Unitless |
| $a_{vert}$ | Vertical Acceleration | g |
| b | Wingspan | ft |
| $b_t$ | Tire Width | ft |
| c | Chord | ft |
| $\bar{c}$ | Mean Geometric Chord | ft |
| $C_D$ | Drag Coefficient | Unitless |
| $C_{D_o}$ | Zero Lift Drag Coefficient | Unitless |
| $C_f$ | Skin Friction Drag | Unitless |
| $C_j$ | Specific Fuel Consumption | $\frac{lb_m}{lb_f/hr}$ |
| $C_L$ | Lift Coefficient | Unitless |
| $C_l$ | Rolling Moment Coefficient | Unitless |
| $C_m$ | Pitching Moment Coefficient | Unitless |
| $C_n$ | Yawing Moment Coefficient | Unitless |
| $C_{ride}$ | Ride Comfort Index | Unitless |
| $C_Y$ | Side-Force Coefficient | Unitless |
| d | Diameter | ft |
| $d_f$ | Fuselage Diameter | ft |
| $d_s$ | Shock Absorber Diameter | ft |
| D | Drag | lbs |
| $D_t$ | Tire Diameter | ft |
| e | Oswald's Efficiency Factor | Unitless |
| E | Endurance | hours |
| $F_{TY}$ | Tensile Yield Strength | KSI |
| g | acceleration due to gravity ($32.2\ \frac{ft}{s^2}$) | $\frac{ft}{s^2}$ |
| h | Altitude | ft |
| $i_w$ | Incidence Angle | Degrees |
| $l_f$ | Fuselage Length | ft |
| $l_{fc}$ | Fuselage Cone Length | ft |
| $l_m$ | Distance from CG to Main Gear | ft |
| $l_n$ | Distance from CG to Nose Gear | ft |
| L | Lift | $lb_f$ |
| $\frac{L}{D}$ | Lift-To-Drag Ratio | Unitless |
| $M$ | Mach Number | Unitless |
| $M_{ff}$ | Mission Fuel Fraction | Unitless |
| n | Load Factor | g |
| $n_s$ | Number of Struts | Unitless |
| N | Number of Engines | Unitless |
| $N_g$ | Landing Gear Load Factor | Unitless |
| $n_{mt}$ | Number of Main Landing Gear Tires | Unitless |
| $n_{nt}$ | Number of Nose Landing Gear Tires | Unitless |
| PAX | Passengers | Unitless |
| $P_m$ | Load on Main Gear Strut | lb |
| $P_n$ | Load on Nose Wheel Strut | lb |
| Q | Quantity | Unitless |
| q | Dynamic pressure | psf |
| R | Range | nm or mi |
| S | Wing Area | $ft^2$ |
| $S_L$ | Landing Distance | ft |
| $S_{TO}$ | Take Off Length | ft |
| $S_h$ | Horizontal Tail Area | $ft^2$ |
| $S_v$ | Vertical Tail Area | $ft^2$ |
| T | Thrust | lb |
| t | Time | sec/min/hr |
| t/c | Thickness to Chord Ratio | unitless |
| V | Speed | fps/mph/kts |
| $\bar{V}_h$ | Horizontal Tail Volume Coefficient | Unitless |
| $\bar{V}_v$ | Vertical Tail Volume Coefficient | Unitless |
| $V_A$ | Design Maneuvering Speed | fps/mph/kts |
| $V_C$ | Design Cruise Speed | fps/mph/kts |
| $V_D$ | Design Diving Speed | fps/mph/kts |
| $V_S$ | Stall Speed | fps/mph/kts |
| W | Weight | lbs |
| $w_t$ | Aircraft Sink Rate | fps |
| $x_h$ | Aircraft CG to AC of Horizontal tail | ft |
| $x_v$ | Aircraft CG to AC of Vertical tail | ft |

**List of Greek Symbols**

| | | |
|---|---|---|
| α | Angle of Attack | Degrees |
| β | Sideslip Angle | Degrees |
| Γ | Dihedral Angle | Degrees |
| δ | Deflection Angle | Degrees |
| Δ | Change in a Parameter | Unitless |
| ε | Downwash | Degrees |
| $\theta_{fc}$ | Fuselage Cone Angle | Degrees |
| $\lambda$ | Taper Ratio | Unitless |
| Λ | Sweep Angle | Degrees |
| ρ | Air Density | $\frac{lb}{ft^3}$ |
| $\sigma$ | Air Density Ratio | Unitless |
| $\phi$ | Lateral Ground Clearance Angle | Degrees |
| $\psi$ | Lateral Tip-Over Angle | Degre |

**List of Subscripts**

| | | |
|---|---|---|
| A | Approach | N/A |
| c | canard | N/A |
| cl | Climb | N/A |
| cr | Cruise | N/A |
| crew | Crew | N/A |
| D | Drag | N/A |
| E | Empty | N/A |
| F | Fuel | N/A |
| ff | Fuel Fraction | N/A |
| guess | Guessed | N/A |
| h | Altitude | N/A |
| L | Landing | N/A |
| max | Maximum | N/A |
| o | Zero Lift | N/A |
| OE | Operating Empty | N/A |
| PL | Payload | N/A |
| RC | Rate of Climb | N/A |
| res | Reserve (Fuel Reserves) | N/A |
| s | stall | N/A |

TO ........................... Take-Off ........................... N/A
TOFL ............ Take-Off Field Length ................ N/A
TOG .............. Take-Off Ground Run ................ N/A
tent ............................ tentative ............................ N/A
tfo .................... trapped fuel and oil .................. N/A
used .................. Used (Fuel Used) ..................... N/A
wet ................. Wetted (Wing Area) ................... N/A
wf .............. wing-fuselage component .............. N/A
23 .................... Far 23 Requirement ................... N/A
25 .................... Far 25 Requirement ...................... N/

**List of Acronyms**

AAA ......... Advanced Aircraft Analysis ............ N/A
APU .............. Auxiliary Power Unit ................. N/A
BFL .............. Balanced Field Length ................ N/A
CG .................... Center of Gravity .................... N/A
CGR .................... Climb Gradient ...................... $rad^{-1}$
CGRP ........ Climb Gradient Parameter ............. $rad^{-1}$
EIS .................... Entry Into Service ................... N/A
EPA ..... Environmental Protection Agency ........ N/A
FAA ...... Federal Aviation Administration ......... N/A
FAR ............. Federal Air Regulation ................ N/A
FBO ............... Fixed Based Operator ................ N/A
FL .......................... Flight Level ......................... N/A
FPM .................... Feet Per Minute ................... ft/min
FPS ................... Feet Per Second ........................ ft/s
FOD ............ Foreign Object Damage ............... N/A
GD .................... General Dynamics .................... N/A
HLD ................... High Lift Device ..................... N/A
LIB ..................... Larger is Better ...................... N/A
LRC ................. Long Range Cruise ................... N/A
MC ...................... Marginal Cost ....................... N/A
MGC ........... Mean Geometric Chord ................ N/A
MTOW ....... Maximum Takeoff Weight .............. N/A
NRC ............... Non Recurring Cost .................. N/A
OEI .............. One Engine Inoperative ................ N/A
RC ........................ Rate of Climb ................... fps/fpm
RMS ................ Root Mean Square .................... N/A
RV ...................... Revealed Value ....................... N/A
RVI ............... Relative Value Index .................. N/A
SD .................... Standard Deviation .................... N/A
SFC ........... Specific Fuel Consumption ............ N/A
SIB ..................... Smaller is Better ...................... N/A
STAMPED Statistical Time and Market Predictive . Engineering Design Vector ............. N/A
TFU ........... Theoretical First Unit Cost .............. N/A
TOFL ............ Take-off Field Length ..................... ft
ULR .................. Ultra Long Range ..................... N/A
USD ................ United States Dollar ................... N/A
VI ....................... Monetary Value ....................... N/A
VLI ...................... Very Light Jet ........................ N/A

## ACKNOWLEDGMENTS

A wide variety of industry professionals were consulted throughout the process of this design, and the team would like to express their gratitude towards those who lent their time and expertise.

- **University of Kansas**
  Dr. Ron Barrett – Faculty Advisor
  Dr. Richard Hale
  Dr. Saeed Farokhi
  Dr. Richard Bramlette
- **Royal Melbourne Institute of Technology University**
  Dr. Cees Bil – Faculty Advisor
- **DAR Corporation**
  Dr. Jan Roskam
  Dr. Willem Anemaat
- **Lockheed Martin**
  Chris Hardin
  Larry Downey
  The Skunk Works design team in Marietta, Georgia
- Ronald P. Barrett
- **Gulfstream**
  Dr. Jason Merret
  Bryan Briscoe
- **Boeing**
  Perry Rea
- **Textron Aviation**
  Albert Dirkzwager
  Jeff Johannsmeyer
  Kent Donaldson
  Alex Alejandro
  Colin Thomas
- **Bombardier, Learjet**
  Dick Kovich
  Kevin Wiedenmann
- **Federal Aviation Administration**
  Marv Nuss
  Wes Ryan

## EXECUTIVE SUMMARY

The business jet market has continued to gain steam following the recession in the late 2000's. Many new business jets are coming to market, both large and small. Many newcomers well represent the large end: The Citation Longitude and upcoming Hemisphere, the Gulfstream G500 and G600, and the Bombardier Global 8000 show that the market for large business jets is rapidly expanding. On the smaller side, there are some new options: The Cirrus Vision Jet, which recently received FAA type certification, the Phenom 100 & 300, and the Honda Jet well represent the very light to light business jet market. Yet there is an advantage to be had. By designing an aircraft with the primary goal of being able to fly faster and further than anything in its class, a market for the individual who greatly values their time is open. The family of aircraft described in this report fulfill that niche, by achieving a max cruise speed of Mach 0.85, and flying 2,500 nm, while offering the latest innovations and comfort that all business jet customers demand.

The design process follows a detailed sweep of potential business jet configurations. After selecting an optimal altitude and cruise speed to size the aircraft to, 6 configurations were chosen to carry forward to Class I and II design. A rigorous down-selection process resulted in two aircraft that could meet both the 70% commonality by structure requirement, and the entry into service date. The MTOW for the 6 and 8 passenger weigh 16,600 and 14,900, respectively. They utilize the same wing, with a span of 53 ft. In order to meet the range requirements, the 5,930 and 6,620 lbs of fuel (6 and 8 passengers, respectively) is stored in the wing, fairing, and fuselage. The wing will utilize double-slotted fowler flaps to accomplish the takeoff and landing requirements. A fly-by-wire system will be utilized for the flight controls, and the aircraft are inherently stable in all phases of flight. The aircraft will be powered by Williams FJ44-4 engines. Both aircraft have a fuselage diameter of 6.25 ft. Aluminum will be primarily used to manufacture the aircraft, with composites used for control surfaces. Prices will start at $4.95 million for the 6 passenger and $7.5 million for the 8 passenger will allow for a 10% profit margin. Manufacturing rate will be 2-3 per month when the 6 passenger enters service, increasing to 5-6 in 2022. Both aircraft will be certified under FAR 23 Commuter class.

**<u>COMPLIANCE MATRIX</u>**

| ***Description*** | ***Requirement*** | ***Compliance*** 6 Pax | 8 Pax | ***Page*** |
|---|---|---|---|---|
| Max Cruise Speed | 0.85 | > 0.85 | | 63 |
| Range | 2,500 nmi | 2,500 nmi | | 62 |
| Rate of Climb | 3,500 fpm | 4,900 fpm | 4,450 fpm | 63 |
| Service Ceiling | 45,000 ft. | > 45,000 ft | | 63 |
| Takeoff Field Length | 4,000 ft. | < 4,000 ft | | 64 |
| Landing Field Length | 3,600 ft. | < 3,600 | | 64 |
| Baggage (6/8 pax) | 500 lb - 30 $ft^3$/ 1,000 lb - 60$ft^3$ | 500 lb - 30 $ft^3$ | 1,000 lb - 60$ft^3$ | Weight: 46 Volume: 35 |
| Description of Design Mission | -- | -- | -- | 12 |
| Performance, Flight Envelope | -- | -- | -- | 56 |
| Payload Range Chart | -- | -- | -- | 62 |
| V-n Diagram | -- | -- | -- | 87 |
| Materials Selection | -- | -- | -- | 85 |
| Geometric Descriptions | -- | -- | -- | 92 |
| Aircraft Weight Summary | -- | -- | -- | 44, 46 |
| Propulsion System Selection | -- | -- | -- | 27 |
| Stability and Control Characteristics | -- | -- | -- | 48 |
| Part Commonality | 70% by Weight | 96% | | 60 |
| Business Case Analysis | -- | -- | -- | 64 |
| Down Selection Process | -- | -- | -- | 20 |

# 1. MISSION SPECIFICATION, MEASURES OF MERIT

## 1.1 DESIGN REQUIREMENTS

The RFP requests a two-member family of fixed-wing light business jets to carry 6 and 8 passengers. The aircraft family is required to have at least 70% part commonality to minimize development and part cost. The following table summarizes the technical requirements for each family member.

**Table 1-1 - Business Jet Family Technical Requirements [1]**

| | 6 Seat Family Member | 8 Seat Family Member |
|---|---|---|
| Max. Passengers | 6 | 8 |
| FAA Certification | FAR 23 | FAR 25 |
| Min. LRC Range | 2500 nmi [1 Pilot + 2 Pax] | 2500 nmi [1-2 Pilots + 4 Pax] |
| Min. Alternate Range | 100 nmi | |
| Baggage Capacity | 500 pounds - 30 $ft^3$ | 1000 pounds - 60 $ft^3$ |
| Entry into Service | 2020 | 2022 |
| Max. Cruise Speed | Mach 0.85 @ 35,000 ft | |
| Min. Rate of Climb | 3,500 fpm | |
| Service Ceiling | 45,000 ft | |
| Max. Sea-level TOFL@ MTOW | 4,000 ft | |
| Max. Landing Field Length | 3,600 ft | |

## 1.2 DESIGN OBJECTIVES

The main design objectives highlighted by the RFP include:

- **Cost Minimization**
  - Minimize production, acquisition and operating cost by choosing appropriate materials and manufacturing methods for the production rate
- **High Part Commonality**
  - Achieve at least 70% part commonality between the two variants. This includes everything in the empty weight of the aircraft but the engines.
- **Marketability**
  - Create a marketable aircraft through visual appeal and providing features demanded by pilots, passengers and owners
- **Maintenance & Reliability**
  - Create a maintainable & reliable aircraft, at least as good as current aircraft

## 2. MARKET REVIEW

As a point of reference for aircraft that currently represent the light business jet market, a discussion of jets currently on the market is provided for the audience's orientation

### 2.1 EMBRAER PHENOM 300

The Embraer Phenom 300 was introduced in 2009, and has quickly come to dominate the market. It has been the best-selling business jet across all categories for the past 3 years. While Embraer initially considered scaling up their Phenom 100, they instead opted for a clean sheet design, with the goal being 1,800 nm range, Mach 0.78 cruise, and all with a larger cabin [2]. Another goal was to be able to get in and out of London City and Telluride. It has an all composite T-tail, which is also all moving [2]. Other notable design characteristics are the spoilers used to augment aileron roll control [3]. The spoilers also automatically deploy on landing to help dump lift and bring the aircraft to a stop quickly. The aircraft was all around designed to feel like a larger jet, with an air-stair door, an impressive lavatory, and the Oval Lite cross-section shape that maximizes cabin space [3].

**Figure 2-1: Embraer Phenom 300**

### 2.2 LEARJET 40

The Learjet 40 is a light business jet derived from the Learjet 45, introduced in 1998. The only difference between the Learjet 40 and 45 is a fuselage plug in front of the wing. The result of this fuselage plug removal is a reduction in the number of passengers from 9 to 7, similar to what the RFP calls for. During meetings with Learjet, they revealed that the 40 has to fly with ballast in the nose from the resulting CG shift. It takes advantage of its ventral strakes to deliver very benign stall characteristics [4]. It was designed primarily to have a flat floor cabin, and the rest of the aircraft was built around that. A major benefit to ground operations is single point refueling, allowing for faster turn-around times on the tarmac. Customers like the aircraft for the capabilities it brings to the light jet market, flying faster, farther, and with lower direct operating costs than similar aircraft [5].

**Figure 2-2: Learjet 40**

## 2.3 SYBERJET SJ30I/SJ30X

Figure 2-3: Syberjet SJ30

The Syberjet SJ30 has had difficulty finding its financial footing. The design has been passed around to many different companies through the 1980-2010s, and only a few prototypes have been built. However, the prototypes have posted impressive range and speed numbers. It comes the closest to the RFP, but the high performance comes at a cost. To meet its high speed cruise performance, the wing is very thin, which leads to a number of design trade-offs. The SJ30 uses slats for takeoff and landing, meaning the wing is more complex and expensive. Landing gear can't be stored in the wing like most other jets, so it retracts into the fuselage fairing. The wing also leaves little room for fuel, and as a result, over 60% of the 4,850 pounds of fuel is stored in the fuselage [6]. Due to this, the aircraft must be fueled from a port on top of the fuselage, an undesirable characteristic for ground crews [6]. Due to the need for fuel volume, cabin volume is sacrificed, and is more comparable to the very light jet market. One advantage of the cabin however is it can be pressurized to sea level at FL410 [7]. The SJ30 is certainly a high performance airplane, but also illustrates that everything comes at a cost.

## 2.4 CESSNA CITATION CJ3+

Figure 2-4: Cessna Citation CJ3+

The CJ3+ is one of the many evolutions of the Cessna Citation Jet, introduced in 1989. Certified in 2014, it excels as a jack-of-all-trades aircraft. All-around, the performance is good, and it offers a well-appointed cabin in its class. The primary selling point is it offers more performance per dollar than other light jets [8]. Because it is a Citation, it has a long history of reliability and predictability. This creates a strong customer base, and as engineers at Cessna will attest to, "loyalty is king." It's a low workload, capable aircraft that builds on the same formula Cessna has worked to perfection over 40 years [9]. This seems to embody the philosophy echoed by Lockheed-Martin and Gulfstream during design meetings: If it isn't broke, don't fix it.

## 2.5 HONDAJET HA-420

Figure 2-5: HondaJet HA-420

While HondaJet may be the most recent newcomer to the market, they are by no means a typical business jet startup. In development for nearly 30 years, and backed by the power and might of the Honda Corporation, this jet is a serious contender out of the gate. It can definitely be called the most innovate design on the market, with its engines mounted on pylons over the wings. The creator, Michimasa Fujino, claims that the design reduced cabin noise and increases performance [10]. Based on two flight tests, these are both true claims [10], [11]. The engine placement isn't the only standout feature: a composite fuselage, laminar flow wings, an intuitive avionics system designed for an owner-operator, single point refueling with four tanks (two in the wing, one in the wing carry-through, and one behind the rear bulkhead), fore and aft baggage compartments, and tail mounted speed-brakes make for an impressive first offering from the Honda Aircraft Company [10].

Table 2-1 displays salient characteristics for each of the aircraft, and compares them to the RFP requirements. Characteristics that meet or exceed the RFP requirements are shown in green, and the RFP requirements that have no equal are highlighted in yellow. The main takeaway of this table is the RFP is asking for a jet that will be competitive in the market, and able to go faster and farther than any other light jet.

**Table 2-1: Comparison between Light Jets**

| Aircraft | Embraer Phenom 300 | SyberJet SJ30 | Bombardier Learjet 40 | Cessna Citation CJ3+ | HondaJet HA-420 | RFP Requirements |
|---|---|---|---|---|---|---|
| **MTOW (lbf)** | 17,968 | 13,950 | 21,000 | 13,870 | 10,600 | -- |
| **Max Service Ceiling (ft)** | 45,000 | 49,000 | 51,000 | 45,000 | 43,000 | 45,000 |
| **Rate of Climb (fpm)** | 4,000 | 3,663 | 2,820 | 4,478 | 4,000 | 3,500 |
| **Max Cruise Speed (Mach)** | 0.78 | 0.83 | 0.81 | 0.73 | 0.72 | 0.85 |
| **Max LRC Range (nmi) (3pax/6Pax)** | ? / 1,971 | 2,472/1,965 | ? / 1,617 | 1,881/1,691 | 1,223 (4 pax) | 2,500 |
| **Storage Capacity ($ft^3$)** | 84 | 84 | 65 | 65 | 66 | 30 – 60 |
| **Max Passengers** | 6 to 10 | 5 to 6 | 7 | Up to 9 | 4 to 5 | 6 to 8 |
| **Takeoff Distance (ft)** | 3,138 | 3,939 | 4,680 | 3,180 | 4,000 | 4,000 |
| **Landing Distance (ft)** | 2,621 | 2,285 | 2,334 | 2,770 | 3,050 | 3,600 |
| **Certification** | FAR 25 | FAR 23 Commuter | FAR 25 | FAR 23 Commuter | FAR 23 | FAR 23 & 25 |

## 2.6 INDUSTRY CONSULTATIONS

To gain a broad understanding of the business jet market, multiple companies were briefed on the design and consulted with. A full list of companies and persons can be found in the acknowledgements section of the report.

The map below displays the companies and locations where the team drew counsel and inspiration from. Over spring break, members of the team embarked on a grand aerospace tour of the Southeastern U.S. The trip was organized by the Aerospace Department at KU. Many of these locations had a wide variety of aircraft from which to draw inspiration, and some had business jets for the team to look at close up.

At Gulfstream, the team was able to tour a customer mockup of the interior of a G600 business jet. Bryan Briscoe was able to answer many of the questions the team had about interior amenities and customer preferences. The team then spoke with Dr. Jason Merret, an Aero and Performance Technical Specialist, about different configuration concepts and technical challenges.

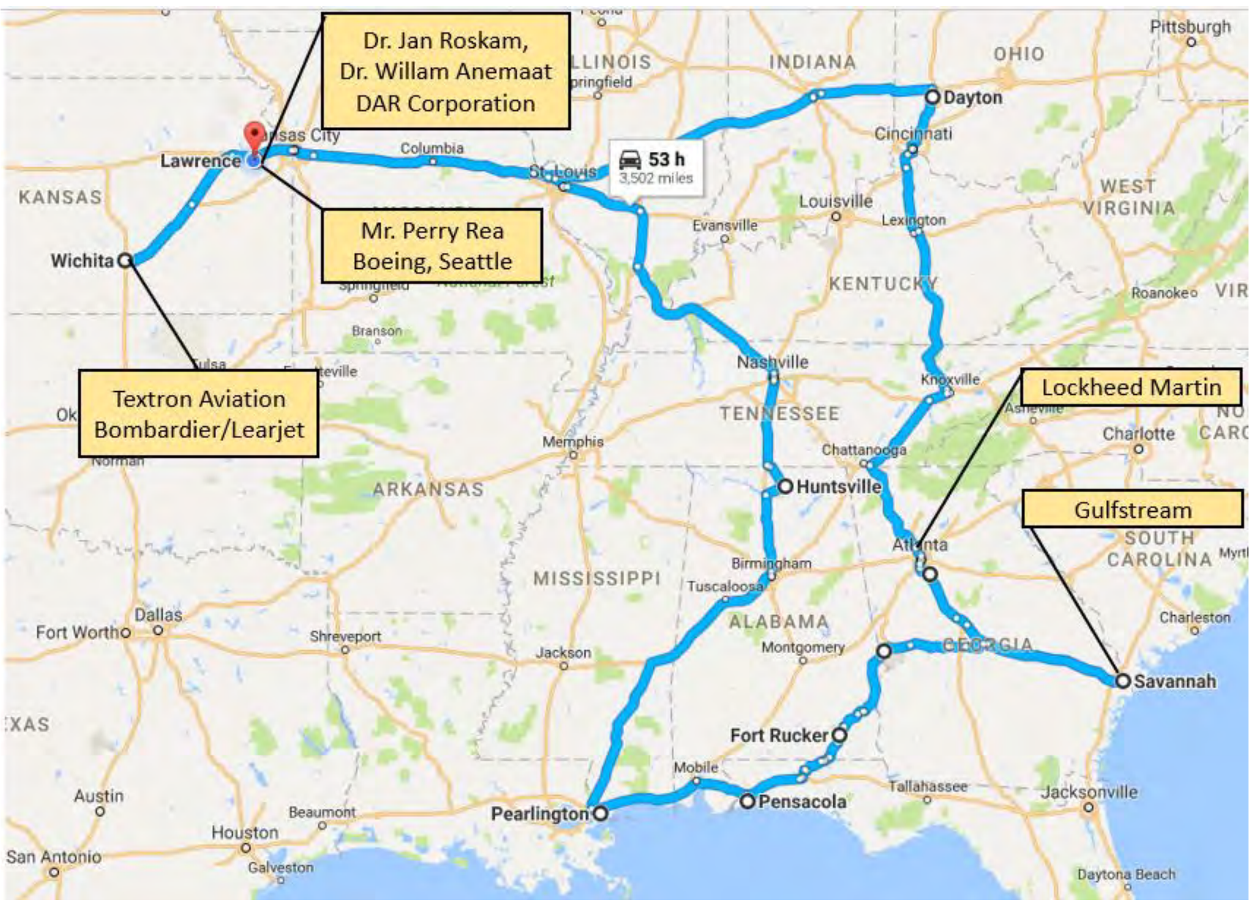



**Figure 2-6: KU Aerospace Industry Visits**

In Marietta, Georgia, the team met with Lockheed Martin's Skunk Works division. Many members of the conceptual design group provided their time in the morning to critique the Class I design concepts. This was a unique opportunity early in the design process to turn over different configuration concepts with a world famous aircraft design group.

Later in the semester, Mr. Perry Rae of Boeing, Seattle visited KU, and took time to advise the team. A final trip was taken to Textron Aviation (Cessna & Beechcraft) and Bombardier/Learjet in Wichita, KS, to receive feedback from both companies on the final design selection. At Learjet, the team was able to tour the flight line, and see how business jets are assembled.

The team also engaged in many consultations with DAR Corporation (Dr. Jan Roskam and Dr. Willem Anemaat), over different aircraft design questions. The team was also able to receive assistance with the Advanced Aircraft Analysis software written by DAR Corporation, which was used extensively for the aircraft design.

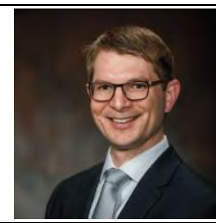
These many consultations proved to be an invaluable resource, and the knowledge gained is referred to many times in this report.


**Figure 2-8: Meetings with Industry**

## 3. FAR 23 VS FAR 25 REQUIREMENTS

The Request for Proposal states that the aircraft are to be certified under two different requirements: the 6 passenger under FAR 23, and the 8 passenger under FAR 25. However, there are considerable downsides to this strategy.

> "Stay Part 23 if at all possible. You're weights are so low, that I see no reason you would go Part 25."
> \- *Jeff Johannsmeyer, Textron Aviation*



The 70% commonality by weight requirement means that very little will change between the two aircraft. This implies that the aircraft should be able to be certified under the same type certificate. This is a common practice in the business jet market. For example, the Cessna Citation CJ series spans 9 different models of aircraft which are all certified under the same type certification, ranging from the 10,800 lb M2 to the 17,200 lb CJ4 (the CJ3+ is also included in this lineup), and all are certified under FAR 23 Commuter. The Learjet 40 and 45 are other examples, both certified under FAR 25.

> "Never ever consider certifying under two FARs. If you did, you would go broke. I recommend certifying under FAR 23 only to save costs."
> \- *Dr. Jason Merret, Gulfstream*

The primary reason aircraft manufacturers do this is to save money. A stated goal of the RFP was to minimize cost. The process to certify aircraft is very costly and time consuming, and to do this two different times for a very similar aircraft is a waste of money, as noted by all of the industry professionals consulted. It would be a much more cost effective strategy to design both aircraft to one type certification, and one set of regulations.

> "Certify only under FAR 23 or 25, but not both … You wouldn't want to run two separate programs and fly two separate flight tests for two different certification bases. Choose one and stick with it. Otherwise your RDT&E costs will be out of control."
> – *Perry Rea, Boeing*

Multiple reasons can be presented for this strategy. One major one would be the requirement differences between FAR 23 and FAR 25. FAR 25 regulations are more stringent and require more certification testing. Examples of the extra requirements that FAR 25 requires over FAR 23 are as follows:

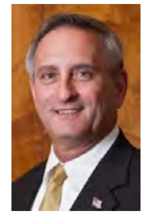
- Larger aisle widths for emergency passenger egress
- Certification against bird strikes
- Greater assurance that a catastrophic event would not occur should a control surface be jammed.
- Takeoff on a wet runway must be quantified and tested.
- More restrictions on where fuel tanks can be located.

To design both aircraft to these different requirements would mean that different manufacturing strategies would have to be employed for different parts of the aircraft to meet the different regulations. This would begin to hurt the part commonality, raising the cost of each aircraft.

“Going for FAR 23 and 25 makes no sense. It would just cost too much to do both.”
*- Albert Dirkzwager, Textron Aviation*

Another reason would be the entry into service date. Due to the very early EIS, making the certification process as short as possible would be a great advantage. As an example of a design timeline, the Phenom 300 started initial design work in 2004, experienced first flight in 2008, and type certification in 2009 [2]. The 6 passenger aircraft would be have a much more aggressive timeline. To give this process the greatest chance of success, simplifying the certification process would be a great advantage over competitors.

“I would certify under FAR 23 and/or FAR 23 Commuter. Don’t do FAR 25 if you don’t have to. It’s too expensive.”
*- Dick Kovich, Bombardier/Learjet*



“FAR 25 & 23 are in many ways, mutually exclusive. I know of no aircraft family that has ever had two models that were independently certified under 23 and 25. This is most likely due to the 1 in $10^{-9}$ failure criteria”
*– Wes Ryan, Federal Aviation Administration*

Overall, the greatest reason to certify under one set of regulations is that not one industry profession the team consulted with in industry thought it was a good idea. The quotes on this and the previous page echo the sentiment expressed by all the industry representatives that the team met with. On the topic of FAR 23 and FAR 25 certification, there is wide concensus: don’t do it.

“Certifying under FAR 23 makes the most sense … Stick with certifying under FAR 23 or FAR 25, not both. You would never be able to recoup the costs.”
*– Dr. Jan Roskam, DAR Corporation*

“Dual FAR certification is a stupid idea.”
*- Dr. Willem Anemaat*

Based on the desire to minimize cost, streamline the certification process, and the resounding consensus of Boeing, Textron Aviation, Gulfstream, Learjet, Lockheed-Martin, and the FAA, it was decided that both aircraft would be best certified under the FAR 23 Commuter class. This is a common category for aircraft of similar weight (Syberjet SJ30, Citation CJ3+). It allows the greatest amount of flexibility with certification, enabling the design to be cost-efficient.

# 4. STATISTICAL TIME AND MARKET PREDICTIVE ENGINEERING DESIGN VECTOR (STAMPED) ANALYSIS

The Statistical Time and Market Predictive Engineering Design (STAMPED) method tracks the change in a given variable over a length of time. Using data collected from the current and past markets, trend lines can be used to show how a salient characteristic might change in the future. For aircraft specifically, this method can be used to predict weight, wing loading, thrust loading, aspect ratio and other characteristics. By charting these variables over time, a prediction can be made about where the general market is going.

To determine the direction of the market for the family, a database of business jet aircraft was collected. From that database, aircraft were sorted into two groups: 5-7 passengers and 7-9 passengers. Combined, this was 65 aircraft spanning over 45 years. The salient characteristics are plotted on graphs that can be seen below. Linear trendlines and standard deviation ranges overlay the data to show the direction and range of the market. These lines are extrapolated to the EIS to give a prediction of the direction that the market is aiming.

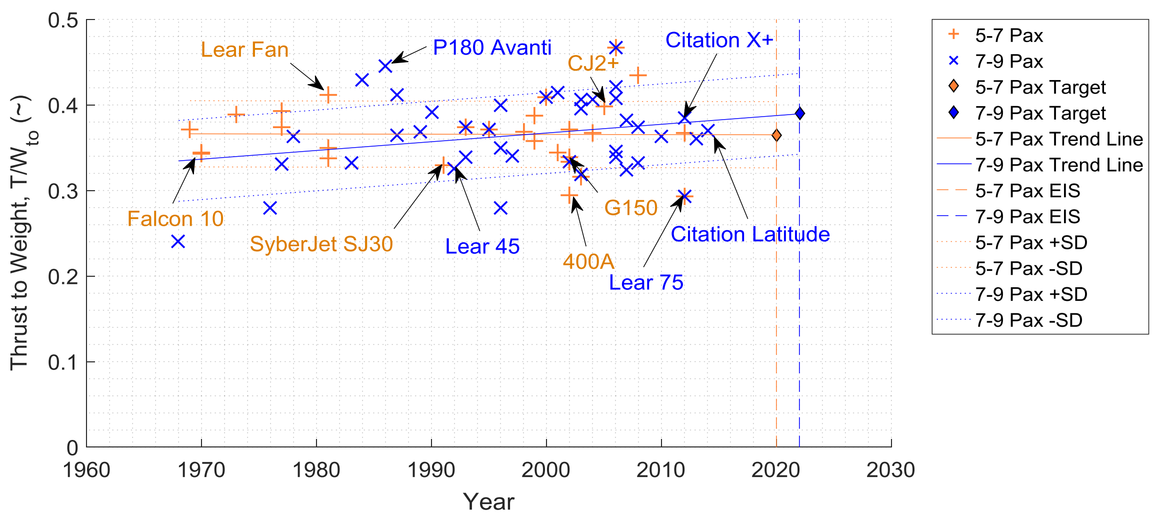



**Figure 4-1: Thrust to Weight STAMPED Data**

Figure 4-1 predicts the amount of thrust required for the aircraft, plotting Thrust over Takeoff Weight. There is a much tighter spread between the two groups, showing that thrust to weight is common between the two classes. This metric also shows the value staying relatively constant throughout the years. Because of this, the aircraft will likely have a thrust to weight ratio very similar to that predicted by the STAMPED data. The two groups have very similar predictions, 0.37 and 0.38 for the 5-7 pax and the 7-9 pax, respectively.

Figure 4-1 displays the information for both categories of aircraft. Aircraft manufacturers are creating wings with increasingly large aspect ratios. The 2 outlier aircraft are the Piaggio P-180 and the Adams A700, which are both turboprop aircraft. The rest of the market has followed the steady upward trend in pursuit of higher L/D.

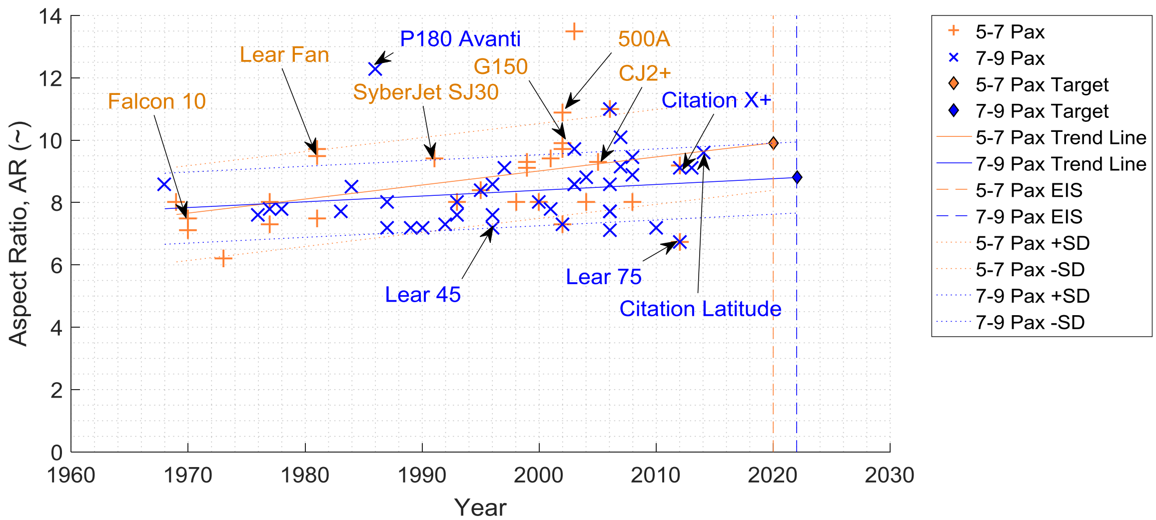



**Figure 4-1: Aspect Ratio STAMPED Data**

## 5. AIRCRAFT WEIGHT SIZING & DESIGN POINT SELECTION

The purpose of this chapter is to size the aircraft to the mission requirements, listed in the RFP. The following airplane design parameters will be determined:

- Take-off Weight ($W_{TO}$)
- Empty Weight ($W_E$)
- Mission Fuel Weight ($W_F$)
- Maximum Take-off Thrust ($T_{TO}$)
- Wing Area (S) and Aspect Ratio (AR)
- Maximum Cruise Lift Coefficient ($C_{LMAX,CR}$)
- Maximum Take-off Lift Coefficient ($C_{LMAX, TO}$)
- Maximum Landing Lift Coefficient ($C_{LMAX, L}$)

### 5.1 MISSION PROFILE

Since business jets in this class fly short-haul missions about 80% of the time [12], it is necessary to consider both the short-haul mission and the long range cruise mission (LRC). The aircraft would then be sized to the more


**Figure 5-2 - Long Range Cruise Mission**

**Table 5-1 - LRC Mission Payload**

| Item | # | Total Weight |
|---|---|---|
| Pilot | 1 | 200 lb |
| Passengers | 4 | 800 lb |
| Baggage | - | 500 lb |
| **Total** | | **1500 lb** |

demanding mission, or the most demanding family member. The 8 passenger was determine to be the most demanding for the mission profile, as it is carrying the most payload. The long range cruise mission (LRC) is specified by the RFP, which includes 1-2 pilots, 4 passengers and 500 pounds of baggage, as illustrated by Figure 5-2. The short-haul mission is described by having full payload, but going only 1,000 nmi.

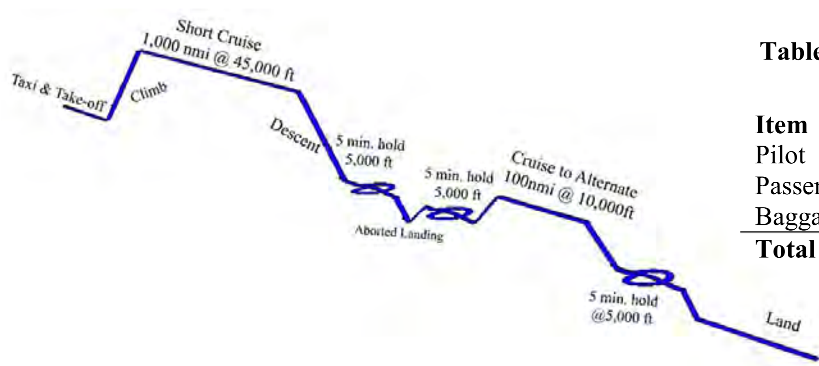



**Figure 5-3 - Short Haul Mission**

**Table 5-2 - Short Haul Mission Payload**

| **Item** | **#** | **Total Weight** |
|---|---|---|
| Pilot | 1 | 200 lb |
| Passengers | 8 | 1600 lb |
| Baggage | - | 1000 lb |
| **Total** | | **2800 lb** |

Through performing sizing calculations described later in this chapter, the LRC mission was found to be more demanding in terms of fuel weight, and thus the aircraft was sized to that mission.

## 5.2 SIZING CHART

A sizing chart, shown on page 19, was created based on the constraints set forth by the RFP:

- Take-off field length of 4,000 ft
- Landing field length of 3,600 ft
- Rate of climb of 3,500 fpm
- FAR23 climb gradient requirements with critical engine inoperative
- Maximum cruise speed of 0.85 at 35,000ft

In addition to the RFP requirements, further considerations were taken into account to allow the aircraft to be more competitive and marketable, as suggested by engineers at Gulfstream, Textron and Learjet. When discussing takeoff and landing requirements, engineers at both Textron and Learjet asked if the aircraft can land in high elevation places such as Aspen & Leadville, Colorado (ski towns), as well as take off in extreme temperatures, such as a hot day in Dubai. These are among popular business jet destinations that could affect whether an aircraft will sell or not.

"Aspen's the big one."
*- Jeff Johannsmeyer, Textron Aviation*

Another major point discussed was getting around high landing lift coefficients by lowering the maximum landing weight. However, an engineer at Textron suggested to the contrary, as customers do not like holding in fuel burning patterns to land right after take-off, especially as fuel cannot be dumped due to strict EPA requirements. Customers also like to have the ability to fly a short distance, land, pick up a friend, and takeoff again without refueling.

## 5.3 DESIGN POINT SELECTION

The LRC cruise speed and altitude requirement was not specified in the RFP, as Dr. Douglas Wells confirmed when inquired:

> "*You are correct that the cruise speed for the ferry range will be determined by your team. The maximum cruise speed of Mach 0.85 at 35,000ft is a requirement, but for what can be a shorter range if your team chooses.*" ***– Dr. Douglas Wells*** [13]

Therefore, in order to select the most efficient LRC speed, altitude and wing-loading, the team developed an automated program designed to perform parametric studies on the effect of each parameter on the aircraft take-off weight. A flow chart of the algorithm used is shown in Figure 5-4 below.

In general, a lower cruise speed would increase the aircraft lift-to-drag ratio, but would also increase the engine specific fuel consumption. This is due to the engines running at partial throttle during cruise, having been sized for take-off requirements. A higher cruise speed in the transonic range defined between Mach 0.6 and Mach 1.0 would introduce parasite and induced wave drag, which is also a strong function of wing and aircraft geometry as well as the required cruise lift coefficient. A higher cruising altitude would increase the lift-to-drag ratio, but would decrease the available thrust from the engines.

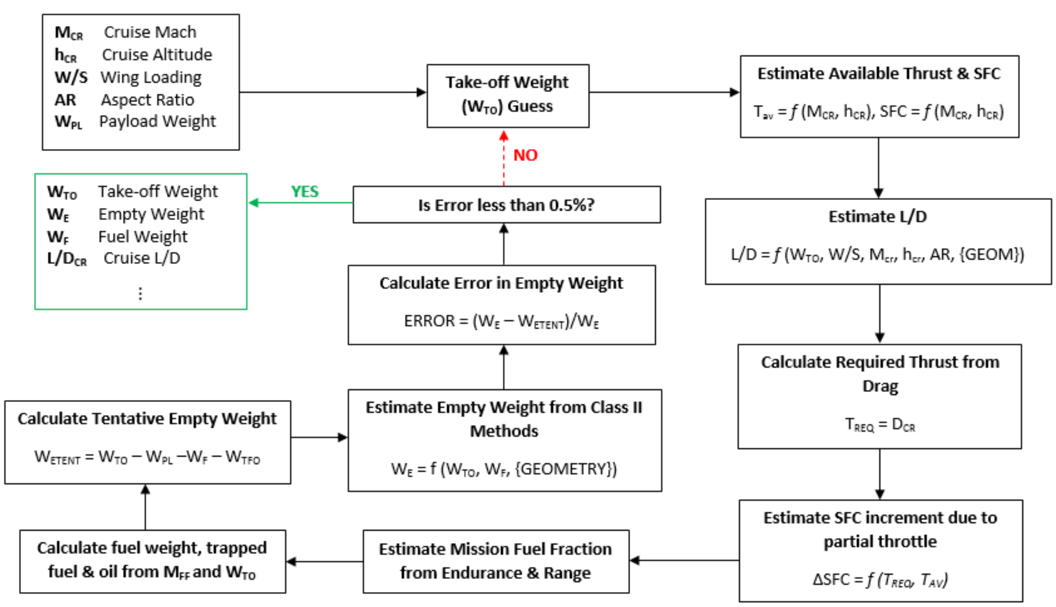



**Figure 5-4 - Parametric Sizing Flow Chart**

### 5.3.1 EFFECT OF SPEED & ALTITUDE ON THRUST & SFC

Thrust and SFC as functions of flight Mach number and altitude for the Williams FJ44-4 were obtained from Maido Saarlas's Aircraft Performance [14], and is shown in the figure below. The reasoning behind the use of this engine will be discussed later in this report.

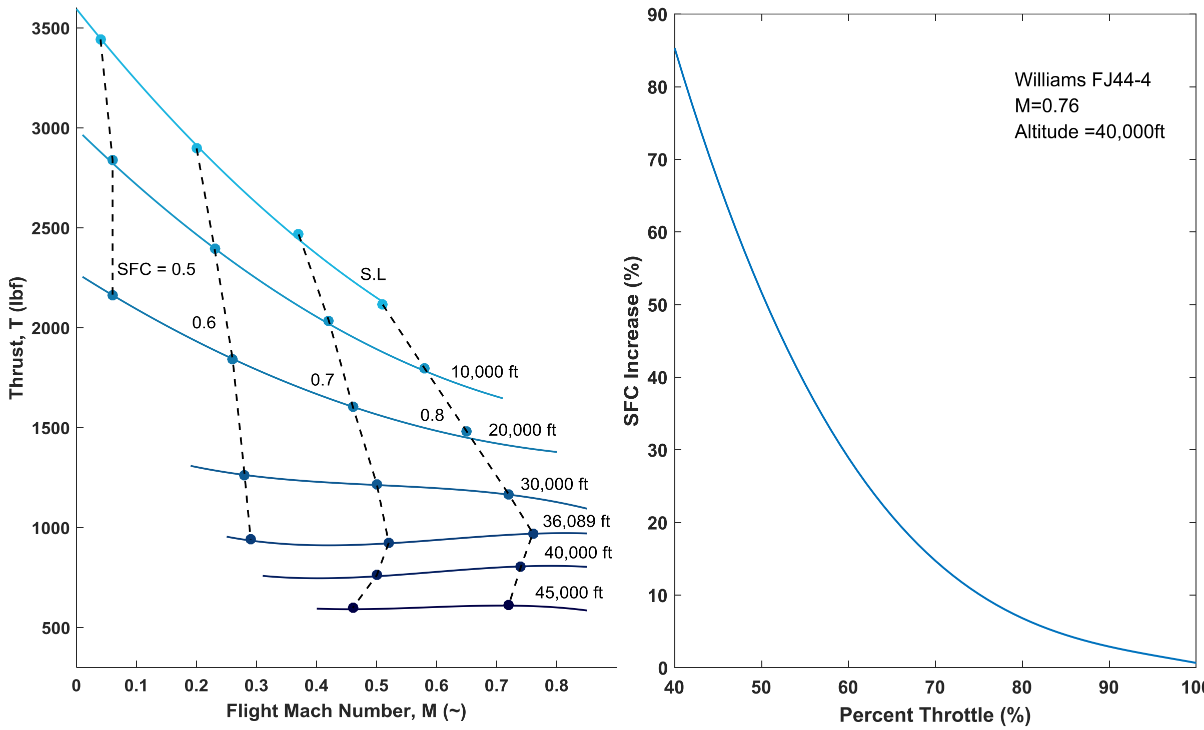



**Figure 5-5: FJ44-4 Thrust & SFC variation with Mach and Altitude [14] (left), Estimation of Partial Throttle vs. SFC Increase for the FJ44-4 [15] (right)**

Since the thrust and SFC shown in Figure 5-5 (left) for maximum continuous output (full throttle), a method to quantify the SFC increase due to reduced throttle was needed. To do this, the engine was recreated in GasTurb 12 [15], a jet engine cycle analysis software. Using the off-design parameters the following relationship was established in Figure 5-5 (right).

### 5.3.2 EFFECT OF SPEED, ALTITUDE & WING LOADING ON LIFT-TO-DRAG RATIO

An accurate lift-to-drag ratio has a significant effect on the take-off weight of the aircraft, and thus design feasibility. Initially, the team attempted to push for higher lift-to-drag ratios to increase the aircraft's efficiency. However, while high L/Ds are obtainable in the subsonic regime, they drop significantly in the transonic regime due to wave drag.

For example, in the subsonic regime, the drag polar can be estimated by using the equations on the left, *assuming the wing is the only lifting surface in cruise*. However, in the transonic regime, the drag polar has to account for the transonic drag rise. For the wing, the equations on the right are used instead:

$$C_D = C_{D_0} + \frac{C_L^2}{\pi ARe}$$
$$where\ C_{D_0}\ is\ the\ aircraft\ parasite\ drag$$
$$C_L^2\ is\ the\ required\ lift\ coefficient$$

$$C_{D_w} = C_{D_{0_w}} + \left(\frac{C_{D_L}}{C_L^2}\right) C_L^2$$
$$C_{D_{0_w}} = C_{D_{0_w}}\Big]_{M=0.6} + C_{D_{w_{wave}}}$$
$$where\ C_{D_{w_{wave}}} is\ a\ function\ of\ geometry$$
$$\left(\frac{C_{D_L}}{C_L^2}\right)\ is\ the\ induced\ drag\ parameter$$

The parasite drag of other aircraft components also increases as a function of skin friction coefficient, $C_f$, which in turn, is a function of Reynolds number. In the program, drag was predicted to a relatively high fidelity, and accounts for aspect ratio, wing area, thickness, and sweep angle at different cruise Mach numbers. It also accounts for wing-fuselage and fuselage-nacelle interference drag at different Mach numbers. The estimations were verified against output from Advanced Aircraft Analysis (AAA), a software produced by DAR Corporation.

### 5.3.3 EFFECT OF SPEED, ALTITUDE & WING LOADING ON EMPTY WEIGHT

The empty weight was calculated through Torenbeek methods by estimating the weight of each component as a function of take-off weight. Further information on the methods and components used can be found in Section 9.5. Methods were taken from Roskam's Airplane Design Part V [16].

### 5.3.4 FUEL WEIGHT ESTIMATION

For the cruise and loiter flight segments, fuel estimation was done using the Breguet range & endurance equations. As for other segments, such as taxi, take-off, and climb, fuel consumed was estimated by fuel fractions selected according to guidelines from Roskam's Airplane Design, Part I [17].

$$R(nm) = \left(\frac{V(kts)}{C_j\left(\frac{lbf}{lbf-hr}\right)}\right)\left(\frac{L}{D}\right)\ln\left({W_i}/{W_{i+1}}\right) \qquad E(hr) = \left(\frac{1}{C_j\left(\frac{lbf}{lbf-hr}\right)}\right)\left(\frac{L}{D}\right)\ln\left({W_i}/{W_{i+1}}\right)$$

The fuel fraction is computed for each segment of the mission profile and the mission fuel fraction is obtained as follows:

$$Mff = \frac{W_1}{W_{TO}}\prod_{i=1}^{n}\frac{W_{i+1}}{W_i}\ W_{Fused} =$$

$$(1 - M_{ff})W_{TOguess}$$

Table 5-3 lists all the calculated and assumed fuel fractions.

**Table 5-3 - Aircraft Fuel Fraction**

| $W_{i+1}/W_i$ | Segment | Fuel Fraction<br>[R] – Roskam Estimation [17]<br>[C] - Calculated | |
|---|---|---|---|
| $W_1/W_{TO}$ | Engine Start & warmup | 0.990 | [R] |
| $W_2/W_1$ | Taxi | 0.995 | [R] |
| $W_3/W_2$ | Take-off | 0.995 | [R] |
| $W_4/W_3$ | Climb | 0.980 | [R] |
| $W_5/W_4$ | Long Range Cruise | 0.683 | [C] |
| $W_6/W_5$ | Descent | 0.990 | [R] |
| $W_7/W_6$ | Loiter | 0.992 | [R] |
| $W_8/W_7$ | Climb to 10,000 ft to alternate | 0.990 | [R] |
| $W_9/W_8$ | 100nm cruise to alternate | 0.960 | [C] |
| $W_{10}/W_9$ | Descent | 0.995 | [R] |
| $W_{11}/W_{10}$ | Loiter | 0.996 | [R] |
| $W_{12}/W_{11}$ | Landing, taxi, and shut down | 0.992 | [R] |
| $M_{ff}$ | Mission Fuel Fraction | 0.602 | |

### 5.3.5 RESULTS

A wing-loading range of 50 to 74 lb/ft$^2$ was selected to be studied, as constrained by take-off and landing $C_{Lmax}$ requirements. A lower wing loading increases the wing area which increases parasite drag and worsens ride quality. Higher wing loadings reduce parasite drag, but complicate the high-lift system and reduces available fuel volume. Further considerations are discussed in the wing design section of this report. A thrust-to-weight ratio was selected to meet an acceptable $C_{Lmax,TO}$ as well as the take-off field length requirements.

Figure 5-6 shows the effect of LRC cruise altitude on the take-off weight of the aircraft. As expected, the most efficient altitude is 45,000ft. However, as per FAR 91.211 on supplemental oxygen, one pilot needs to be on oxygen at all times when above FL410. Thus, the team decided to size the aircraft at FL400, as endorsed by engineers at both Textron and Learjet. Table 5-4 displays the design points used for the sizing.

**Table 5-4 - Design Point for 6 and 8 Passenger Jets**

| | *6 Passenger* | | | *8 Passenger* | | |
|---|---|---|---|---|---|---|
| | **Sea Level** | **10,000 ft** | **ΔT of 50°F** | **Sea Level** | **10,000 ft** | **ΔT of 50°F** |
| **T/W** | 0.48 | 0.40 | 0.43 | 0.43 | 0.36 | 0.39 |
| **W/S** | 59 | | | 66 | | |
| **$C_{LMAX\ TO}$** | 1.6 | 1.9 | 1.7 | 1.6 | 2.0 | 1.7 |
| **$C_{LMAX\ L}$** | 2.3 | 2.7 | 2.4 | 2.44 | 2.8 | 2.5 |
| **$W_L/W_{TO}$** | 90% | 80% | 90% | 90% | 74% | 90% |

At 40,000 feet, the take-off weight variation with cruise speed and wing loading is shown in the carpet plot below. The asterisks represent the local minimums along each wing loading. Required landing maximum lift coefficients are also shown.

From the sizing charts, the following design parameters are selected. The wing is sized to the larger jet and is the reason the wing loading drops on the 6 passenger jet. Flaps are sized to the maximum landing lift coefficient of 2.8.

Finally, after selecting an optimal cruise Mach number and wing loading that meet all the take-off and landing requirements, the following aircraft weights are established.

**Table 5-5: Final Weights for 6 and 8 Passenger Jets**

| | *6 Pax* | *8 Pax* |
|---|---|---|
| $W_{TO}$ | 14,900 lb. | 16,630 lb. |
| $W_E$ | 8,140 lb. | 8,460 lb. |
| $W_F$ | 5,930 lb. | 6,620 lb. |
| $W_{mzfw}$ | 9,640 lb. | 11,460 lb |

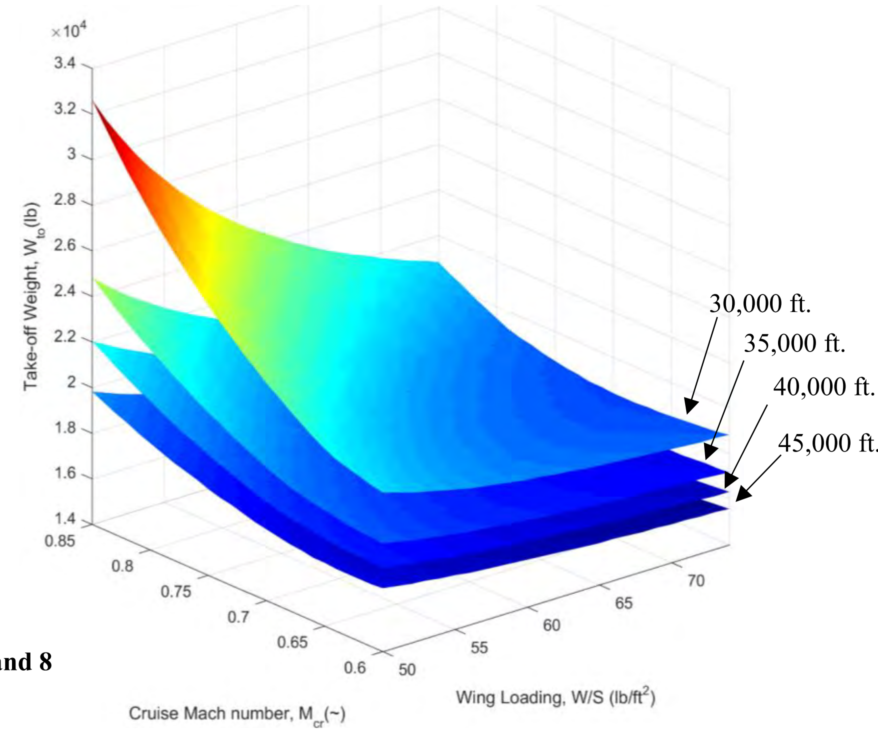



**Figure 5-6 - Take-off Weight, Mach Number and Wing Loading at Different Cruising Altitudes**

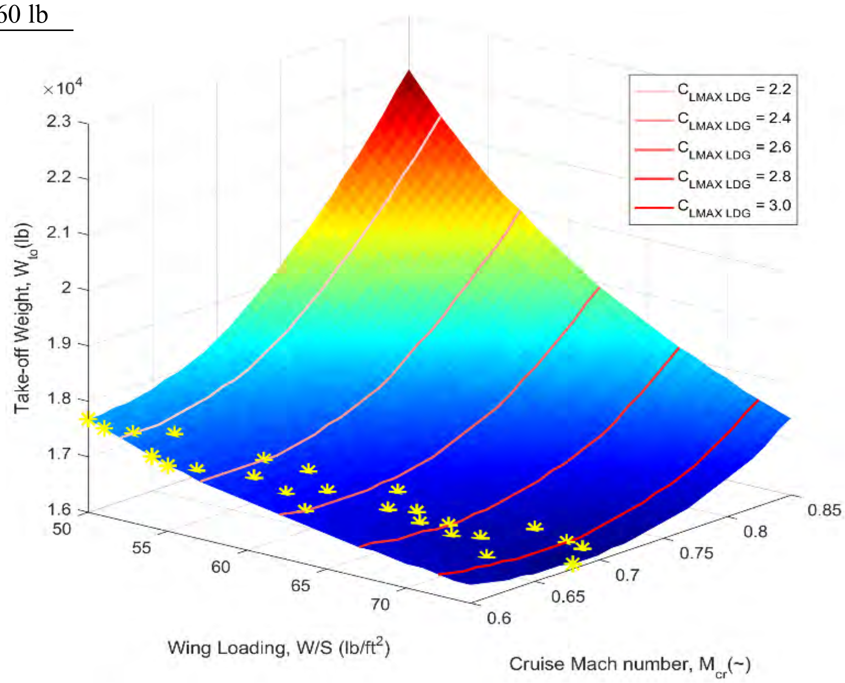



**Figure 5-7 Take-off Weight, Mach Number and Wing Loading at 40,000 ft: 3-D (top), 2-D (bottom)**

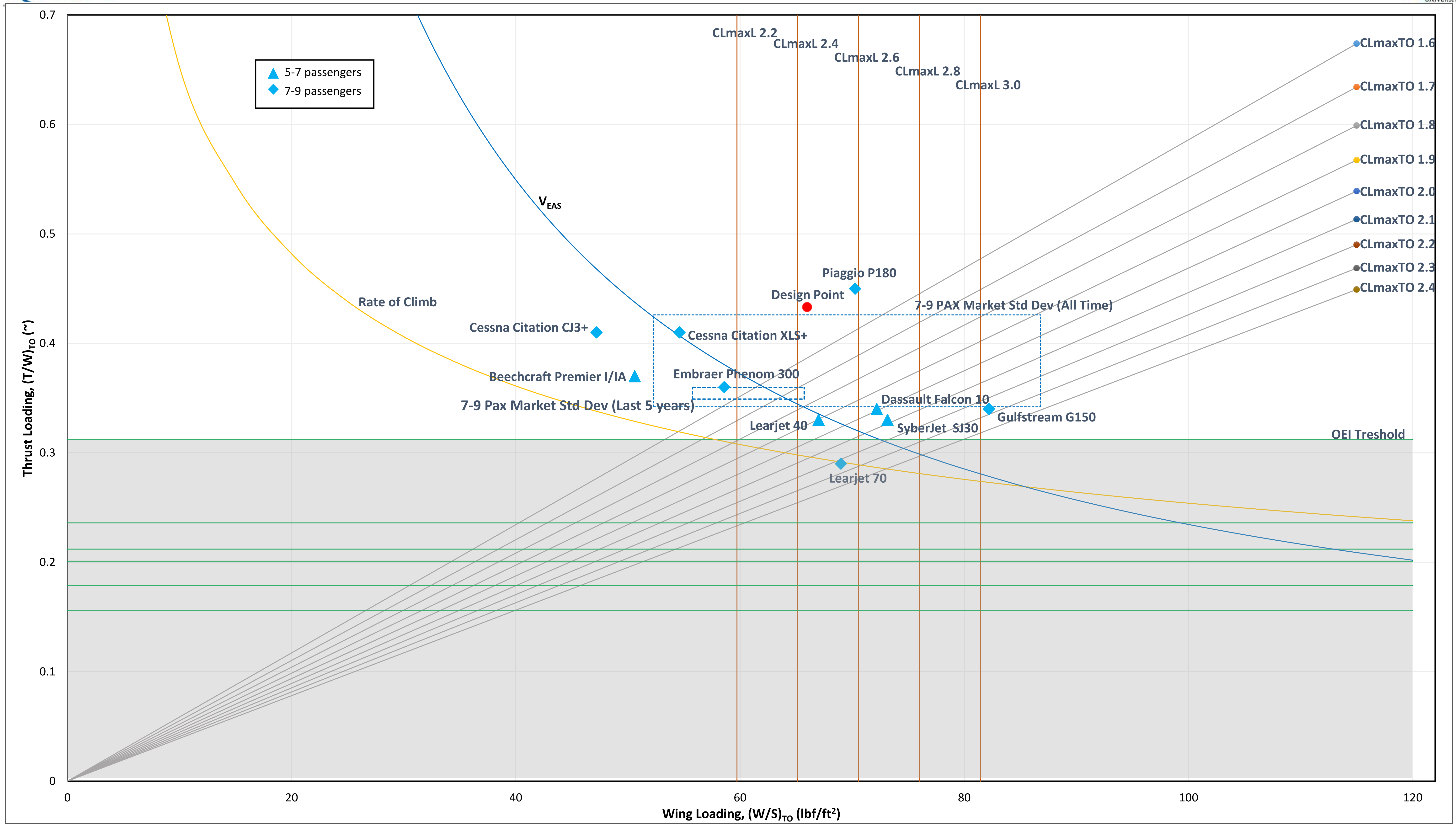



**Figure 5-8 - Thrust Loading vs Wing Loading (Turbofan, 2 engines, Std)**

# 6. CLASS I CONFIGURATION DOWN SELECTION

The first step in the design process was to determine configurations that could be viable for a Class I design analysis. To do this, a sweep of configurations that would be viable contenders in the business jet market were conceived. Both conventional and radical configurations were considered in an attempt to ensure that all avenues were considered before down selection. The following figure shows the 19 configurations considered for Class I design.

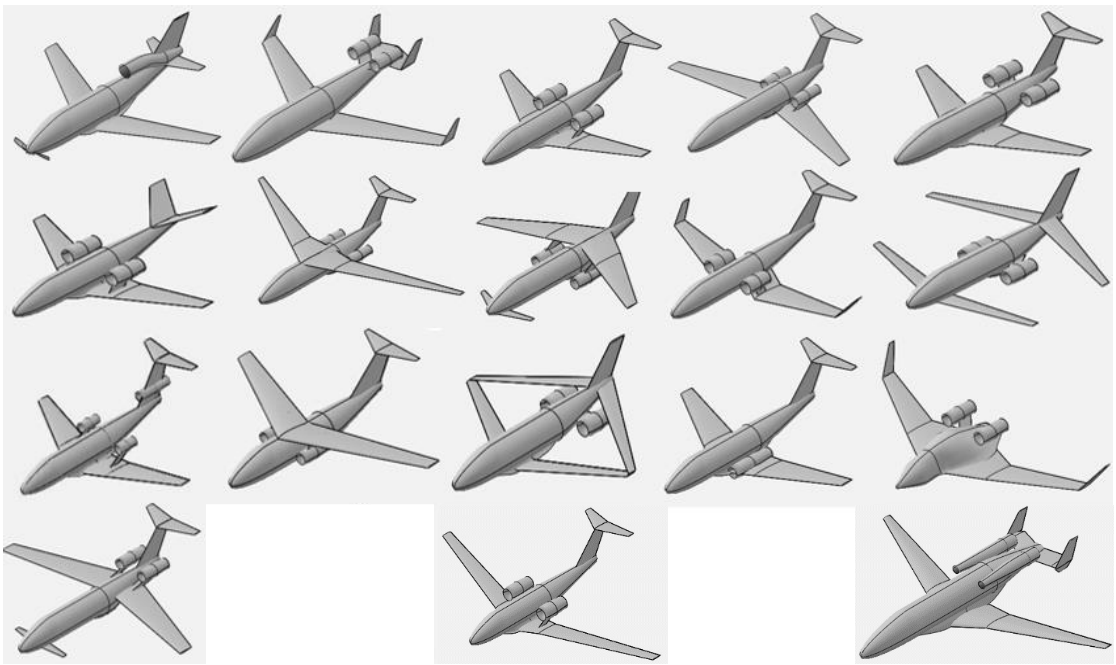


**Figure 6-1: Configurations Considered for Class I Design**

Once a list of configurations had been complied, the pros and cons of each configurations were considered. This process is detailed in the following section.

## 6.1 REJECTED CONFIGURATIONS

This section presents the configurations that were discarded for Class I design. Pros and cons of each configuration are listed, and a summary is included at the end of the section.

| Blended Wing Body | |
|---|---|
| + High L/D | – Structural Commonality |
| + Large Cabin Size | – Engine Accessibility |
| | – Passenger Comfort |
| | – Pilot Handling Qualities |
| | – Certification Cost |

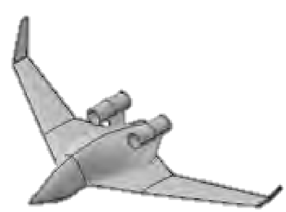


**Figure 6-2: Blended Wing Body Concept**

Wing Podded Engines

| | |
|---|---|
| + Lower Interference Drag | – Spar Discontinuity – Adds Weight |
| + Blown Flaps | – Engine Accessibility |
| | – Less Wing Fuel Volume |
| | – No Room for Engine Growth |

**Figure 6-3: Wing Podded Engines**

Delta Wing

| | |
|---|---|
| + Delayed Stall | – Engine Accessibility |
| + Transonic Performance | – Passenger Visibility Low |
| | – High Landing Angle of Attack |
| | – Low L/D |
| | – "Are you trying to go to space?" – Dr. Willam Anemaat |

**Figure 6-4: Delta Wing**

Tandem Wing

| | |
|---|---|
| + High AR | – Landing Gear Integration |
| + Low Trim Drag | – Engine Placement |
| | – Cabin Noise/Vibration |
| | – Pitch Break Characteristics |
| | – Certification Cost |

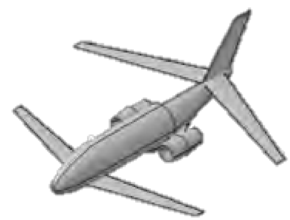


**Figure 6-5: Tandem**

Joined Wing

| | |
|---|---|
| + High L/D | – Requires Composites |
| + Less Trim Drag | – Certification Cost |
| | – EIS |

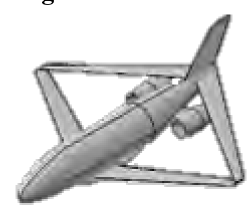


**Figure 6-6: Joined Wing**

Strut-Braced

| | |
|---|---|
| + High AR | – Landing Gear Integration |
| + Lower Structural Weight | – Low Fuel Volume |
| + Lower Span Loading | – Interference Drag |
| | – Certification Cost |
| | – EIS |

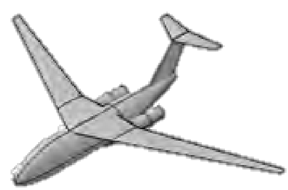


**Figure 6-7: Strut-Braced**

High Wing

| | |
|---|---|
| + Easy Engine Access | – Interference Drag |
| + Good Passenger Visibility | – Landing Gear Integration |
| + Lateral Ground Clearance | – Jet Noise Radiated Down |
| | – Engine Exhaust Washes Cabin |
| | – Market Appeal |

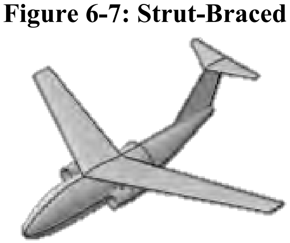


**Figure 6-8: High Wing**

High Wing + Canard

| | | | |
|---|---|---|---|
| + | Co-Locate Wing Spar & Rear Bulkhead | – | Canard/Engine Interference |
| | | – | Unstable Pitch Break |
| | | – | Certification Cost |

**Figure 6-9: High Wing + Canard**

Three Engine

| | | | |
|---|---|---|---|
| + | Smaller Vertical Tail | – | Increased Engine Cost |
| + | Favorable OEI characteristics | – | Fuel System Complexity |
| | | – | Increased Drag |

**Figure 6-10: Three**

Inverted Gull Wing

| | | | |
|---|---|---|---|
| + | Ground Effect Lift Boost | – | Split Spar – Increased Weight |
| + | Lower Interference Drag | – | Lower Wing Fuel Volume |
| + | Co-Location of Engine, Landing Gear | – | Lower Wing, Increased FOD chance |

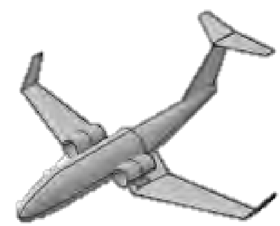


**Figure 6-11: Inverted Gull Wing**

V-Tail

| | | | |
|---|---|---|---|
| + | Less Wetted Area | – | Roll-Yaw Coupling |
| | | – | Engine Out: Large Rolling Moment |

**Figure 6-12: V-Tail**

Mixed Propulsion

| | | | |
|---|---|---|---|
| + | Improved Fuel Consumption | – | Feathering Prop at High Mach |
| + | Low Trim Drag | – | Maintenance Cost |
| + | Improved Takeoff, Climb Performance | – | Certification Cost |
| | | – | "Avoid mixed powerplant types like the plague" – J. Roskam |

**Figure 6-13: Mixed Propulsion**

### 6.1.1 SUMMARY OF REJECTED CONFIGURATIONS

For many of the discarded configurations, the biggest challenge would be FAA certification. Advice from industry professionals stated that for designs which have not been previously certified by the FAA, it would be nearly impossible to get certification in 3 years time, which is already an ambitious goal. This guided the down selection to favor more conventional designs.

Of the more conventional designs that have seen FAA certification, many of them are unsuitable for business jets. Wing podded engines add unnecessary complexity while only adding a marginal improvement in interference drag. Similarly, three engine configurations add unnecessary complexity and raise operating costs when a two engine configuration can deliver the same amount of thrust. Delta wings are more desirable for supersonic aircraft, and not efficient for subsonic flight. A high wing design would not have good market appeal, as high wing designs are more associated with small general aviation aircraft. Trying to improve the design with a canard makes the design more unlikely to be certified. While the inverted gull wing may reduce interference drag at the wing-fuselage interface, it adds a structural break that would add weight. A V-Tail may have better market appeal, but the OEI handling characteristics would make it a challenging for pilots to manage in emergency conditions.

## 6.2 ACCEPTED CONFIGURATIONS

The aircraft presented here represent what is typically seen in the business jet market, and what has been seen in the market.

| Wing Mounted Engines | |
|---|---|
| + Reduced Cabin Noise | – Engine Maintenance |
| + Low CG excursion | – Engine Placement w/ respect to Engine Non-Containment Event |
| + Co-Locate Landing Gear & Engine Pylon Structure | |
| + Reduced Risk of Engine FOD | |

**Figure 6-14: Wing Mounted Engines**

Wing mounted engines have been very recently introduced into the market by the Honda Jet, which has been well received by pilots. When asked which competitor was the largest threat, a Cessna design engineer picked Honda Jet, because of Honda's track record of dominating markets they have entered. Based on their reputation, it would be wise to follow Honda's lead.

| Three Surface | |
|---|---|
| + Co-Locate Wing Spar & Rear Bulkhead | – Landing Gear Integration |
| + Low Trim Drag | – Not Widely Accepted |
| + Passenger Ground View | |
| + High L/D | |

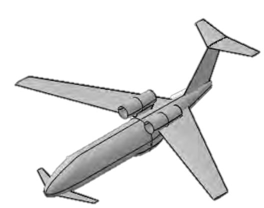


**Figure 6-15: Three Surface**

The three-surface aircraft represents the most efficient layout of lifting surfaces for an aircraft. This configuration allows for all surfaces to produce lift, helping to mitigate trim drag. The primary market example of a three-surface business jet is the Piaggio P-180. It is widely regarded as the most efficient business jet by design standards, with a laminar flow fuselage and wing.

| T-Tail | | | |
|---|---|---|---|
| + | Standard Business Jet Design | – | CG Excursion |
| + | Low Certification Cost | – | Not Unique to Market |

**Figure 6-16: T-Tail**

The T-tail is the tried and true business aircraft design that is dominate in the market. This suggests that over the evolution of the business jet category, this is the optimal design based on market acceptance. For the purposes of Class I design, it is used as the baseline that the competing designs must rise above to be chosen.

| U-Tail | | | |
|---|---|---|---|
| + | Reduced Noise Pollution | – | CG Excursion |
| + | Restorative Engine-Out Moment | – | Jet Blast Over Tail |
| + | End-Plating of Horizontal Tail | | |

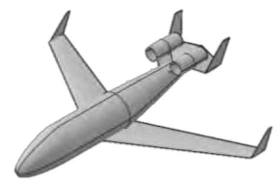
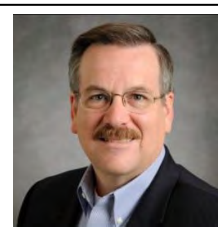


**Figure 6-17: U-Tail**

Of the configurations presented, the most intriguing is the U-tail configuration, a derivative of the H-tail. While H-tails have been used previously in commercial and military applications, a business jet with a U-tail would be the first of its kind. The placement of the engines optimizes OEI by using the exhaust over the vertical tail to create a counteracting moment to the yaw produced by the operative engine. There is also research currently being done in Europe to investigate the effect of U-tails to mitigate noise pollution, where a Dassault Falcon 7x is being retrofitted with a U-tail to determine the effect of ground noise mitigation [18]. However, this notion was disputed by Perry Rea, who stated the empennage would only shield high frequency noise, and not the low frequency noise that residential areas near airports complain about.

"Take a look at your noise frequency, it (wavelength) is bigger than the tail, it's not giving you any shielding, is it?"
*– Perry Rea, Boeing*



## 6.3 ADVANCED EFFICIENCY DESIGNS

Based on the RFP's design objective to minimize operating costs, two concepts were conceived with the goal to push current technologies as far as possible. One configuration was an aircraft with an extremely high aspect ratio, to quantify the gain that could be had with a wing that nearly doubled aspect ratio. A second concept was to place the engines side by side in the fuselage in the rear of the aircraft, similar to an F-22. This concept would allow for one engine to be shut off in cruise, and require little to no rudder trim to compensate for the engine-out yawing moment.

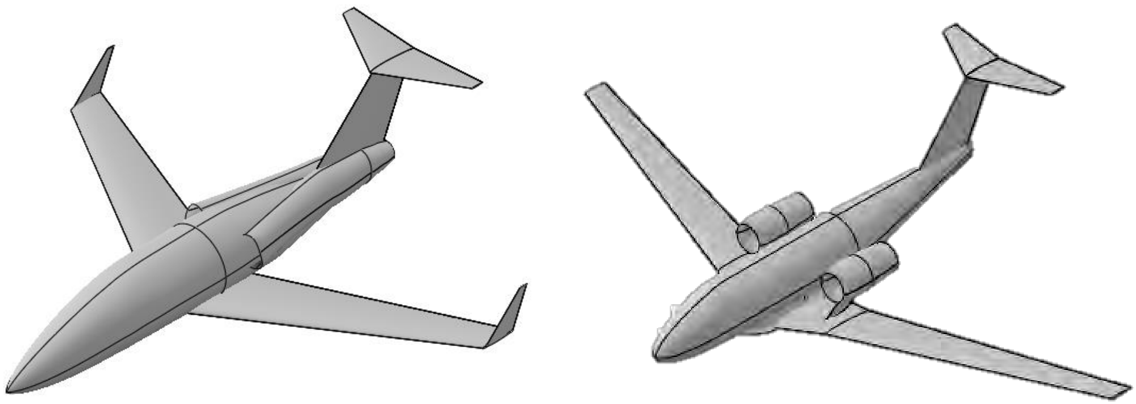


**Figure 6-18: Advanced Efficiency Concepts: Ducted Engines (left), High Aspect Ratio (right)**

These two concepts were carried through a Class II design to determine what kind of efficiency gains would be possible. For the high aspect ratio concept, AAA predicted an L/D of 19, while the advantage of shutting down one engine reduced the fuel required by approximately 2,000 lb. Both of these options would redefine the business jet market in terms of efficiency and operating cost, but they have many difficulties. The high aspect ratio wing would have to be very far forward to achieve the necessary sweep to meet the critical Mach number. The structure would also be a large challenge to manufacture. The ducted engine concept relies on being able to shut down an engine in flight, which engineers at Learjet were apprehensive about. They stated that pilots and the FAA would not be comfortable being one failure deep during cruise. By cutting an engine, the electrical power to the plane would also be reduced, creating another system challenge. To maximize the efficiency gains, the inlet and nozzle exit would need to be closed off, requiring a whole new system to be designed and certified. For the EIS date, neither of these options are possible concepts.

# 7. CLASS I DESIGN AND ANALYSIS

Once the Class I designs were selected, a full analysis was done on each, with the use of Advanced Aircraft Analysis (AAA). This software is produced by DAR Corporation, and can be described as a computer software wrapped around Roskam's Airplane Design series. It allows a user to define the weight and balance and geometry of an aircraft, and will output lift, drag, and stability and control values.

Based on the desire of the RFP to minimize costs, the goal was to choose the aircraft that would deliver the most efficient cruise. This was quantified by the value of L/D at cruise. This section discusses the procedure to analyze each configuration's efficiency.

## 7.1 FUSELAGE

For parity across all designs, the geometry for the fuselage was taken from a Hawker 400, a 7-9 passenger business jet produced by Beechcraft in the 1990's. This fuselage was selected as the closest representation to the RFP from a batch of AAA example files available from DAR Corporation. Salient characteristics from the fuselage are shown in Table 7-1.

**Table 7-1: Hawker 400 Fuselage Geometric Parameters**

| Diameter | Length | Tail-Cone Length | Tail-Cone Angle | Tail-Cone Fineness Ratio | Fuselage Fineness Ratio |
|---|---|---|---|---|---|
| 5.5 ft. | 42.6 ft. | 15.7 ft. | 14° | 2.9 | 7.7 |

## 7.2 PROPULSION SYSTEM LAYOUT AND INTEGRATION

The purpose of this chapter is to select and integrate the propulsion system to meet the mission requirements.

### 7.2.1 ENGINE SELECTION

In order to meet the cruise requirements at altitude, a turbofan is the preferred option. This is the option that is used on all business jets currently on the market.

Due to the entry-into-service requirements as well as cost constraints, the engines selected need to be an already developed and certified. Typical lead times for new jet engine development is 7-10 years. Engineers at Learjet verified that engine design and certification can take twice as long as the airframe, so specifying a new engine to be developed and certified is unrealistic.

Based on the current market, there are many engines that could be used. A Williams FJ44-4 was chosen, as it represents proven, reliable, and current technology, produces the required thrust for takeoff. A big plus was readily available engine data on a different model, the FJ44-1, which can be assumed to have similar characteristics. This data was scaled for engine modeling (see Section 5.3.1). Another key feature is the "Quiet Power Mode", which allows the engine to provide quiet, efficient ground power, eliminating the need for an APU [19]. The first aircraft to take advantage of this system will be the Pilatus PC-24. This also eliminates the need for a ground power unit. A representative picture and table of figures for the FJ44-4 is displayed below.

**Table 7-2: FJ44-4 Characteristics**

| Parameter | Value |
|---|---|
| Max Thrust | 3,600 lb |
| Length | 52.8 in |
| Diameter | 25.3 in |
| Dry Weight | 650 lb |

### 7.2.2 ENGINE INSTALLATION

Each concept had its own need for specific engine installation. For the wing mounted engines concept, the engines were cantilevered off the back of the wing, much like the HondaJet. Care was taken to try and position them far enough back to avoid having the compressor section crossing the occupiable cabin. The three surface concept engines were cantilevered off the front of the wing, again making sure the compressor face was aft of the cabin. The conventional and U-tail arrangements had their engines placed on the aft portion of the fuselage. The U-tail configuration had the engines placed higher on the fuselage to send the jet flow over the horizontal tail rather than hit it directly.

After initial engine placement, the engines were moved around within reason to satisfy weight and balance requirements.

## 7.3 WING & HIGH LIFT

The wing planform for each configuration was designed following the methodology of Roskam's Airplane Design Part II [20]. From initial aircraft sizing, the wing area and aspect ratio were predetermined, and by extension, the wingspan was also set. Wings were then designed for each configuration according to the unique characteristics of the aircraft.

### 7.3.1 WING DESIGNS

Due to the high range and speed requirements set by the RFP, dominating factors that drove the wing designs were the amount of fuel volume that could be stored, and the critical Mach number on the wing. A 2 panel solution was used for all wings, allowing for a thicker inboard section to store more fuel. For the wing mounted engines design, the engines were placed on pylons at the location of the wing crank. All wings utilized a thickness to chord of 15-12% from root to tip.

All wings were low-wing arrangements, excluding the three-surface. A mid-wing solution was sought to avoid downwash of the canard influencing flow over the wing. For optimal structural design, the wing was envisioned to attach to the structure supporting the rear pressure bulkhead. It was also the only wing to incorporate forward sweep.

**Table 7-3: Wing Characteristics for Each Design**

| | Wing Mounted Engines | Three Surface | T-Tail | U-Tail |
|---|---|---|---|---|
| Wing Area, *S* | 210 $ft^2$ | | | |
| Aspect Ratio, *AR* | 11 | | | |
| Span, *b* | 48 ft | | | |
| Sweep Angle, $\Lambda_{c/4}$ | 27° | -18° | 34° | 26° |
| Root Thickness Ratio, $(t/c)_r$ | 15% | 15% | 10% | 15% |
| Tip Thickness Ratio, $(t/c)_t$ | 12% | 12% | 10% | 12% |
| Taper Ratio, $\lambda$ | 0.17 | 0.17 | 0.20 | 0.16 |
| Dihedral Angle, $\Gamma_w$ | 0° | 0° | 0-3° | 0° |
| Airfoil | sc20414-sc20410 | | | |

## 7.4 EMPENNAGE & CONTROL SURFACES

For a quick sizing of the empennage (and canard for the three surface), the tail volume coefficient method was used for each design. This gave a good first approximation, and was adjusted later in the design for trim and stability and control purposes.

**Table 7-4: Empennage Characteristics**

| | Wing Mounted Engines | | Three Surface | | | T-Tail | | U-Tail | |
|---|---|---|---|---|---|---|---|---|---|
| | H. Tail | V. Tail | H. Tail | V. Tail | Canard | H. Tail | V. Tail | H. Tail | V. Tail |
| Area ($ft^2$) | 32 | 32 | 32 | 32 | 26 | 40 | 36 | 54 | 19 |
| Sweep (°) | 29 | 48 | 29 | 48 | 24 | 31 | 50 | 21 | 34 |
| Aspect Ratio | 4.5 | 1.1 | 4.5 | 1.1 | 7.7 | 5.3 | 1.2 | 2.7 | 1.6 |
| Taper Ratio | 0.4 | 0.5 | 0.4 | 0.5 | 0.4 | 0.4 | 0.6 | 0.8 | 0.7 |
| Thickness Ratio | 8% | 8% | 8% | 8% | 9% | 8% | 8% | 8% | 8% |
| Incidence (°) | 1 | 0 | 0.5 | 0 | 1 | 1.5 | 0 | 1.2 | 0 |
| Dihedral (°) | -3 | 90 | -3 | 90 | 0 | -3 | 90 | -3 | 75 |
| Volume Coefficient | 0.71 | 0.06 | 0.76 | 0.06 | 0.29 | 0.80 | 0.06 | 0.92 | 0.08 |

## 7.5 WEIGHT & BALANCE

For each configuration, AAA gave the advantage of performing Class II Weight and Balance on each aircraft. This allowed for greater flexibility in balancing the aircraft for cruise, being able to place components like cargo and systems in places that can help the weight and balance. For each configuration, the weight and balance was adjusted, along with wing placement, to achieve the best cruise static margin. This presented some challenges for each aircraft, which will be discussed in a later section.

## 7.6 LIFT TO DRAG RATIOS

After the aircraft had been configured to their ideal cruise condition, AAA was used to determine the drag polars for the aircraft. For all configurations, the zero lift drag coefficient is between 0.017 for the T-tail, and 0.025 for the three-surface. Cruise $C_L$ range is similar for all configurations at 0.45, varying by about 7% between designs.

**Table 7-5: $L/D_{cr}$ Values for Each Configuration**

| Configuration | L/D |
|---|---|
| Wing Mounted Engines | 12.8 |
| Three Surface | 15 |
| T-Tail | 12.8 |
| U-Tail | 12.1 |

Along with the drag polars, the L/D values for each aircraft were calculated. They are presented in Table 7-5.

## 7.7 CONCLUSIONS

Based on the L/D values, it would appear the three surface configuration would be the ideal aircraft to carry forward. However, during the Class I design process, it was discovered there would be large issues with bringing the three surface to market. The three surface must use a forward sweep wing, which would be ideal for composites. However, Dr. Jason Merret stated that composites would not be a good option on a short timeline, stating for primary structure, “By 2020, it’d be very tough.” The added complexity of utilizing the inherent bend-twist nature of composites to create aero-adaptive structures makes the composite wing unrealistic.

The forward sweep itself was not well received by industry professionals. Engineers at Lockheed Martin stated that doing forward sweep would be a challenge in itself. For anything different than what the FAA has recently certified, the “FAA wants documentation six ways to Sunday.” Perry Rea of Boeing concurred that aircraft with forward sweep would be difficult to certify by the EIS date. While the three surface may have been a viable contender were the EIS 5-6 years away, it is not viable for the current timeline, and had to be disregarded as a candidate.

## 8. CLASS II DOWNSELECTION – MARKET SURVEY

After deselecting the three surface option, the wing mounted engines, T-tail, and U-tail options are very similar, all with their own pros and cons. To make the final down selection, the decision was left to the market to decide.

To determine which of the concepts a discerning business jet customer would be most likely to buy, as well as what factors were most important to a business jet customer, a market survey was created. These were left at FBOs in Lawrence, KS, and the Kansas City Metro area. Business jet owners were to fill out the survey, and mail it back in a self-addressed stamped envelope to the Aerospace Engineering department at KU. The survey was shown to Lockheed-Martin and Gulfstream, both approving of the questions chosen by the team. It was decided that demographics would be left out in an attempt to appeal to the owner/operators time.

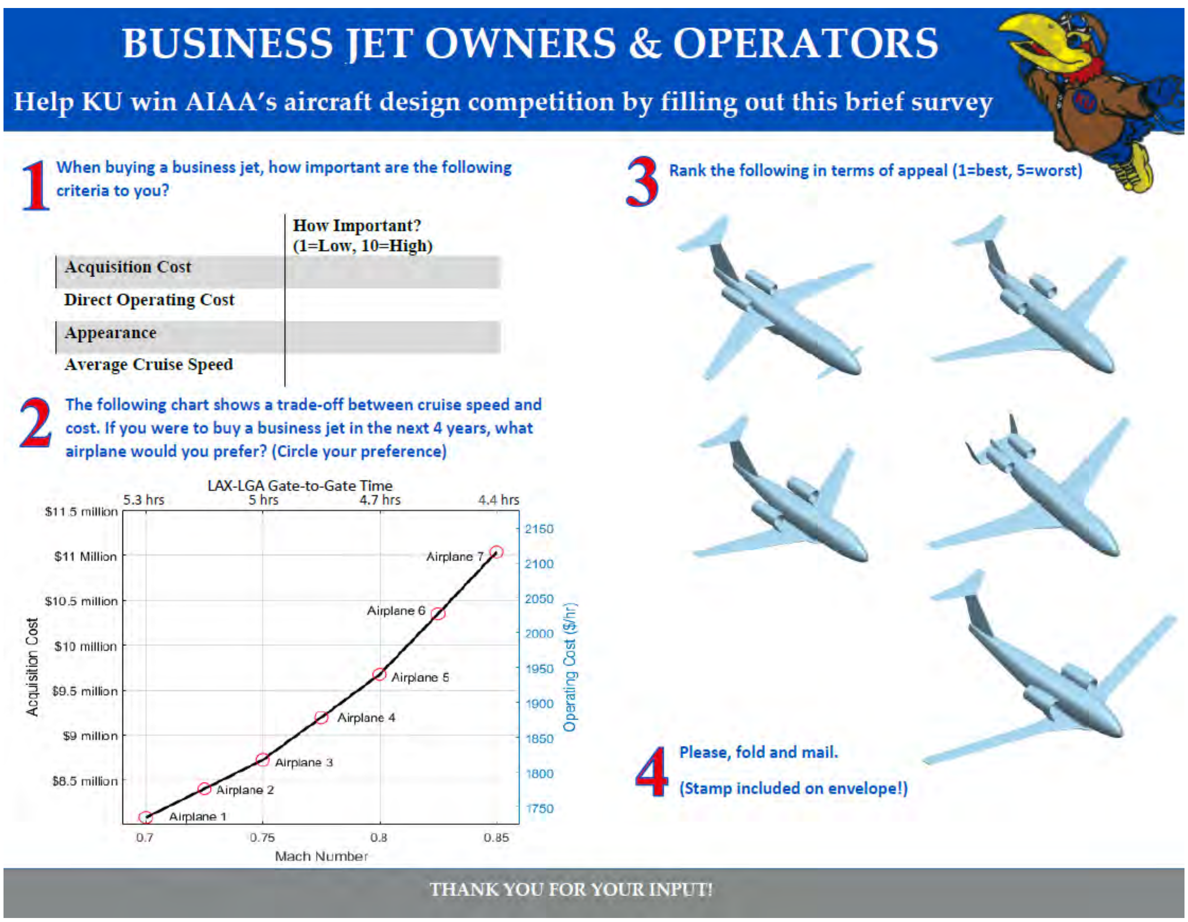



**Figure 8-1: KU Market Survey**

The team received 7 surveys back. The results of the 2nd question are displayed in Figure 8-2. Respondents are willing to pay more in acquisition and operating cost for an increase in the average cruise Mach number of their aircraft. This means that a premium could be charged for speed, and can be leveraged in the pricing of the final aircraft.

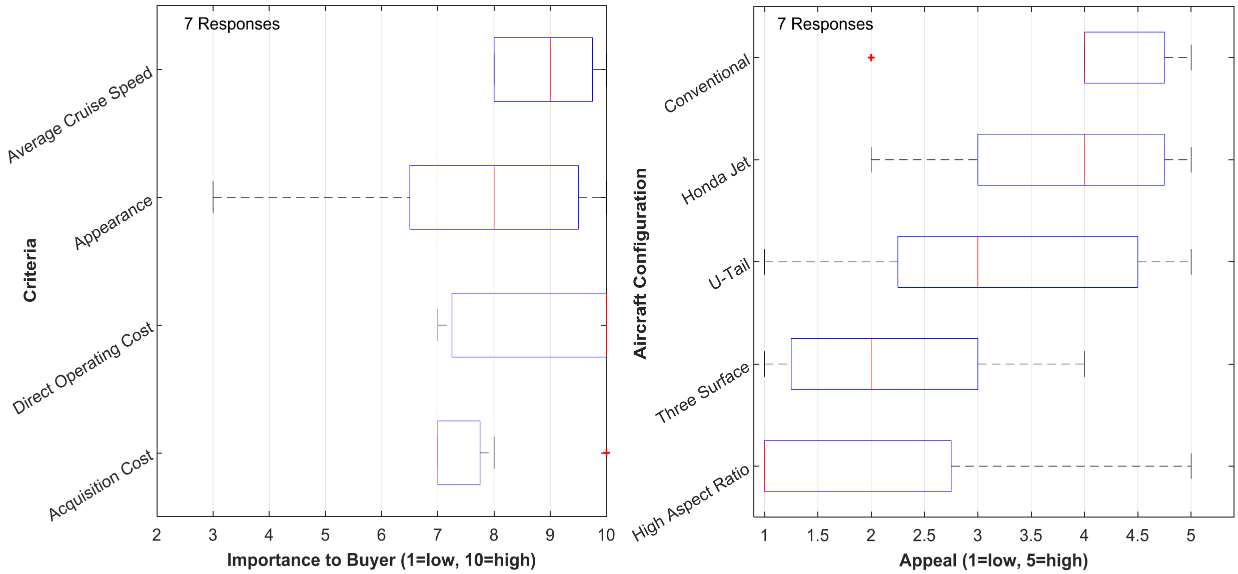



**Figure 8-2: Responses to Questions 1 and 3**

The results for the 1st and 3rd questions are shown in Figure 8-3 in the box-and-whisker plot. The vertical red line represents the mean response. The blue edges represent the upper and lower quartile, which are the median of the upper and lower halves of the data. The dashed black lines represent the upper and lower 25% of the data. Outliers (much greater than the upper and lower quartile) are marked with a red plus. This type of plot allows for a good representation of the range of data received.

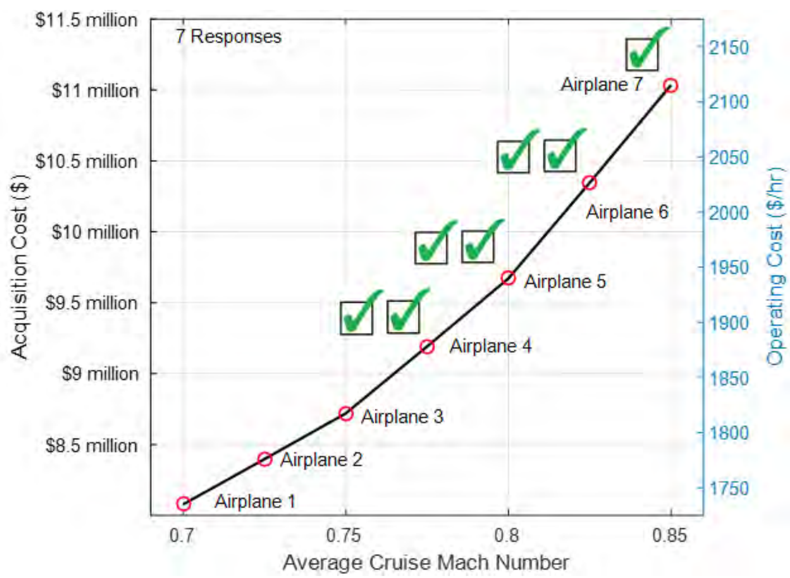



**Figure 8-3: Results of Question 2**

Based on the results of the survey, business jet owners value a high average cruise, aligning with the priorities of the RFP. While acquisition cost may not be the most imporatant variable, direct operating cost is highly valued.

The appearance of the business jet is valued fairly high, meaning that attention should be paid to the aircraft configration results, which peg designs that are already out on the market high. This suggests that the market would not react well to a non-traditional design entering the market. This fact was emphasized by Dr. Jason Merret of Gulfstream, stating: “If you aren’t doing conventional, you better have a good reason.”

Based on the results of the survey, and the lack of differentiation in performance between the different concepts, it was decided that a conventional design would be the best chance to achieve success in the market and meet the RFP.

> “If you got into a new car with a joystick for a wheel, you’d be apprehensive about buying it, regardless of how much better it was.”
> - *Dr. Jason Merret, Gulfstream*

## 9. CLASS II DESIGN

The purpose of this section is to present the detailed work for the final aircraft configuration.

### 9.1 FUSELAGE & COCKPIT LAYOUT

The purpose of this section is to layout the cockpit and fuselage design for both the 6-passenger and 8 passenger to meet the mission requirements in terms of crew, passengers and payload. The following table recalls the items needed to be accommodated in the fuselage.

**Table 9-1 – Fuselage Operational Items**

| Item | Number | |
|---|---|---|
| | 6 Passenger | 8 Passenger |
| Cockpit Crew | 1 to 2 | |
| Passengers | 6 | 8 |
| Baggage | $30 ft^3$/500lb | $60\ ft^3$ / 1,000lb |

During the team’s discussion with engineers at Textron on customer preference and marketability, the team learned that cabin diameter and volume is one of the biggest business jet selling points today. A design cabin width

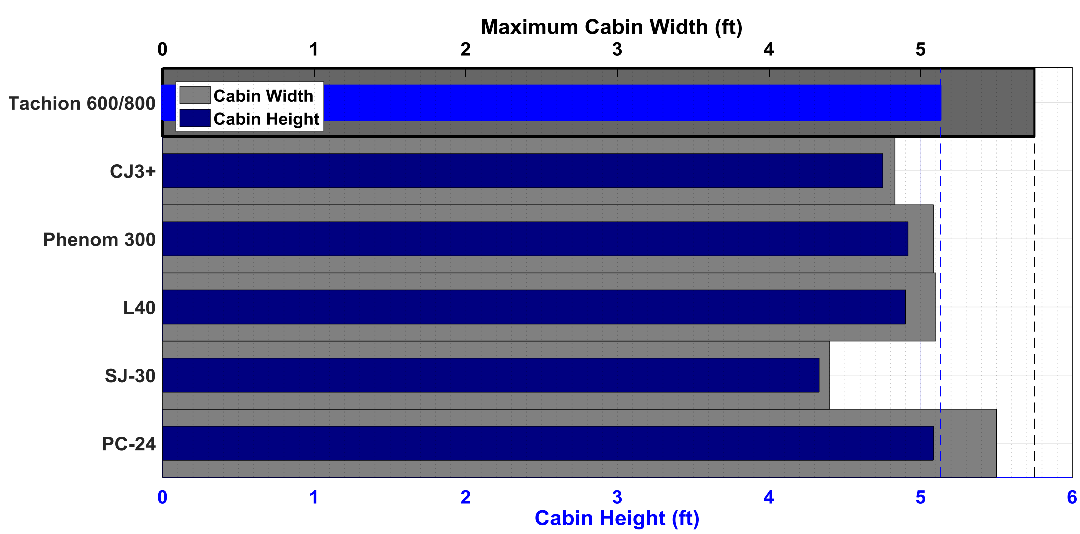



**Figure 9-1: Comparison of Maximum Cabin Width and Height with Competitors**

and height was selected to be larger than any of the direct competitors. The following figure shows a comparison of cabin dimensions of our aircraft and competitors. The superiority in this aspect would improve the marketability of this aircraft significantly.

> "Particularly in the last 10 years: Speed and range are okay. Cabin diameter is best. Things have shifted over the years."
> - *Albert Dirkzwager, Textron Aviation*

The design cross section is shown in the Figure 9-2. Circular cross-sections are most efficient for pressurization. However, a circular cross-section would sacrifice standing room height for floor width. Several companies like Embraer and Cessna make use of a squared-out cross sections to maximize the flat floor width and cabin height. A circular cross section would require a dropped aisle for the same standing room height as a squared-out cross section. After learning at Textron Aviation that cost would not be increased significantly, a squared-out cross section was used.

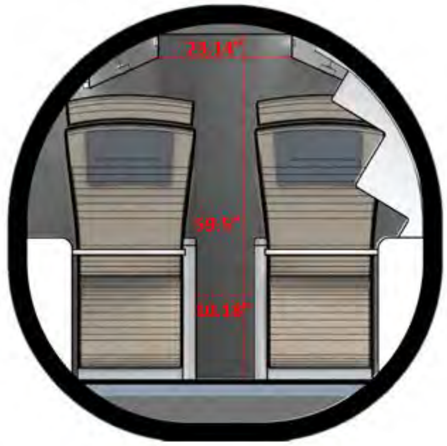



**Figure 9-2: Cabin Cross Section**

A seating layout was created in order to provide enough room for the passengers as well as facilities such as a galley area and a bathroom. In the design philosophy, it was determined that the difference between the 6 & 8 passenger version would be to shorten the fuselage. Therefore one row of seating was taken out. Various interior options are shown in Table 9-2.

**Table 9-2. Interior choices**

| Interior | 6-pax | 8-pax |
|---|---|---|
| **Standard** | Five seats club four arrangement | Seven forward facing seats |
| **Option 1** | Divan and two seats | Seven seats and divan |
| **Option 2** | -- | Eight seats |

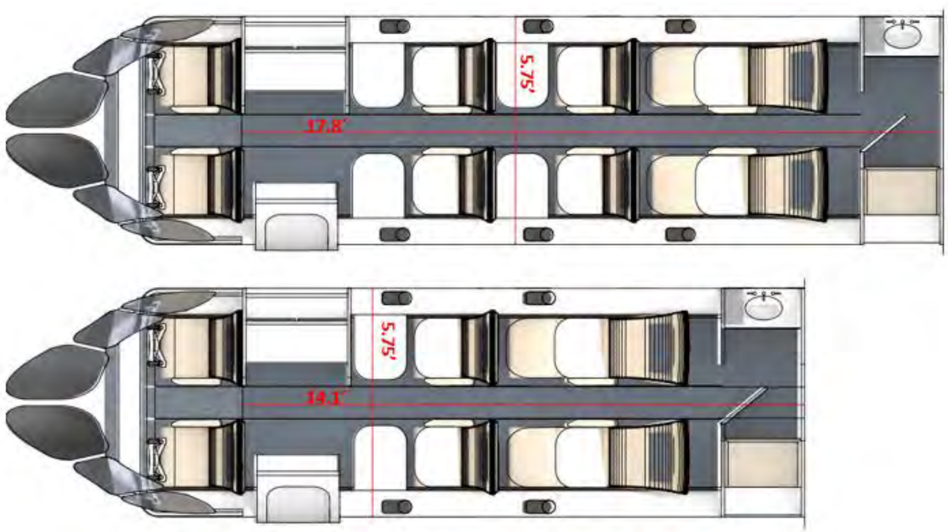



**Figure 9-3: Interior Layout**

Figure 9-4 and Table 9-3 define the major geometric parameters of the fuselage.

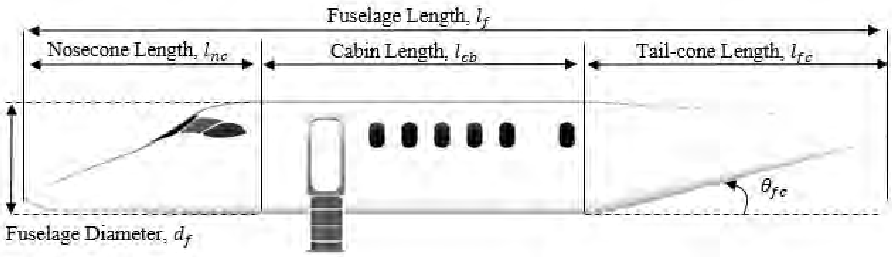



**Figure 9-4 - Fuselage Dimensions**

**Table 9-3 - Fuselage Dimensions**

| | 6 Pax | 8 Pax |
|---|---|---|
| $l_{nc}$ | 12.9 ft. | |
| $l_{cb}$ | 14.1 ft. | 17.8 ft. |
| $l_{fc}$ | 16.8 ft. | |
| $l_f$ | 43.7 ft. | 47.5 ft. |
| $\theta_{fc}$ | 15° | |
| $d_f$ | 6.25 ft. | |

**Table 9-4 - Fuselage Geometric Ratios**

| | 6 Pax | 8 Pax | Acceptable Range [20] |
|---|---|---|---|
| $l_f/d_f$ | 7 | 7.6 | 7 - 9.5 |
| $l_{fc}/d_f$ | 2.7 | | 2.5 - 5 |

The fuselage geometric parameters for both variants are listed in the following table. The finess ratios for both variants are met as shown in Table 9-4.

The cockpit was designed with emphasis on following FAR 25 pilot visibility, and reduce workload. Two baggage compartments were designed to accommodate the volume requirements for both variants. They were placed forward and aft to help with weight and balance among a wide variety of loading conditions. The team considered having a pressurized cargo area, but decided it would be a large weight and cost increment, which was echoed by Dr. Roskam. From talking to industry, the major sales factors for cargo bays is the ability to fit golf clubs and skis. The rear cargo bay can hold skis up to 6' diagonally.

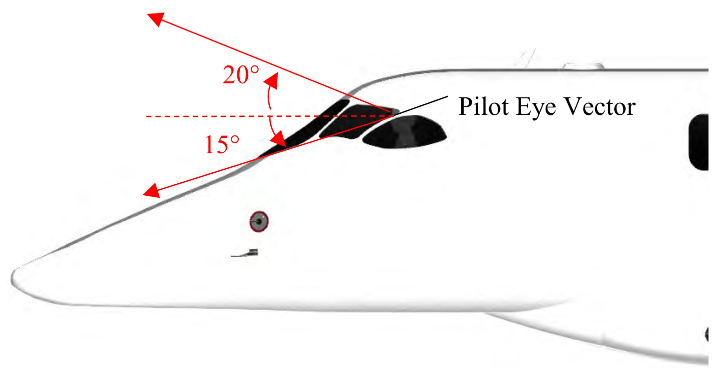



**Figure 9-5: Cockpit Visability**

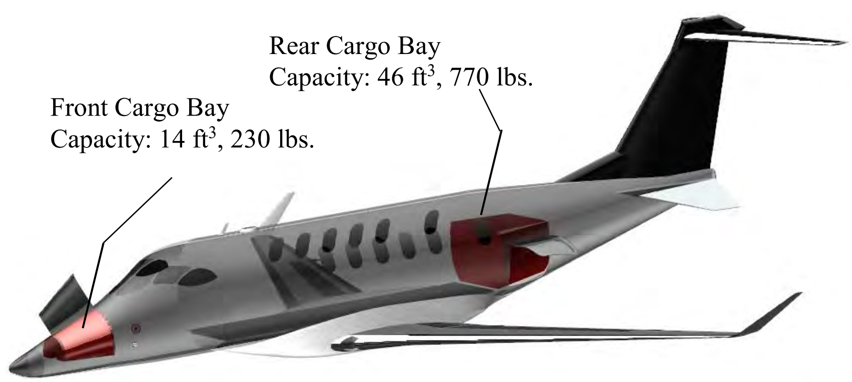



**Figure 9-6: Baggage Compartments**

## 9.2 ENGINE INSTALLATION

For engine lateral spacing the most paramount aspect was interference drag and engine rotor non-containment events. Engine-out yawing moment was considered secondary to these since the interference drag affect performance, and FAR 23 states that the chance of one engine disabling the other must be minimized.

Engine nacelle interference drag was taken into account for the spacing of the nacelle from the side of the fuselage. Figure 9-7 from Reference [21] gives the optimal ratios for nacelle diameter to the engine centerline spacing. For the cruise condition with lift coefficient values between 0.4 and 0.5, a value for t/d of 0.65 was chosen. This yielded a "t" value of 19.5 inches.

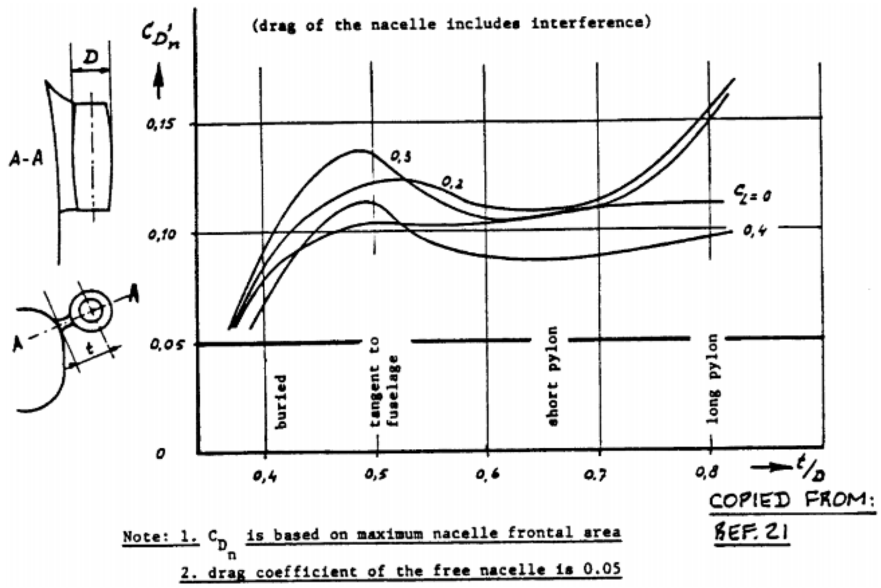



**Figure 9-7: Fuselage-Nacelle Drag Estimation [21]**

Another consideration for engine nacelle lateral spacing was the rotor non-containment event. The failure of one third of the rotor disk must have a low chance of disabling the second engine. Perry Rea from Boeing informed the team that the Boeing standard is to have a 1/20 chance of this occurring. Using this metric, the distance between engines was calculated to be 11.5 feet. This was considered to be unacceptable for a business jet because of the adverse yaw due to the engine-out condition. The Citation CJ4, which uses the same size engines, was calculated to chance of impact was closer to 1/13. Since the fuselage is larger in

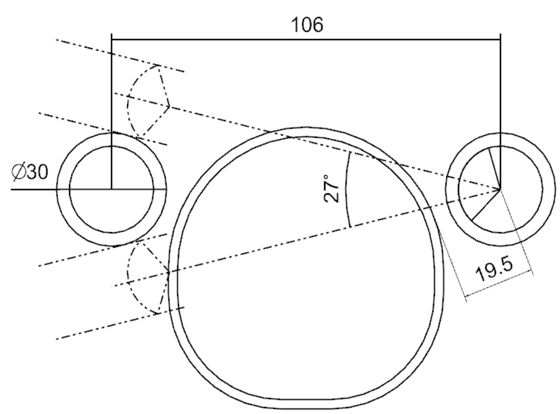
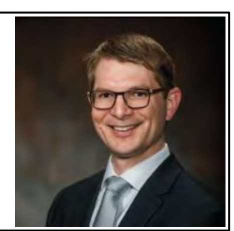



**Figure 9-8: Placement of Engine Nacelles: Rotor Non-Containment**

"The goal for certification is to show that you have attempted to minimize the risk."
- *Jeff Johannsmeyer, Textron Aviation*



diameter than the CJ4, the interference drag placement leads to larger spacing, and thus was considered to be an acceptable risk. Figure 9-8 shows the fuselage cross section and nacelle lateral placement. In the event of a rotor non-containment event, the probability of hitting the second engine is 1:13.

Thrust reversers were considered as an option, but were excluded after meetings with Textron and Learjet. They informed the team of a study where told their operators that they could remove 500 lbs. from the aircraft and a maintenance problem, and in exchange, they would lose 1,000 ft. of runway on a wet day. The response was "Sold." Thrust reversers would add significant weight, and increase the complexity of the propulsion system. Based on performance analysis of the landing distance, thrust reversers were not necessary to meet the RFP, and were therefore excluded. Engineers at Textron stated that it would be cheaper to replace brakes than it would be to acquire and maintain thrust reversers.

"The sales you'll lose from not having thrust reversers are likely not very big compared to the 30 or so you'll sell."
- *Albert Dirkzwager, Textron Aviation*

The longitudinal placement was set by the weight and balance with the restriction that any rotary component should not pass through the aft pressure bulkhead. For vertical placement, the engines were placed to be as close to the vertical CG location as possible while still allowing access to a baggage door. The engines were not placed higher because of an unfavorable nose down pitching moment that will increase with increased vertical displacement from the CG.

The inclination angle of the engine nacelle was set based on the calculated downwash from the wing. For the 8-pax variant the downwash is 1.6° and the 6-pax variant, 1.8°. To minimize the change in structure, the inclination is set to 1.7° for both variants.

## 9.3 WING

The wing was sized for the heaviest aircraft in the family since the same wing structure would be used between both the six and eight passengers. From the sizing chart for the eight passenger, a wing loading of 66 lbs/ft$^2$ coupled with the chosen aspect ratio of 11 gave the wing geometry seen in Figure 9-11.

The wing is cranked with two separate sections. This had a couple of advantages: First, the inboard section, being at a higher sweep angle, can then be made thicker, and allow for more fuel volume. Second, the jahuti at the aft inboard section can be used to store the strut of the landing gear.

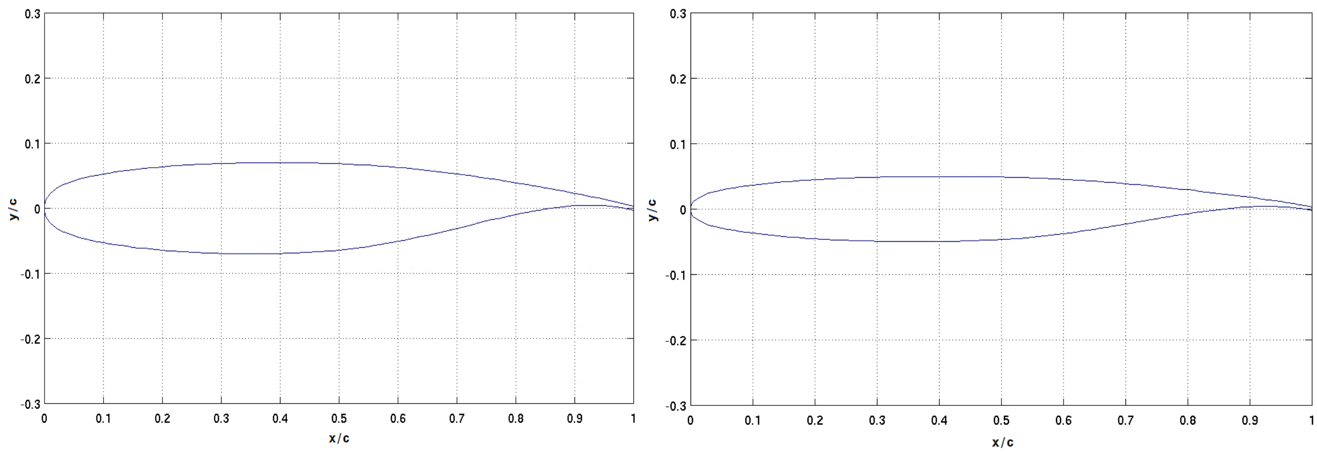



**Figure 9-9: Wing Root and Tip Airfoils, NASA SC20414 and NASA SC20410**

For the airfoil, the NASA SC204XX series of super critical airfoils was chosen. The main factor in choosing this airfoil was the benefit of dropping the critical Mach number for transonic speeds and reducing wave drag, based on Figure 6.1b from Ref [21]. This was done to avoid large rises in transonic drag. The design coefficient of lift also closely matches that of the coefficient needed in the cruise condition. The lift curve of the airfoil can be seen in Figure 9-10.

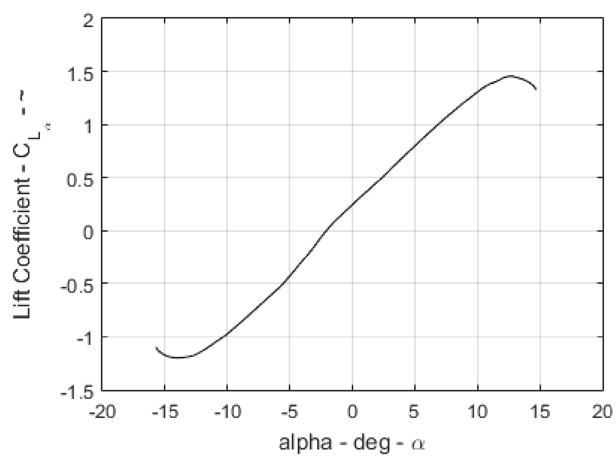



**Figure 9-10 – NASA SC20414 Lift Curve**

Forward and aft spar placement was based on a need to maximize fuel volume while simultaneously leaving sufficient room for control surfaces and systems. A three spar configuration was chosen so the forward spar could be moved forward to increase fuel volume in the wing torque box. The spar locations chosen were at 15%, 45%, and 75% of the wing chord. At the wing crank, the number of spars increases to four, and three of them cross perpendicular to the fuselage to accommodate mounting to the fuselage, and the landing gear. For the anti-ice system, the wing will use an electric ceramic coating around the leading edge, which is similar to what Cessna uses in its business jet family

Flap sizing was performed based on the landing condition, which require the highest max lift coefficient of 2.8. Unfortunately, plain flaps did not provide enough wing area to accomplish this, so more complex double slotted flaps were chosen. The flap area extends from 12% to 70% of the half span to achieve the required lift. The aileron was placed in the remaining 30% of the half span. No leading edge devices were needed, giving the wing lower maintenance and lower drag, as laminar flow will be preserved over more of the wing surface.

**Table 9-5: Wing Salient Characteristics**

| | |
|---|---|
| Wing Area – S | 252 $ft^2$ |
| Span – b | 52.7 ft |
| Aspect Ratio | 11 |
| Airfoil Thickness – t/c | 14%-10% |
| Dihedral inboard/outboard | 4°/3° |
| Inboard Sweep, $\Lambda_{LE}$ | 35° |
| Outboard Sweep, $\Lambda_{LE}$ | 25° |

Spoilers were run along the surface of the wing in front of the flaps to destroy the excess lift upon landing. The inboard spoilers will also be used for roll control.

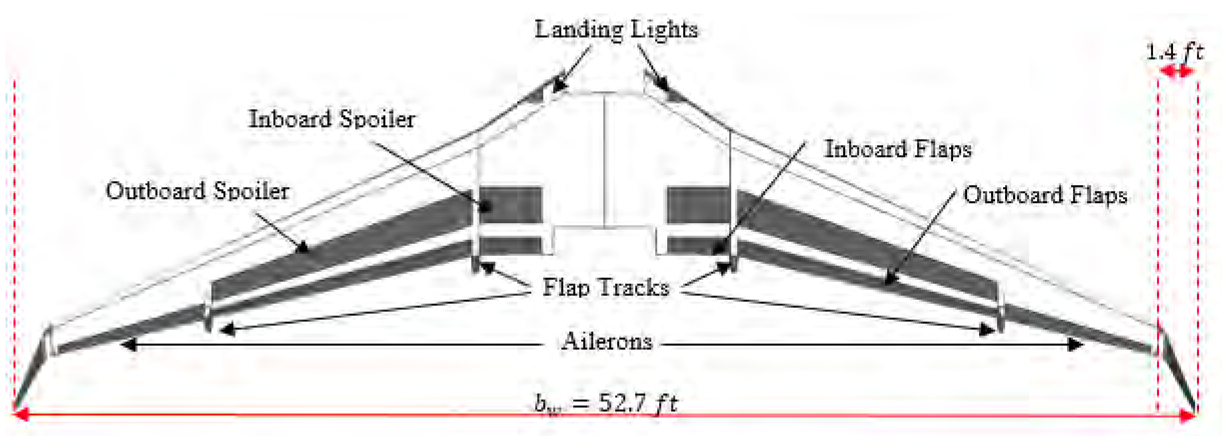



**Figure 9-11 - Wing Configuration**

## 9.4 EMPENNAGE

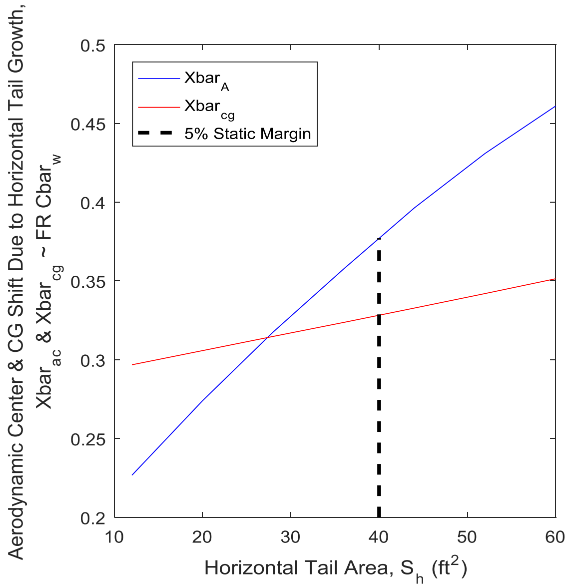
For empennage design, there are some potential design issues to keep in mind. The placement of the horizontal tail must be kept out of the jet stream. This can cause the tail to buffet, which can lead to fuselage vibration and cabin noise. Prolonged exposure to high temperatures can rapidly age the structure, and large increases or decreases in throttle setting can result in an undesirably large trim changes. The engine-out condition dictates the size of the vertical tail due to the yawing moment produced by the inoperative engine, which must be counteracted by a rudder deflection of no more than 25° as dictated by Roskam [20]. The stability, control, and handling characteristics of the empennage are later discussed in the Section 9.6.

The empennage configuration was already pre-determined by the Class I sweep of configurations, with a conventional T-tail design, which is used by most of the direct competitors of the Tachion. The approach for sizing the empennage is followed according to Roskam's methods, which uses the tail volume coefficient method to give a first approximation of the size, and historical data to establish limits on salient characteristics: sweep angle, aspect ratio, and taper ratio. The empennage design is done for the 6 passenger version, due to the shorter moment arm once the fuselage plugs are removed, and lower stall speed, which affects $V_{mc}$. Designing the empennage in this manner will also comply with the advice given from Learjet: to size the empennage for the smaller aircraft version, so the empennage would not have to be resized for the larger one.

Tail volume coefficient data can be found in Roskam's Aircraft Design Part II [20], which has tables for both vertical and horizontal characteristics of business jets. Tables 8.5a and 8.5b [20] contain eight aircraft with a T-tail configuration, of which the Learjet 35 is picked to be the baseline. This is due to similarities between wing area and gross weight to the Tachion. The $\overline{V}_h$ and $\overline{V}_v$ are 0.65 and 0.066 respectively. Using an approximation of the moment arms, the horizontal and vertical tail area can be estimated. The areas are estimated to be 43 ft$^2$ and 51 ft$^2$.

$$S_h = \frac{\overline{V}_h S_w \bar{c}}{x_h} \qquad S_v = \frac{\overline{V}_v S_w b}{x_v}$$

The second and more accurate method for horizontal and vertical tail area is the X-Plot method. With assistance from Advanced Aircraft Analysis (AAA), the longitudinal and directional X-Plot can be created with higher accuracy. The method for longitudinal is based on a desired static margin of 5% for business jets, recommended in Roskam [20]. The directional method aims for an airplane yawing moment coefficient due to sideslip ($C_{n\beta}$) of 0.0573 rad$^{-1}$ for the vertical tail $C_{n\beta}$.



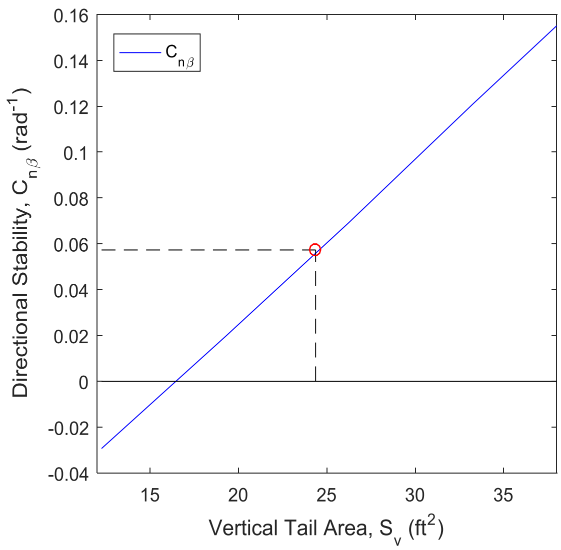




**Figure 9-12 - Longitudinal X-Plot (a) and Directional X-Plot (b)**

According to the directional X-Plot, for a minimum static margin of 5% at the most aft cg position, the horizontal area must be at least 40 $ft^2$. For the directional X-Plot, the vertical tail must be at least 24.3 $ft^2$. However, this minimum area will prove later to be too small for the minimum control speed with one engine inoperative, where rudder deflection should not exceed 25°. Therefore the vertical tail area used is 38.5 $ft^2$.

To check for the minimum control speed with one engine inoperative, the steps from Roskam's Part II, Section 11.3 are followed, with the assistance of the software AAA to verify the result. The engine out deflections are calculated for the most critical flight segment: take-off. This is due to both engines running at max continuous thrust. The results for one engine out are presented on the table below.

**Table 9-6: Engine-Out Rudder Deflection**

| | ***6 Passenger*** | | | | ***8 Passenger*** | | | |
|---|---|---|---|---|---|---|---|---|
| **Take-off Condition** | Sea Level, Std | Sea Level, Std+50°F | 10,000 ft, Std | 10,000 ft, Std+50°F | Sea Level, Std | Sea Level, Std+50°F | 10,000 ft, Std | 10,000 ft, Std+50°F |
| **Deflection (°)** | 22 | 22 | 21 | 21 | 17 | 17 | 16 | 16 |

The rudder deflections for every condition of both aircraft versions do not exceed the maximum allowable deflection of 25°, therefore the size of the vertical tail is acceptable.

Based on the design parameters limits presented on Tables 8.13 and 8.14 of Roskam's Airplane Design Part II [20] the following characteristics were selected. Care was taken to keep the sweep on the empennage surfaces higher than the wing to prevent the empennage stalling before the wing.

**Table 9-7: Empennage Characteristics**

| | Dihedral (°) | Incidence (°) | Aspect Ratio | Sweep$_{c/4}$ (°) | Taper Ratio | Area ($ft^2$) |
|---|---|---|---|---|---|---|
| **Horizontal** | -3 | 0 | 6.40 | 32 | 0.33 | 40 |
| **Vertical** | -- | 0 | 1.27 | 34 | 0.57 | 38.5 |

The elevator is set at 40% of the chord, while the rudder is set to cover a maximum of 30%. Historical data on Roskam's Part II suggests that business jets use two different series of symmetrical airfoils for the empennage, NACA 00 and NACA 6 series. The Tachion uses NACA 64A012 for both the vertical and horizontal planforms, bearing in mind the critical Mach number for both surfaces have to be higher than the wing.

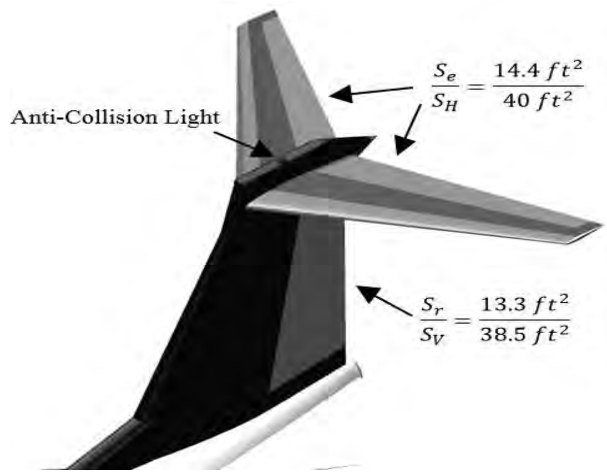



**Figure 9-13 - Empennage Layout**

## 9.5 WEIGHT & BALANCE

The purpose of this chapter is to perform the weight and balance analysis on both aircraft variants. The weight of each component is estimated using Class II GD (General Dynamics) & Toreenbeek methods for commercial transport, presented in Roskam's Airplane Design Part V [16]. The center of gravity location of each component is estimated based on methods from Part V as well. These estimations are functions of the following parameters:

- Aircraft maximum take-off weight
- Wing & empennage geometry (area, sweep, taper ratio, thickness ratio)
- Limit and ultimate load factor
- Design cruise & dive speed
- Fuselage configuration and interior requirements
- Powerplant installation
- Landing gear design & disposition
- Systems requirements
- Structural arrangement

The take-off weight and empty weight are defined as:

$$W_{TO} = W_E + W_F + W_{PL} + W_{tfo} + W_{crew} \qquad W_E = W_{struct} + W_{pwr} + W_{feq}$$

The following figures show the center of gravity location of each component in the 8 (top) and 6 (bottom) passenger aircraft's empty weight. Since the major difference between the two variants is the shorter fuselage, the major systems were placed so that they accommodate CG requirements for both the 6 passenger and 8 passenger versions without relocating components. The majority of the systems were placed aft in the tailcone to minimize CG excursion. The fuel tank located in the tailcone can be used to trim the aircraft in flight, if needed.

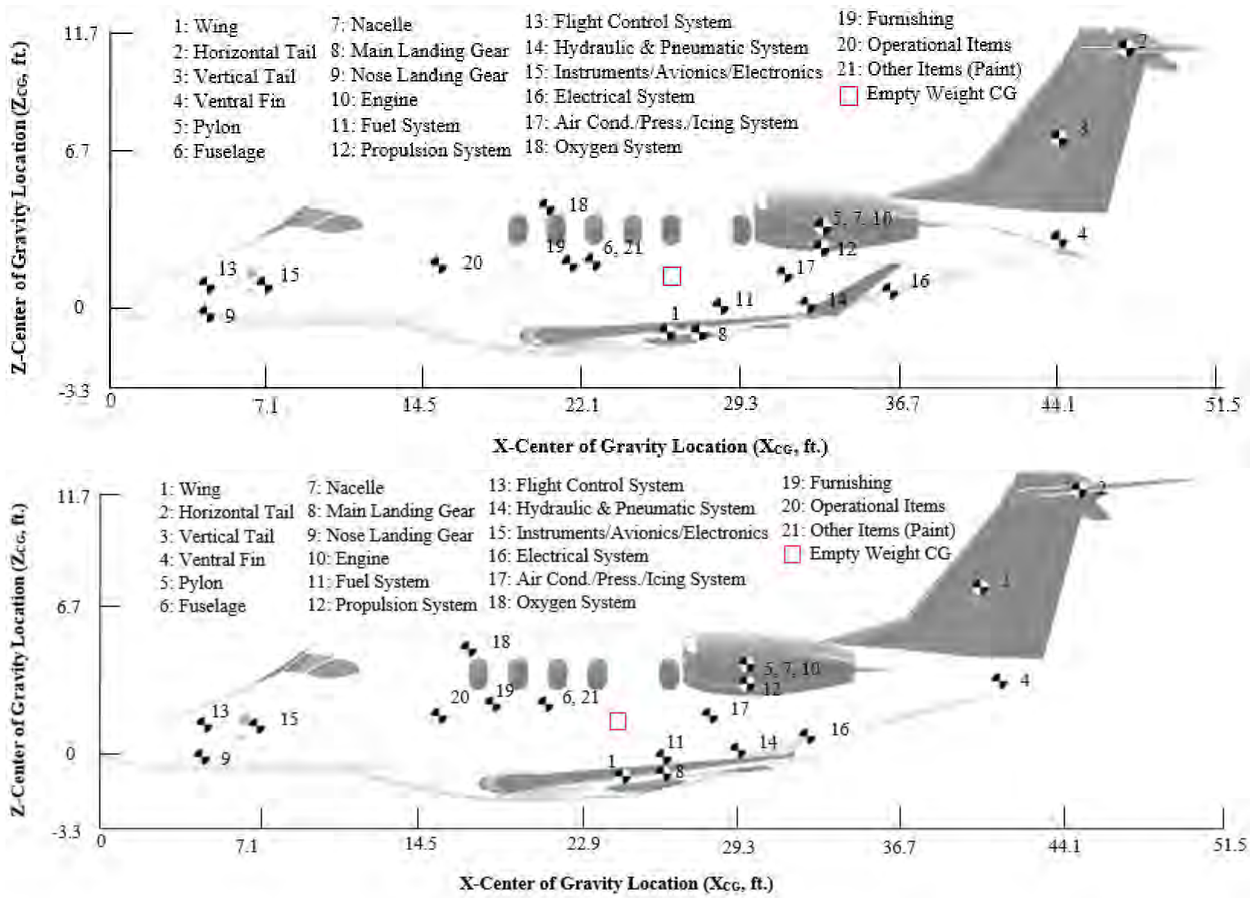



**Figure 9-14: 8 (top) and 6 (bottom) Passenger Empty Weight CG Locations**

The following table shows the weight and center of gravity location of each component for the 8 and 6 passenger. Weights that change from the 8 to the 6 are highlighted in green.

**Table 9-8: Empty Weight Breakdown (Relative to Nose)**

| | 8 Passenger | | | 6 Passenger | | |
|---|---|---|---|---|---|---|
| **Component** | **Weight (lb)** | **$X_{CG}$ (ft)** | **$Z_{CG}$ (ft)** | **Weight (lb)** | **$X_{CG}$ (ft)** | **$Z_{CG}$ (ft)** |
| Wing | 1311 | 26.3 | -1.1 | SAME | 24.4 | -1.3 |
| Horizontal Tail | 119 | 47.9 | 9.9 | SAME | 44.3 | 9.4 |
| Vertical Tail | 138 | 44.5 | 7.8 | SAME | 40.6 | 7.4 |
| Ventral Fin | 19 | 44.2 | 2.3 | SAME | 40.6 | 2.3 |
| Pylon | 80 | 34.2 | 3.5 | SAME | 30.5 | 3.5 |
| Fuselage | 1600 | 22.7 | 2.2 | 1400 | 21.0 | 2.2 |
| Nacelle | 250 | 33.4 | 3.9 | SAME | 29.8 | 3.9 |
| Fairing | 200 | 24.2 | -1.3 | 180 | 24.2 | -1.3 |
| Nose Landing Gear | 95 | 4.7 | -0.5 | SAME | 4.7 | -0.3 |
| Main Landing Gear | 416 | 27.7 | -1.3 | SAME | 24.9 | -0.5 |
| Engine | 1090 | 33.4 | 3.6 | SAME | 29.8 | 3.6 |
| Fuel System | 724 | 28.7 | 0.2 | SAME | 25.0 | 0.2 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Propulsion System | 69 | 33.4 | 3.2 | SAME | 33.4 | 3.2 |
| Flight Control System | 317 | 4.7 | 1.2 | SAME | 4.7 | 1.2 |
| Hydraulic and Pneumatic System | 128 | 32.7 | 0.2 | SAME | 29.4 | 0.2 |
| Instruments/Avionics/Electronics | 256 | 7.2 | 1.2 | SAME | 7.2 | 1.2 |
| Electrical System | 365 | 36.7 | 0.7 | SAME | 32.7 | 0.7 |
| Air Cond./Press./Icing System | 254 | 31.7 | 1.7 | SAME | 28.0 | 1.7 |
| Oxygen System | 41 | 20.6 | 4.7 | SAME | 16.9 | 4.7 |
| Furnishings | 704 | 21.7 | 2.2 | 604 | 18.0 | 2.2 |
| Operational Items | 207 | 15.7 | 1.7 | SAME | 15.7 | 1.7 |
| Other Items | 63 | 22.7 | 2.2 | SAME | 19.1 | 2.2 |
| Structures | 4228 | 26.5 | 1.3 | 4008 | 24.5 | 1.2 |
| Powerplant | 1882 | 31.6 | 2.3 | SAME | 28.1 | 2.3 |
| Fixed Equipment | 2333 | 21.3 | 1.5 | 2223 | 18.9 | 1.5 |
| **Empty Weight** | **8444** | **26.1** | **1.5** | **8124** | **23.8** | **1.5** |

The following figures show the center of gravity location of operational items for the 8 (top) and 6 (bottom) passenger versions. The empennage fuel tank was added to allow for more favorable trim at cruise conditions. Both the 8 and the 6 passenger variants use the bathroom seat and the co-pilot's seat to meet the passenger requirements.

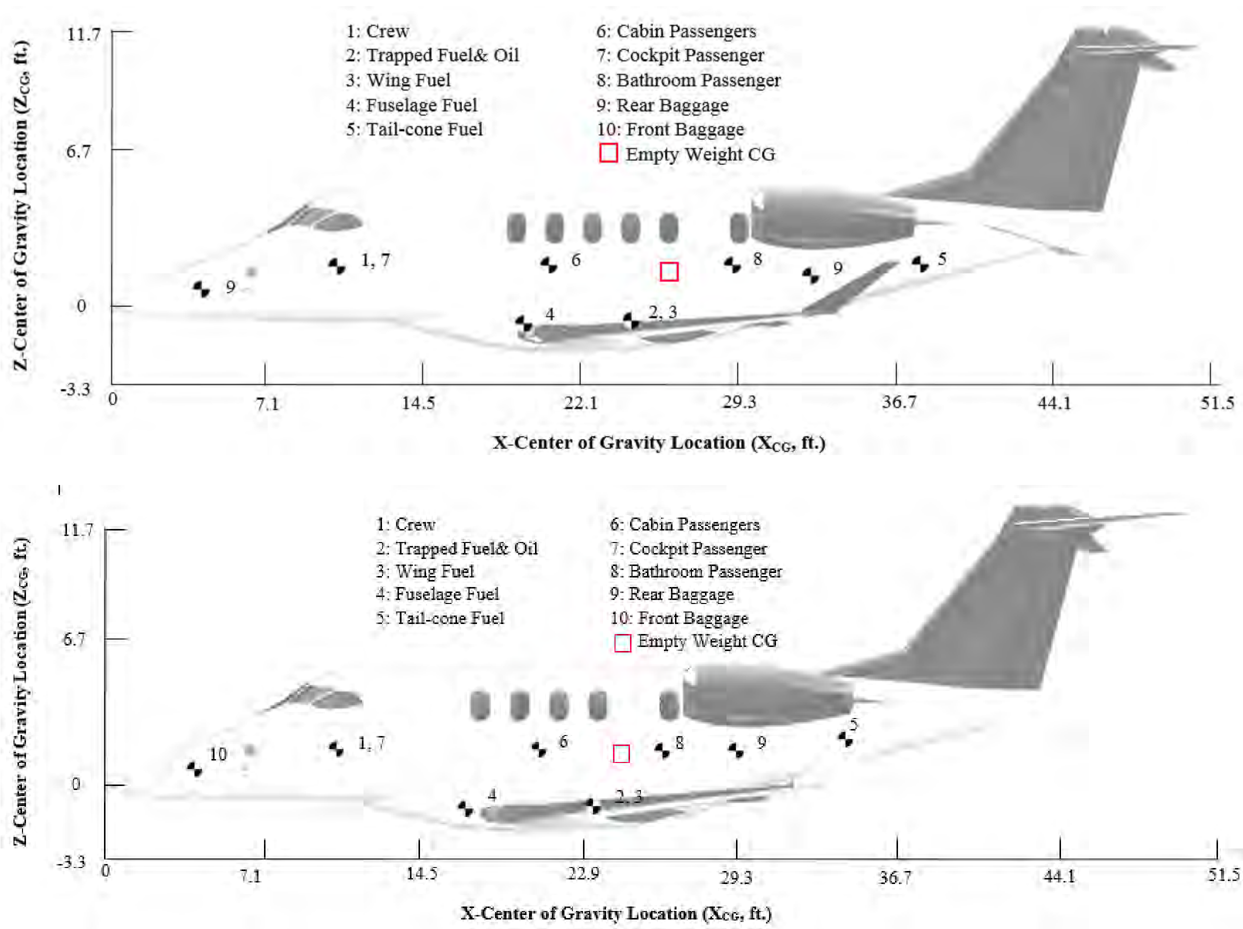



**Figure 9-15: 8 (top) and 6 (bottom) Passenger Operational Items CG Locations**

**Table 9-9: 8 (right) and 6 (left) Passenger Total Weight (Weight Differences Highlighted)**

| | 8 Passenger | | | 6 Passenger | | |
|---|---|---|---|---|---|---|
| **Component** | **Weight Range (lb)** | **$X_{CG}$ (ft)** | **$Z_{CG}$ (ft)** | **Weight Range (lb)** | **$X_{CG}$ (ft)** | **$Z_{CG}$ (ft)** |
| Crew | 200 - 400 | 10.7 | 1.7 | SAME | 10.7 | 1.7 |
| Trapped Fuel and Oil | 88 | 25.3 | -0.7 | SAME | 22.6 | -1.0 |
| Wing Fuel | Up to 4940 | 25.3 | -0.7 | SAME | 22.6 | -1.0 |
| Fairing Fuel | Up to 750 | 19.4 | -0.8 | ZERO | 16.6 | -0.8 |
| Cabin Passengers | Up to 1200 | 20.7 | 1.7 | Up to 800 | 20.0 | 1.7 |
| Cockpit Passenger | Up to 200 | 10.7 | 1.7 | SAME | 10.7 | 1.7 |
| Bathroom Passenger | Up to 200 | 29.2 | 1.7 | SAME | 25.7 | 1.7 |
| Rear Baggage | Up to 770 | 32.9 | 1.2 | SAME | 29.2 | 1.7 |
| Front Baggage | Up to 230 | 4.3 | 0.1 | SAME | 4.3 | 0.1 |
| Empennage Fuel | Up to 935 | 36.9 | 1.2 | SAME | 33.3 | 2.7 |

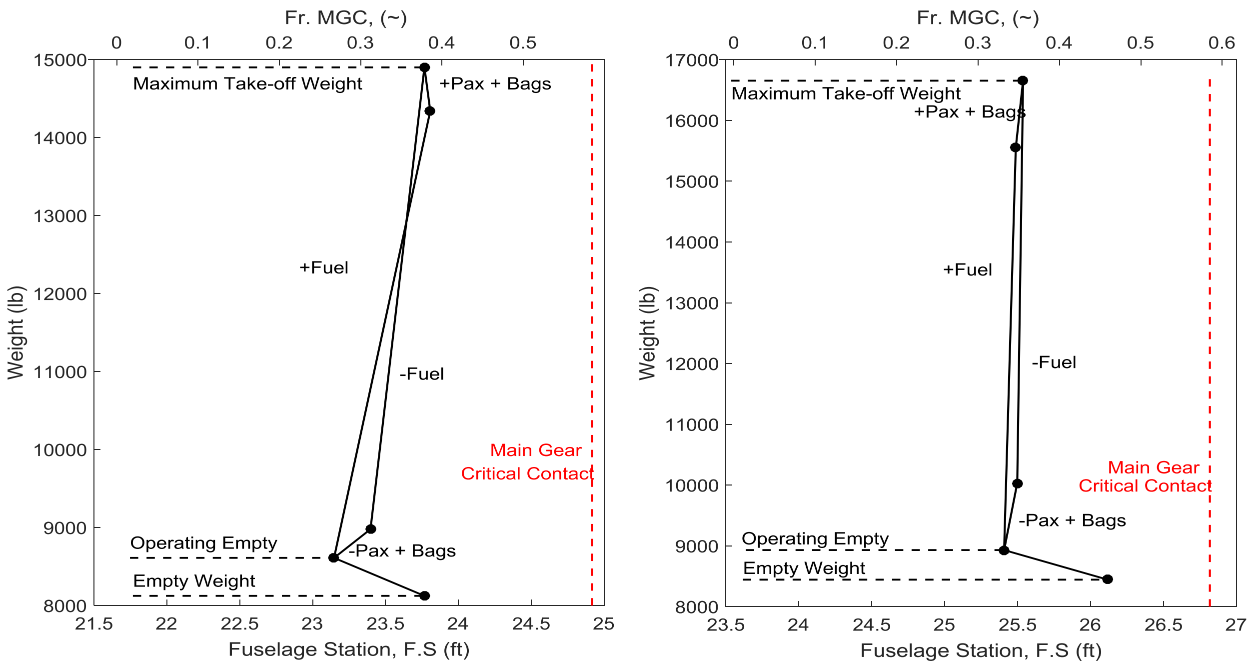



**Figure 9-16: CG Range for 6 (left), 8 (right) Passenger**

Since the majority of fuel is forward of the empty weight, the CG is expected to shift backwards as fuel is burnt. The most forward CG location will occur when the aircraft is fully loaded with passengers and fuel. The following figure shows the CG excursion range going from full fuel to no fuel with full payload

Table 9-10 shows that both aircraft have excellent CG excursion ranges, compared to average ranges in business jets. This verifies the location of the major components and systems are satisfactory from the weight and balance stand point.

**Table 9-10: Current CG Excursion Range & Acceptable Range**

| Variant | Max CG Excursion | Acceptable Range [16] |
|---|---|---|
| 6 Passenger | 7.9 in. | 8-17 in. |
| 8 Passenger | 8.5 in. | |

The empty weight distribution for both variants are shown in the following plots:

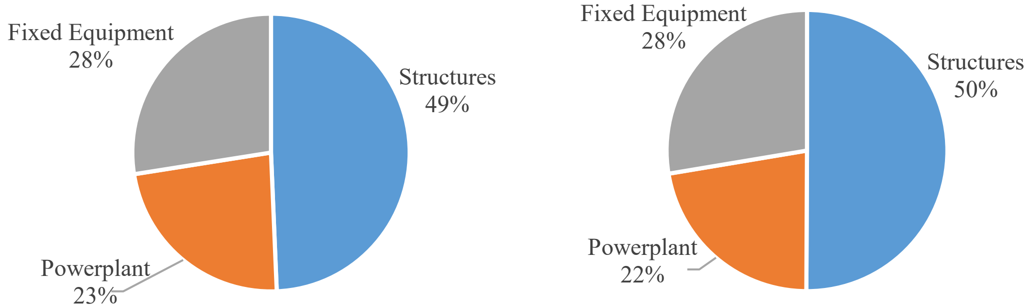



**Figure 9-17: Empty Weight Distribution for the Tachion 600 (left) and 800 (right)**

The total weight distribution for the 800 variant is shown below:

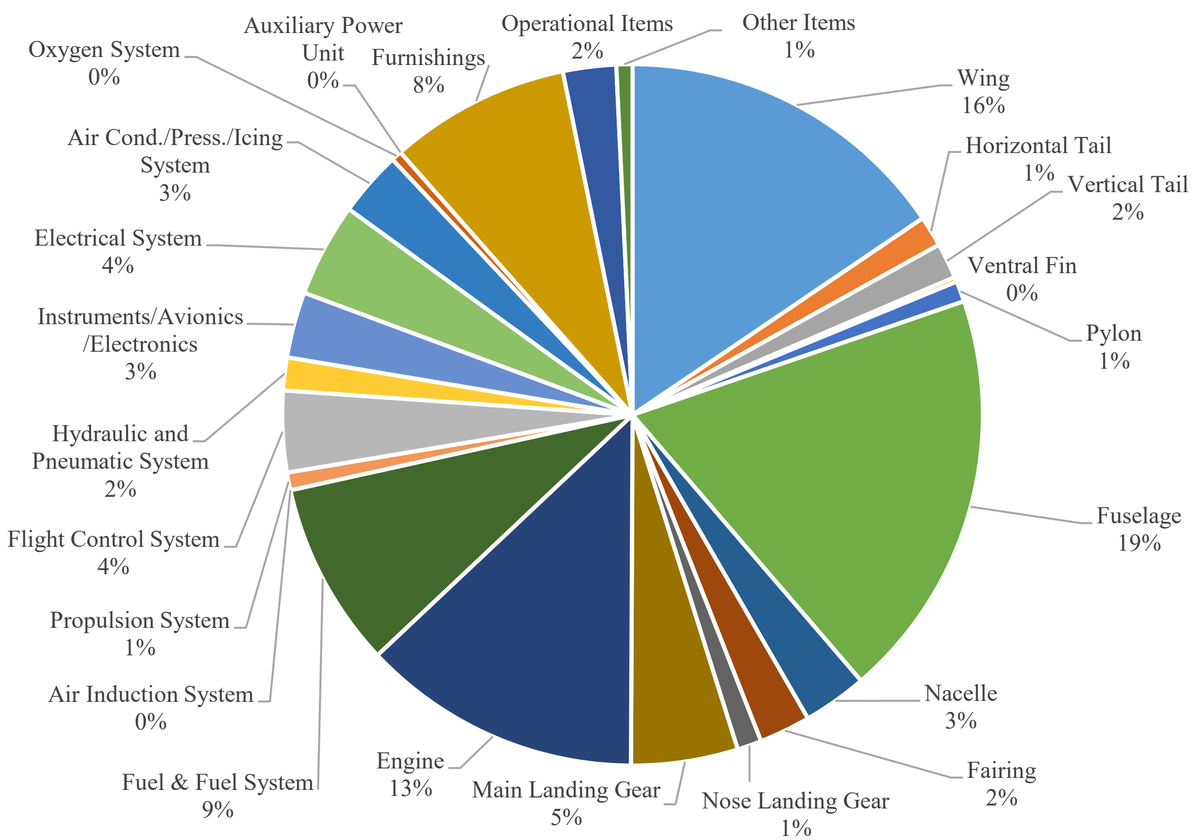



**Figure 9-18: Total Weight Distribution for the 800 Variant**

## 9.6 STABILITY AND CONTROL

During the weight and balance analysis, a careful eye must be kept on static margin to ensure that is does not fall to less than 5% in flight condition. This static margin is prescribed for business jets by Roskam [20]. Several different load cases are examined to guarantee the static margin does not violate the static margin rules. These load cases, detailed in Table 9-11 were chosen as the most extreme cases from the weight and balance analysis. The load cases are presented in Table 9-12.

The static margins were also checked for high Mach conditions in flight due to the shift of the AC at high Mach numbers. The aircraft became slightly more stable than if it were flying at slower speeds, and the static margin rule was still not broken.

Below are presented a few of the aircraft stability and control derivatives, the derivatives were obtained from AAA software, which permits a more accurate calculation of the derivatives. The cruise condition is trimmed for 40,000 ft at Mach 0.76 for both aircraft, with their angle of attack being the same and the incidence of the horizontal stabilizer being slightly different to trim the aircraft. Ventral strakes were added to the design to ensure a stable pitch break, and will be properly sized in flight test. Take off conditions are trimmed for 50 ft off the ground and speeds of 1.3 $V_{S_{TO}}$ of each aircraft. Landing conditions are trimmed for 50 ft off the ground, and the $V_A$ speeds of each aircraft. Stable derivatives are marked in green.

**Table 9-11: Static Margin Check, Load Cases**

| Load Case Number | Load Case |
|---|---|
| 1 | Empty |
| 2 | 2 pilots<br>Maximum fuel |
| 3 | 2 pilots<br>Zero fuel |
| 4 | 1 pilot<br>1 passenger in bathroom<br>1 passenger in cockpit<br>Maximum fuel |
| 5 | 1 pilot<br>1 passenger in bathroom<br>1 passenger in cockpit<br>Max baggage (F:230 lbf, R:770 lbf)<br>Maximum fuel |
| 6 | 1 pilot<br>1 passenger in bathroom<br>Max baggage (F:230 lbf, R:770 lbf)<br>Zero fuel |

**Table 9-12: Static Margin Check**

| | *Tachion 600* | | | *Tachion 800* | | |
|---|---|---|---|---|---|---|
| Load Case | $X_{CG}$ (ft) | $X_{ac}$ (ft) | Static Margin (%) | $X_{CG}$ (ft) | $X_{ac}$ (ft) | Static Margin (%) |
| 1 | 23.8 | 24.3 | 9 | 26.1 | 26.3 | 2 |
| 2 | 23.6 | | 13 | 25.5 | | 14 |
| 3 | 23.1 | | 21 | 25.4 | | 15 |
| 4 | 23.6 | | 12 | 25.3 | | 17 |
| 5 | 23.8 | | 10 | 25.5 | | 13 |
| 6 | 23.8 | | 8 | 25.5 | | 13 |

**Table 9-13 - Stability and Control Derivatives – Longitudinal**

| Symbol | *Tachion 600* | | | *Tachion 800* | | |
|---|---|---|---|---|---|---|
| | Cruise | Take Off | Landing | Cruise | Take Off | Landing |
| $C_{D_\alpha}$ | 0.269 | 0.402 | 0.683 | 0.269 | 0.552 | 0.712 |
| $C_{L_\alpha}$ | 7.123 | 5.553 | 5.553 | 7.154 | 5.668 | 5.760 |
| $C_{m_\alpha}$ | -0.902 | -0.659 | -0.733 | -0.358 | -0.816 | -0.826 |
| $C_{D_u}$ | 0.080 | -* | -* | 0.075 | -* | -* |
| $C_{L_u}$ | 0.348 | 0.032 | 0.034 | 0.396 | 0.038 | 0.036 |
| $C_{m_u}$ | 0.014 | 0.002 | 0.002 | 0.023 | 0.003 | 0.003 |
| $C_{L_q}$ | 9.251 | 6.769 | 6.991 | 8.600 | 7.385 | 7.456 |
| $C_{m_q}$ | -26.234 | -21.111 | -20.266 | -29.272 | -23.342 | -23.385 |
| $C_{L_{\dot{\alpha}}}$ | 1.900 | 1.102 | 1.122 | 1.934 | 1.158 | 1.176 |
| $C_{m_{\dot{\alpha}}}$ | -7.093 | -4.092 | -4.195 | -7.644 | -4.675 | -4.757 |
| $C_{L_{i_H}}$ | 0.796 | 0.613 | 0.611 | 0.796 | 0.613 | 0.611 |
| $C_{m_{iH}}$ | -2.917 | -2.277 | -2.283 | -3.146 | -2.472 | -2.472 |
| $C_{L_{\delta E}}$ | 0.253 | 0.294 | 0.295 | 0.253 | 0.294 | 0.295 |
| $C_{m_{\delta E}}$ | -0.943 | -1.091 | -1.102 | -0.999 | -1.161 | -1.192 |

*** - The variation of drag coefficient with speed derivative ($C_{D_u}$) is frequently negligible for subsonic speed, but for high Mach numbers, this derivative becomes important to look at due to wave drag.**

**Table 9-14: Stability and Control Derivatives – Lateral**

| Symbol | *6 Passenger* | | | *8 Passenger* | | |
|---|---|---|---|---|---|---|
| | Cruise | Take Off | Landing | Cruise | Take Off | Landing |
| $C_{y_\beta}$ | -1.181 | -1.181 | -1.181 | -1.177 | -1.177 | -1.177 |
| $C_{l_\beta}$ | -0.159 | -0.141 | -0.176 | -0.151 | -0.148 | -0.173 |
| $C_{n_\beta}$ | 0.168 | 0.175 | 0.181 | 0.174 | 0.196 | 0.198 |
| $C_{y_p}$ | -0.084 | -0.021 | -0.023 | -0.083 | -0.014 | -0.023 |
| $C_{l_p}$ | -0.551 | -0.473 | -0.499 | -0.558 | -0.487 | -0.502 |
| $C_{n_p}$ | -0.053 | -0.120 | -0.108 | -0.052 | -0.124 | -0.105 |
| $C_{y_r}$ | 0.550 | 0.564 | 0.568 | 0.593 | 0.626 | 0.626 |
| $C_{l_r}$ | 0.217 | 0.258 | 0.239 | 0.221 | 0.260 | 0.235 |
| $C_{n_r}$ | -0.170 | -0.180 | -0.182 | -0.198 | -0.223 | -0.222 |
| $C_{y_{\delta A}}$ | 0 | 0 | 0 | 0 | 0 | 0 |
| $C_{l_{\delta A}}$ | 0.095 | 0.105 | 0.105 | 0.095 | 0.105 | 0.105 |
| $C_{n_{\delta A}}$ | -0.004 | -0.008 | -0.008 | -0.004 | -0.008 | -0.007 |
| $C_{y_{\delta R}}$ | 0.251 | 0.378 | 0.381 | 0.249 | 0.376 | 0.378 |
| $C_{l_{\delta R}}$ | 0.031 | 0.034 | 0.036 | 0.030 | 0.033 | 0.036 |
| $C_{n_{\delta R}}$ | -0.089 | -0.137 | -0.139 | -0.095 | -0.150 | -0.151 |

The ride and comfort characteristics of the aircraft are important, and can be an important factor in selling an aircraft. A method for estimation of ride and comfort characteristics is presented in Roskam's Aircraft Design Part VII [22]. The method uses the ride comfort index ($C_{ride}$) calculation to estimate customer satisfaction. The index relies on two variables: vertical and lateral acceleration, which depend on the flight characteristics and root mean square lateral and vertical gust velocities. The RMS lateral ($\sigma_v$) and vertical ($\sigma_w$) are obtained from the Figure 9-19.

$$a_{vert} = \frac{0.5\,\rho\,U_1\,C_{L_\alpha}\,\sigma_w}{W/S} \qquad a_{lat} = \frac{0.5\,\rho\,U_1\,C_{y_\beta}\,\sigma_v}{W/S}$$

At altitude, $\sigma_w = \sigma_v$ [23]. After the vertical and lateral acceleration are calculated,

$$if\ a_{vert} > 1.6\,a_{lat} \qquad C_{ride} = 2 + 18.9a_{vert} + 12.1a_{lat}$$

$$if\ a_{vert} < 1.6\,a_{lat} \qquad C_{ride} = 2 + 1.62a_{vert} + 38.9a_{lat}$$

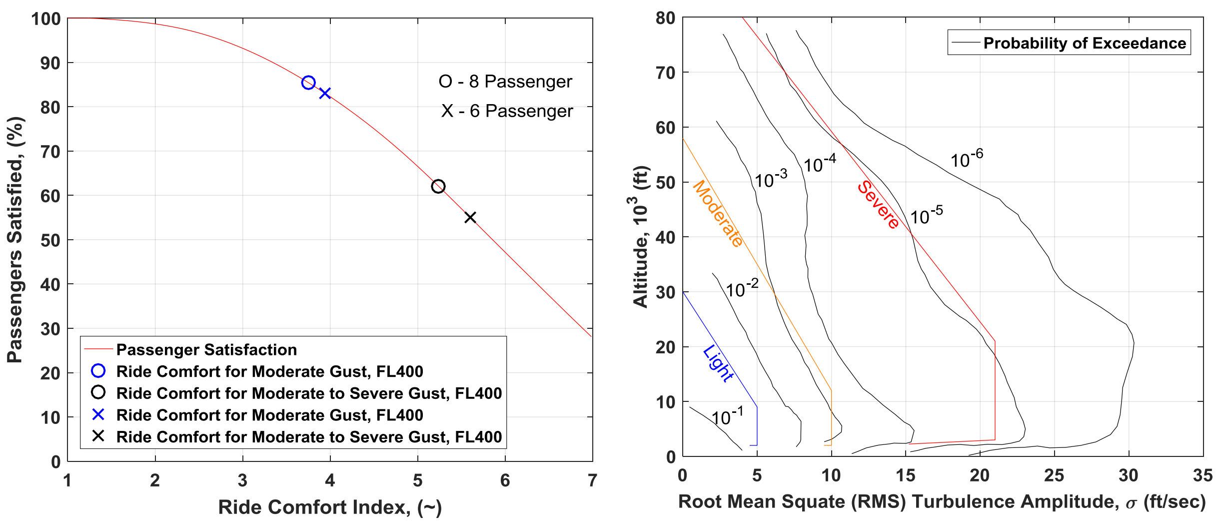



**Figure 9-19: Ride Comfort (left), Root Mean Square (RMS) Gust Amplitudes as Related to Altitude and Probability of Exceedance**

Once the $C_{ride}$ is calculated, the following figure is used to find customer satisfaction. The preliminary ride and comfort analysis shows the aircraft has an acceptable response to turbulence, and therefore a ride control system will be offered as an option for both aircraft version.

To ensure the Tachion is controllable in flight, an analysis of the flying qualities was performed. The results of this analysis are presented in Table 9-15 and Table 9-16. Most qualities are level 1, ensuring that the aircraft will be easy to control in all phases of flight. While a fly-by-wire system is planned for implementation, the need for feedback gains to control the aircraft will be minimal.

**Table 9-15: Longitudinal Handling Qualities**

| Aircraft | Flight Condition | $\omega_{n_{SP}}$ (rad/s) | $\zeta_{SP}$ (-) | $\omega_{n_{P_{long}}}$ (rad/s) | $\zeta_{P_{long}}$ (-) | $n/\alpha$ (g/rad) | Level S.P Damping | Level Phugoid Stability | Level S.P Frequency |
|---|---|---|---|---|---|---|---|---|---|
| **Tachion-600** | Take-off | 1.69 | 0.515 | 0.24 | 0.041 | 4.4 | 1 | 1 | 1 |
| | Cruise | 1.99 | 0.495 | 0.11 | 0.067 | 17.7 | 1 | 1 | 1 |
| **Tachion-800** | Take-off | 1.73 | 0.540 | 0.22 | 0.021 | 5.4 | 1 | 2 | 1 |
| | Cruise | 3.10 | 0.335 | 0.09 | 0.089 | 20.0 | 1 | 1 | 1 |

**Table 9-16: Lateral Handling Qualities - Cruise**

| Aircraft | $T_R$ (s) | $\zeta_D$ (-) | $T_{2_S}$ (s) | Level Roll Time Constant | Level Roll Performance | Level D. Roll Frequency | Level D. Roll Damping | Level Spiral Stability |
|---|---|---|---|---|---|---|---|---|
| **600** | 0.66 | 0.045 | 226 | 1 | 1 | 1 | 2 | 1 |
| **800** | 0.59 | 0.039 | 188 | 1 | 1 | 1 | 2 | 1 |

## 9.7 DRAG POLARS

The drag polars for each aircraft variant were calculated at different flight conditions using Class II methods from Roskam's Airplane Design Part II [20]. The following figures represent the drag polars for the Tachion 600/800.

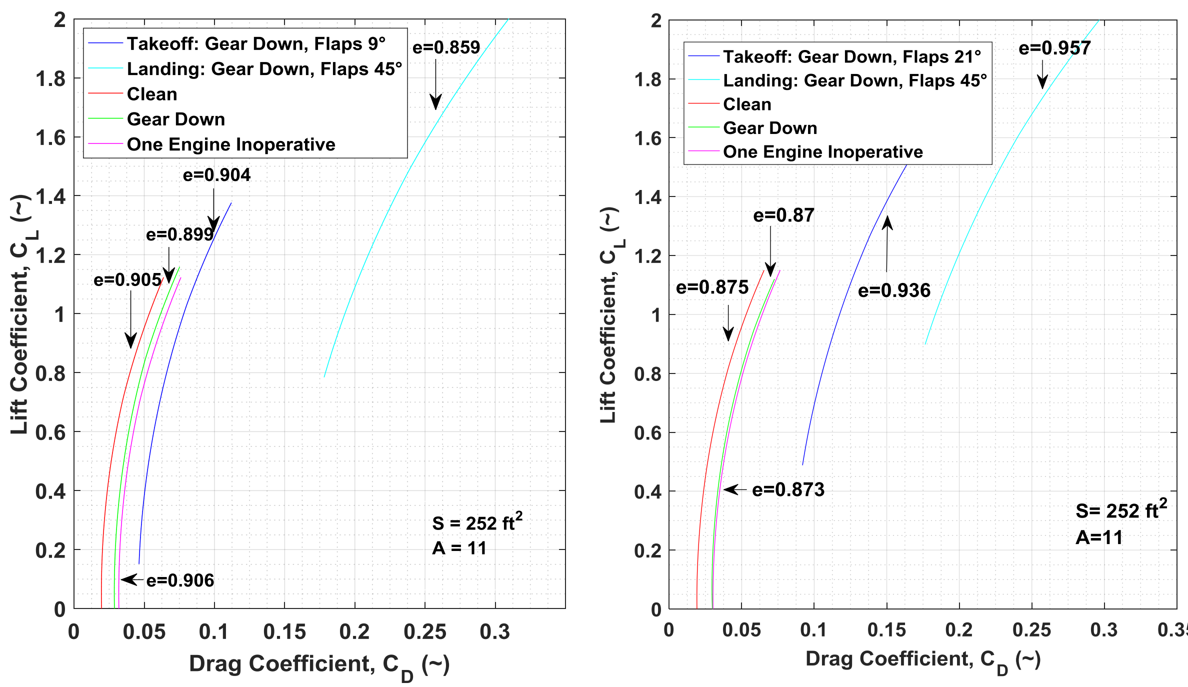



**Figure 9-20 - Multiple Flight Configurations Drag Polars for the Tachion-600 (left), Tachion-800 (right)**

The drag polars for various cruise speeds for the Tachion 600/800 are shown in the figure below.

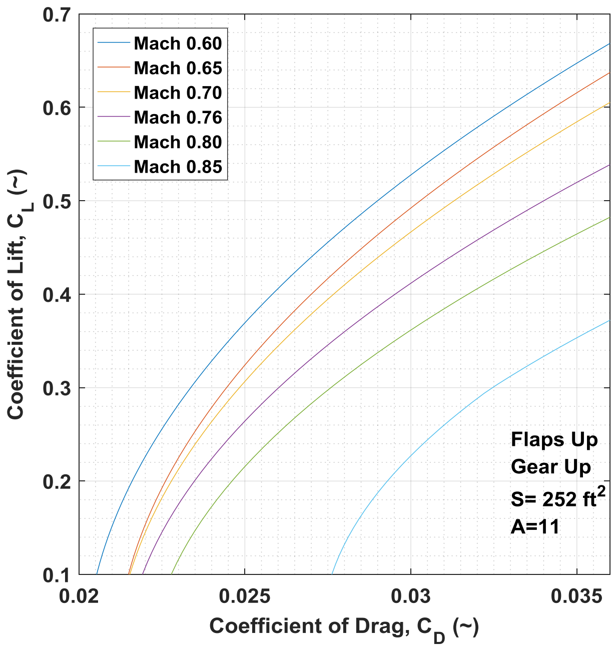



**Figure 9-21 - Drag Polar at Various Cruise Mach Numbers for the Tachion-600 (left), Tachion-800 (right)**

The component-wise wetted area contribution of each component is shown in the table below.

**Table 9-17 - Wetted Area Breakdown for the Tachion 600 & Tachion 800**

| Component | | Fuselage | Wing | Horizontal Tail | Vertical Tail | Fairing | Ventral Strakes | Dorsal Fin |
|---|---|---|---|---|---|---|---|---|
| Wetted Area (ft$^2$) | Tachion-600 | 639 | 420 | 82 | 72 | 132 | 39 | 9 |
| | Tachion-800 | 710 | 420 | 82 | 72 | 140 | 39 | 9 |

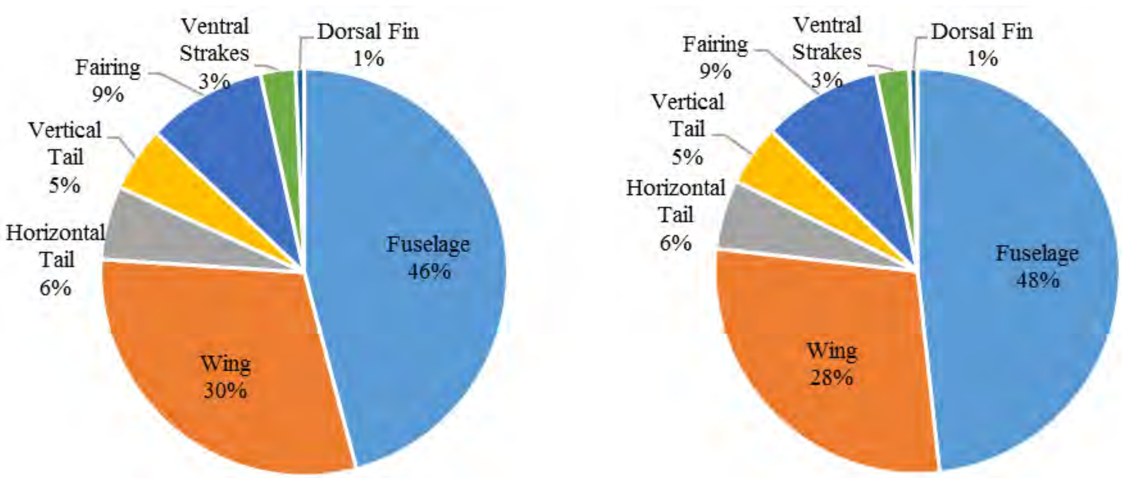



**Figure 9-22 - Component-wise wetted area distribution (a) Left: Tachion 600 (b) Right: Tachion 800**

## 9.8 LANDING GEAR

The purpose of this chapter is to present the landing gear design for both variants of the aircraft. The landing gear is primarily sized for the 8 passenger variant as it experiences higher landing loads. As a result, it meets all the requirements for the 6 passenger variant, and will be used for the 6 passenger variant to maximize commonality and reduce development costs.

A retractable tricycle landing gear was deemed best for this aircraft configuration and specifications as it provides:

- Good visibility over the nose;
- Level floor on the ground;
- Good steering characteristics and stability against ground loops.

The following figure defines the longitudinal geometric parameters and loads acting on the aircraft:

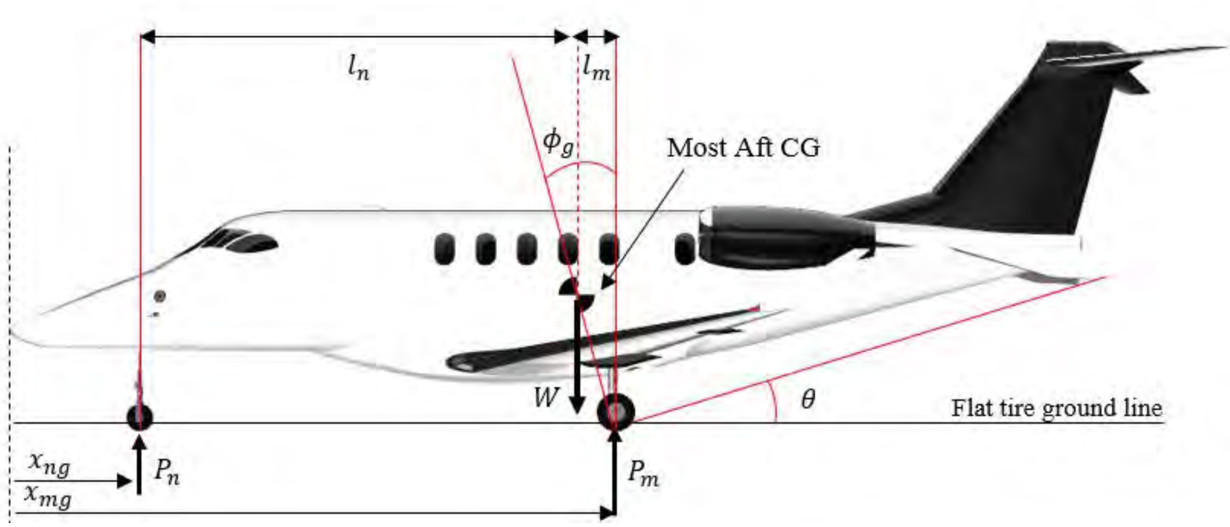



**Figure 9-23 - Longitudinal Landing Gear Geometric Parameters & Loads**

**Table 9-18 - Landing Gear Loads**

| | $x_{ng}$ | $x_{mg}$ | $l_m$ | $l_n$ | $\phi_g$ | $\theta$ |
|---|---|---|---|---|---|---|
| **6 Passenger** | 14.05 ft. | 33.25 ft. | 1.15 | 18 | 15° | 17° |
| **8 Passenger** | | 35.15 ft. | 0.7 | 20.4 | 13° | 15.5° |

To meet longitudinal tip over requirements, the landing gear contact point should range from 10° to 15° behind the most aft CG. A lower value would risk tipping the aircraft over and a higher value may cause take-off rotation issues. Table 9-18 lists the values for these parameters for both variants.

Static and dynamic loads acting on the landing gear on landing were calculated using equations from [24]. The nose-wheel tires are sized for maximum dynamic loads while the main gear tires are sized for maximum static loads. To reduce landing gear weight and size, a single tire per strut was selected for both the nose and main gear. Landing on unpaved runways is a feature marketed by Pilatus and would require two tires per strut. The feature was downplayed by Dr. Roskam while discussing as only a feature that looks good on paper, but not realistic.

**Table 9-19 - Landing Gear Loads**

| | 6 Passenger | 8 Passenger |
|---|---|---|
| $W\ (lb)$ | 14,900 | 16,630 |
| $P_{m_{static}}\ (lb)$ | 7,004 | 8,063 |
| $P_{n_{static}}\ (lb)$ | 892 | 553 |
| $P_{n_{dynamic}}\ (lb)$ | 1,440 | 1,111 |

After considering many different tires from manufacturers, the following tires were selected due to their load capacity and minimal dimensions.

**Table 9-20: Tire Selection and Specifications**

| | Tire | Outer Diameter (in) | Width (in) | Max load (lb) | Pressure (psi) | Loaded Radius (in) |
|---|---|---|---|---|---|---|
| **Main Gear** | Goodrich Type VII 20x5.5 | 20 | 5.5 | 8750 | 270 | 8.6 |
| **Nose Gear** | Goodrich Type VII 20x5.5 | 12.5 | 4.5 | 1800 | 75 | 5.4 |

The struts were for each gear were sized using the following equations [24].

$$S_s = \frac{\left(\frac{0.5\left(\frac{W_L}{g}\right)\left(w_t^2\right)}{n_s P_m N_g}\right) - \eta_t s_t}{\eta_s} \qquad d_s = 0.041 + 0.0025\sqrt{P_m}$$

Liquid spring shock absorbers were selected due to their high shock absorption efficiency, $\eta_s$. Average tire energy absorption efficiency, $\eta_t$, was assumed based on Roskam's Airplane Design Part IV [24]. The landing gear load factor, $N_g$ as well as the maximum sink rate were selected based on FAR certification requirements. Table 9-21 lists the assumed values and the strut dimensions.

The main landing gear is designed to be attached to the rear spar of the wing to maximize structural synergy. Since the wing is wet at the fuselage intersection, the landing gear is designed to retract into the fairing, behind the wet center bay.

For main landing gear doors, it was decided that the tire would retract and be flush with the fairing and thus no tire door is used. Only a small strut and retraction linkage door would be used to maintain aerodynamic flow. The gap between the tire and fairing is sealed when the gear is retracted. It is notable that the Boeing 737 and Pilatus PC24 follow the same approach and can cruise in the transonic range. To prevent flap & landing gear door conflict, the door would have to be split into two, which adds weight. The team suspects that the drag penalty is less significant to the weight penalty associated with having landing gear doors in this configuration, but further analysis is needed.

**Table 9-21 - Strut Design Parameters**

| | Nose Gear | Main Gear |
|---|---|---|
| $N_g$ | 3 | |
| $w_t$ | 12 ft/s | |
| $\eta_t$ | 0.47 | |
| $\eta_s$ | 0.85 | |
| $S_s$ | 15 in | 8 in |
| $d_s$ | 3 in | 1.5 in |

The lateral ground clearance criteria requires that there is no obstacle within at least 5 degrees of the main gear contact point. Figure 9-25 shows the requirement satisfied.

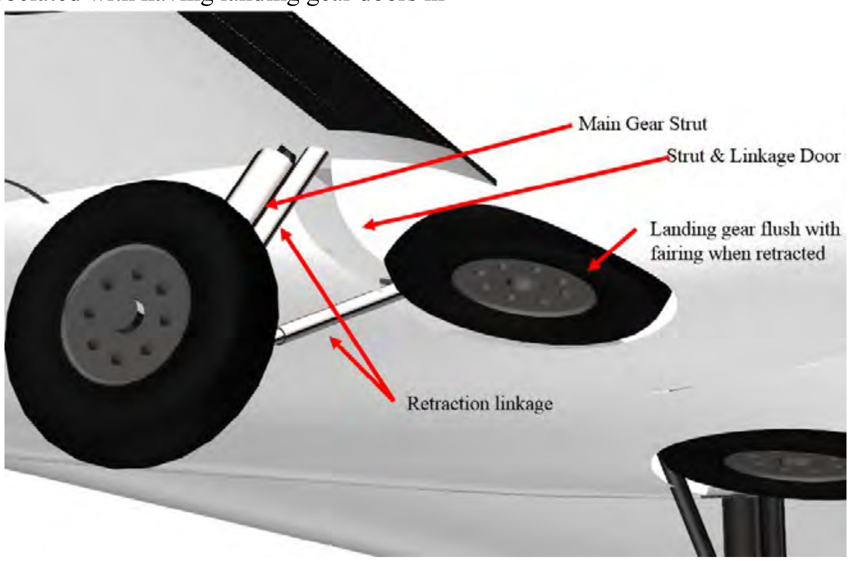



**Figure 9-24 - Landing Gear Bay & Retraction**


**Figure 9-25 - Landing Gear Lateral Clearance Requirement**

The following figure defines the lateral tip over criterion, ψ, as being no larger than 55 degrees for the most forward center of gravity. An appropriate lateral spacing was selected to meet this requirement.


Figure 9-26: Lateral Tip-Over Criteria [20]

**Table 9-22: Landing Gear Lateral Stability**

| | 6 Pax | 8 Pax | Requirement |
|---|---|---|---|
| $\psi$ | 53.5° | 51.4° | $\leq 55°$ |
| $Y_{gear}$ | $\pm 4.25\ ft$ | | |

## 9.9 SYSTEMS

This section details the different systems that will be installed in the aircraft.

### 9.9.1 FUEL SYSTEM

The fuel system's primary jobs are the storage of fuel and delivery of fuel to the engines. The fuel system can also be used to alter the CG of the aircraft in flight.

**Table 9-23: Fuel System Components**

| | |
|---|---|
| Fuel tanks/bays | Fuel pumps |
| Fuel lines | Fuel vents |
| Fuelling inlet | Fuel indicators |
| Fuel dump system | Fuel sump |
| Temperature sensors | Tank selection system |

Both aircraft will use a wet wing, using 85% of the length of the aircraft wing for the fuel tanks. Because there is not enough volume for the fuel in the wing, fuel tanks are also placed in the tail and the front of each wing fairing. This requires

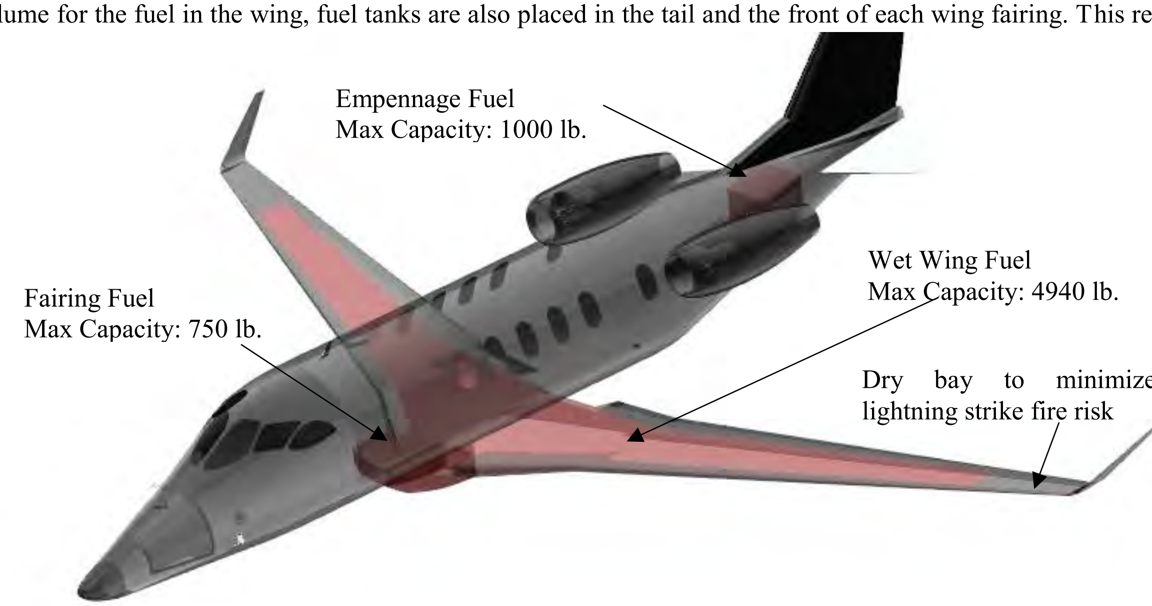



**Figure 9-27: Fuel Tank Location and Capacity**

the use of a fuel management and pumping system for balance. Fuel lines shall be located away from potentially easily damaged regions, and require shut off valves in case of damage. For ease of refuel, a single point refuelling system will be implemented. The primary fuel fill will be located in the empennage where it will be gravity fed into the wings. Figure 9-27 displays the location and capacity of the fuel tanks for the aircraft.

### 9.9.2 HYDRAULIC AND PNEUMATIC SYSTEMS

The hydraulic and pneumatic systems primary jobs are the traditionally the actuation of the control surfaces and landing gear. For the fly-by-wire system, hydrostatic actuators will be used, which contain their own hydraulic system. The aircraft's hydraulic and pneumatic system will be primarily for the landing gear and braking system. The weight of the actuators and brakes for the landing gear system are already included in the weight estimates specified in Table 9-8.

**Table 9-24: Hydraulic and Pneumatic Components**

| | |
|---|---|
| Hydraulic reservoir | Hydraulic fluid |
| Hydraulic tubing | Hydraulic fluid pump |
| Hydrostatic Actuators | |

### 9.9.3 ELECTRICAL/AVIONICS SYSTEM

The electrical systems primary job is the supply of power to all flight critical and passenger entertainment needs. Emergency systems that require battery power are considered part of the emergency system, and are included as a part of Section 9.9.5. An APU will not be an option, with the aircraft instead relying on the FJ44-4's Quiet Power Mode for ground ops (see Section 7.2.1).

**Table 9-25: Electrical Components**

| | |
|---|---|
| Fly-by-wire system | Internal lighting |
| Food/water heating and cooling | Passenger Entertainment |
| Battery | External Lighting |
| Power Cabling | Avionics |

Wiring shall be located away from areas likely to be struck by lightning, and wiring to flight critical components shall be triply redundant and located separately. 3 actuators shall be used for each outboard flap, spoiler, and aileron. 2 actuators shall be used for each inboard flap and spoiler, the rudder, and the elevators. This is designed for each control surface to be fully functional with one actuator failure.

**Figure 9-28: Embraer Prodigy Flight Deck 300 [3]**

As the designed aircrafts have a strong focus on seeking single pilot certification, the avionics displays shall provide simplicity and as much pilot assistance as possible. Therefore, a modern system of large, multipurpose, adjustable displays is to be used. These systems provide the data of tens of instruments on one screen, saving on weight and complexity. An example of this system is the Embraer Prodigy Flight Deck 300, which is built around a Garmin G3000 avionics system.

### 9.9.4 ENVIRONMENTAL CONTROL SYSTEM

Environmental control systems encompasses the temperature and humidity control of the cabin, the pressurization system, and the anti-icing systems. The system therefore maintains passenger comfort, maintains human-survivable pressures, and keeps the engine and wings free of ice obstructions that hinder or endanger their function. Airflow is provided via ram air, which is temperature controlled through cooling units and bleed air, and pressurised by bleed air.

Significant cooling must be given to the avionics systems of the aircraft. High pressurization reliability is required, as the results of depressurization at altitude can be fatal. Reliability is achieved through redundancy. Pressurization can therefore be powered by the bleed air of each engine, in the case of one engine failure, and by an electrically powered air pump in the case of double engine failure. 20 $ft^3$ of air per passenger per minute shall be provided as per recommendation by Roskam [24]. This can be achieved by either ram air intake located on the engines, in the case of single intake failure.

**Table 9-26: Environmental Control System Components**

| | |
|---|---|
| Air Cooling Unit | Air ducting |
| Pressure and temperature sensors | Air heat exchange from bleed air |
| Leading edge anti-ice heater | Bleed air pressurization |
| Engine intake anti-ice heater | Pressure release valves |
| De/humidifier | Oxygen sensors |
| Pressurized oxygen cylinders | Oxygen tubing and masks |
| Mask door actuators | |

The oxygen system provides oxygen to crew and passengers in the case of low oxygen levels, such as that which may happen during unexpected decompression of the aircraft. High reliability systems must be used for the crew. Therefore, the crew shall have their own cylinders of oxygen while the passengers shall require one larger cylinder of oxygen.

### 9.9.5 WATER AND WASTE SYSTEMS

The water and waste systems of the aircraft provide hot and cold potable water for consumption, provide water for toilet use and personal hygiene, and provide storage of waste for removal upon landing.

**Table 9-27: Water and Waste Components**

| | |
|---|---|
| Portable water supply | Waste storage tanks |
| Water storage tanks | Water pump |
| Electrical heat exchanges | |

A water quantity of 0.3 US gallons per passenger shall be supplied as recommended by Roskam [24]. Water shall be supplied in the galley and in the bathroom. Heated water shall be provided by running cold water through an electronic heat exchanger powered by the electrical system.

### 9.9.6 EMERGENCY SYSTEM

The emergency system allows the passengers to quickly and safely evacuate the aircraft in emergency situations, and emergency communications and safety while rescue arrives. This system predominantly consists of emergency lighting, passenger and crew personal flotation devices, emergency rafts, and a communications system separate from the main system.

**Table 9-28: Emergency System Components**

| | |
|---|---|
| Personal flotation devices | Emergency communications (rescue beacon) |
| Emergency lighting | Separate power supply |
| Self-inflating raft | Separate power supply |

Emergency lighting and the emergency communications system shall be powered by a battery separate from the main supply. Any electronic closing/locking systems on doors shall be able to be manually overcome in case of emergency. The use of two six-person emergency rafts, with the assistance of personal floatation devices, provides emergency floatation for 10 people in the case that one raft fails.

Figure 9-29 shows a diagram of the final layout for the systems of the aircraft.

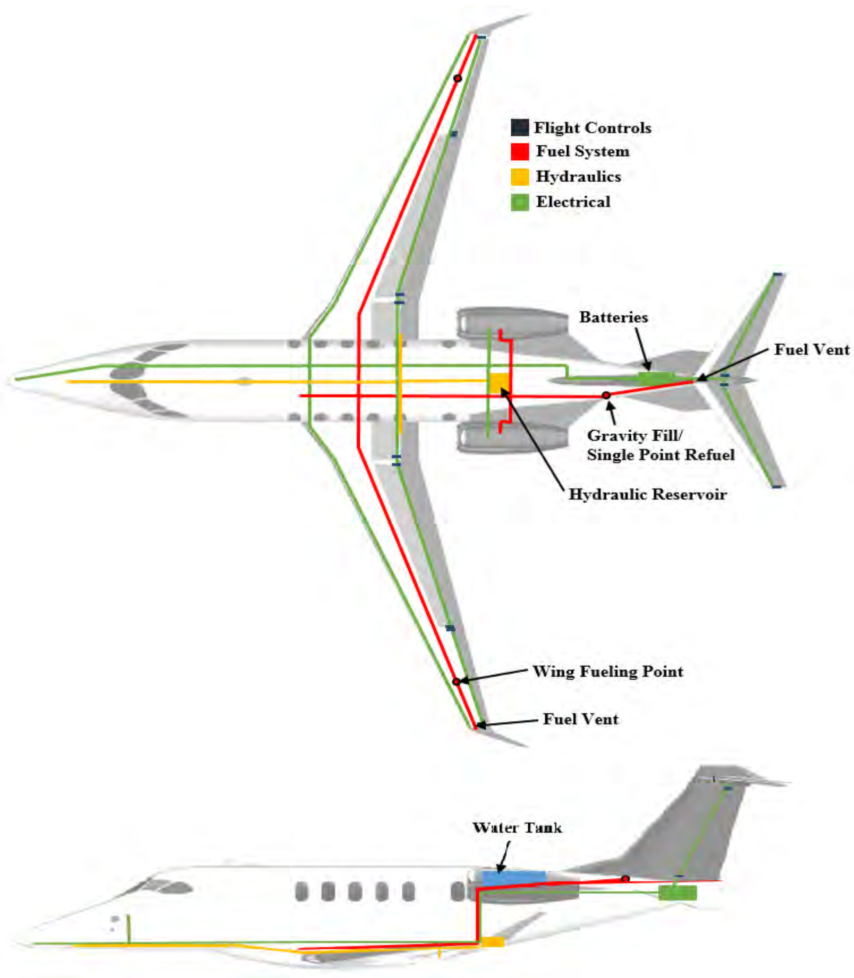



**Figure 9-29: Systems Layout**

## 9.10 COMMONALITY SUMMARY

Major aircraft components including the wing, landing gear, empennage and systems were designed to satisfy mission requirements for both the 6-passenger and 8-passenger versions to minimize RDT&E, manufacturing and certification cost for the aircraft. The fuselage and fairing are the only structural components that are not fully common between the variants, but still maintain a high commonality. Since a shorter cabin length is needed for the 6-passenger variant, the fuselage ring frame spacing was sized so a simple forward and aft plug can extend or shorten the fuselage both fore and aft of the wing. The length of each plug was determined by obtaining satisfactory weight and balance, and stability and control characteristics between the two variants. Figure 9-30 shows the fuselage plug design between the 6-passenger (bottom) to 8 passenger (top). The fairing's aft section behind the landing gear is redesigned to meet the tail-cone's curvature. Table 9-29 shows the empty weight part commonality between the two variants.

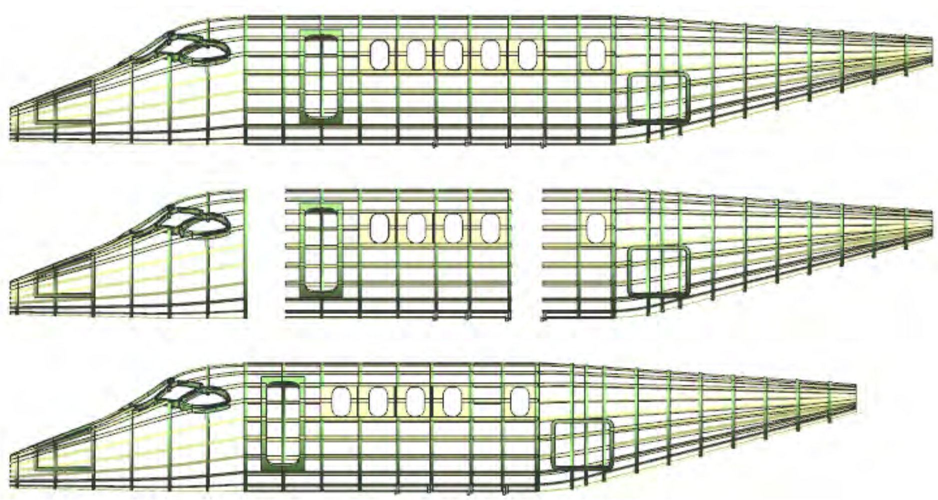


**Figure 9-30 - Fuselage Structural Commonality Design: 8 Pax (top), 6 Pax (bottom)**

**Table 9-29 - Empty Weight Commonality Summary**

| Component | 6Pax Weight | 8Pax Weight | Percent Difference | Commonality |
|---|---|---|---|---|
| **Structure** | 4228 lb | 4008 lb | 5.5% | 96.1% |
| **Powerplant** | 1882 lb | 1882 lb | 0.0% | |
| **Fixed Equipment** | 2333 lb | 2233 lb | 4.5% | |
| **Empty Weight** | 8444 lb | 8124 lb | 3.9% | |

## 10. PERFORMANCE VERIFICATION

The purpose of this section is to verify the performance of the aircraft, and ensure the specifications set forth by the RFP are met.

### 10.1 PAYLOAD AND RANGE DIAGRAMS

Payload and range diagrams can be seen in Figure 10-1. These represent the maximum range that can be achieved under the various loading conditions. The harmonic range is the first segment from point A to point B, which

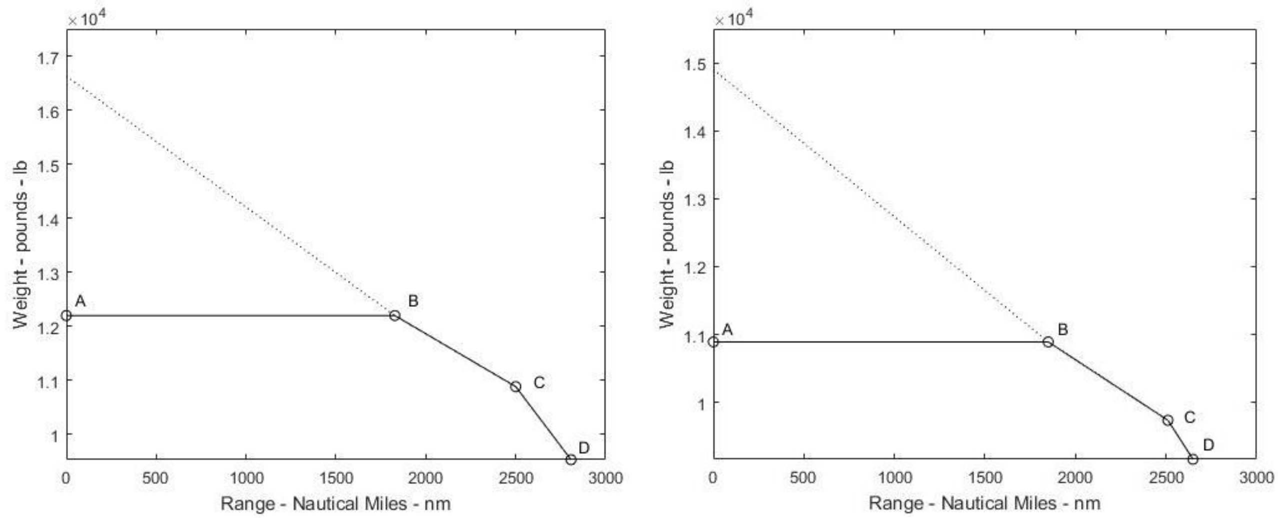



**Figure 10-1: Payload Range Diagrams for the 6 Passenger (left), 8 Passenger (right)**

represents the longest range with the maximum payload. Then the range is extended to point C by trading payload for fuel. Once the maximum fuel volume is reached at point C, the payload is decreased until the minimum operating payload is reached at point D. This minimum operational weight consists of only a pilot, the trapped fuel and oil, and the fuel reserves. The fuel reserve as laid out in the mission specification consists of 2 half-hour loiters and a 100 nm divert to alternate airport. The range at point D is the maximum ferry range.

### 10.2 RATE OF CLIMB

The rate of climb was calculated by iterating through a range of alpha angles over various flight speeds at sea level using the following equations from Roskam's Airplane Design Part VII [22].

$$Tcos(\alpha + \phi_T) - C_D\bar{q}S - Wsin\gamma = \left(\frac{W}{g}\right)\dot{U}$$

$$Tsin(\alpha + \phi_T) + C_L\bar{q}S - Wcos\gamma = \left(\frac{W}{g}\right)U\dot{\gamma}$$

The maximum rate of climb for each flight speed is shown in Figure 10-2. The max rates of climb for both aircraft occur between 225 and 237 knots. The requirement of 3,500 fpm outlined in the mission spec by the RFP has been easily met. This is due to the large trust-to-weight ratio required for the high speed cruise. Since the same engines and wing are used between the two variants, the lighter six passenger variant has a better climb performance.

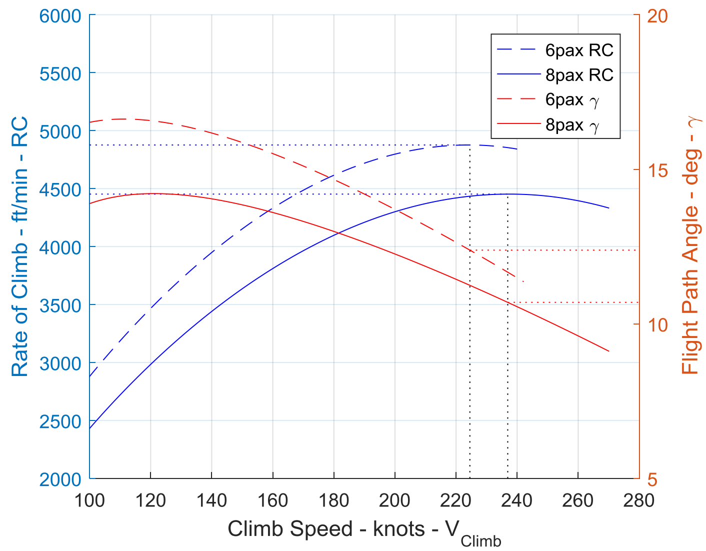



**Figure 10-2: Rate of Climb for Both Variants at Sea Level**

## 10.3 SERVICE CEILING & $M_{MO}$ VERIFICATION

To calculate the service ceiling, the stall speed in the clean configuration was evaluated at increasing altitudes above 40,000 ft. Then using the same techniques to find the Class II drag estimates described in Section 5.3.2, the drag force was estimated over a range of speeds. The 8 passenger variant was used since the 6 passenger variant will inevitably perform better with the same engines, wing geometry, and a lower weight. The weight used for this flight condition was 90 percent of the gross takeoff weight of the 8 passenger variant, 15,000 lbs. When the drag force increased to the point of maximum thrust, this point was taken as the maximum level flight speed at that altitude. By increasing the altitude in steps, a curve was constructed to show where the maximum altitude the aircraft in this configuration could achieve. This is seen in Figure 10-3, where the two curves intersect. This is also known as “Coffin Corner”, as it is a particularly difficult region to fly in since the minimum airspeed to

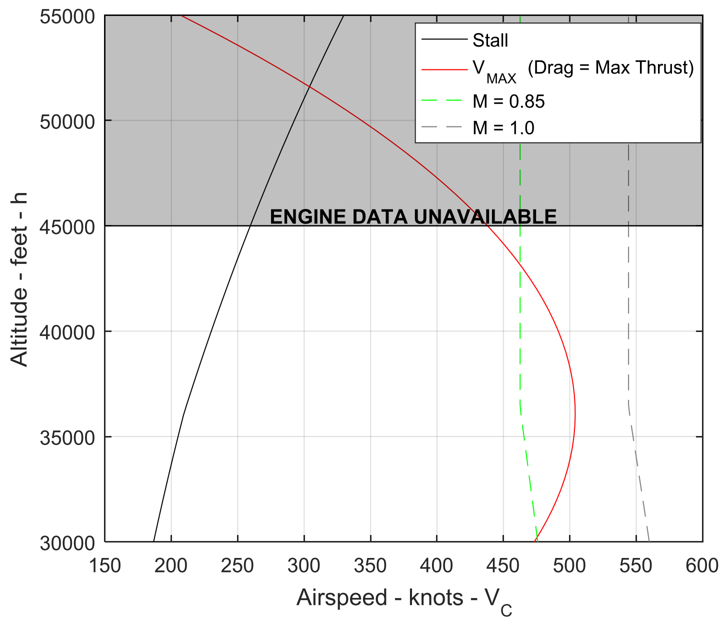



**Figure 10-3: 8 Passenger Variant at 0.9*$W_{TO}$ Service Ceiling, $M_{MO}$ Verification**

sustain flight without stall is so close to the maximum achievable airspeed. It should be noted that the engine data available shows performance only to 45,000 ft. To account for higher flight levels the data was extrapolated based on the data available. As requested by the RFP, it is clear the service ceiling of 45,000 ft. can be met and exceeded. However, without further engine performance information, it is hard to say by how much. This process has also verified that the aircraft can reach Mach 0.85 at FL350.

## 10.4 TAKEOFF AND LANDING PERFORMANCE VERIFICATION

As mentioned in Section 5, locations often traveled to by business jet owners were taken into account in evaluate landing. With Class II drag polars for the takeoff and landing configurations, as well as the estimated available installed thrust, the balanced field length was calculated. For the respective drag polars see Section 9.7. Using this Class II data, it was confirmed that the 4,000 ft. balanced field length could be met with both the 6 and 8 passenger variants at sea level under standard atmospheric conditions. Most business airports at high altitudes have longer runways, so the field length needed was also calculated for high altitude landings. Table 10-1 shows the performance data for the heaviest variant, which will be the worst performer because of higher wing loading with the same achievable $C_L$.

**Table 10-1: 8 Passenger Takeoff and Landing Performance**

| Takeoff Altitude | S.L. | 10,000 ft |
|---|---|---|
| BFL @ $\Delta T = 0$ | 3,880 ft | 5,630 ft |
| BFL @ $\Delta T = +50$ | 4,050 ft | 5,800 ft |
| **Landing** | | |
| Field Length | 3,180 ft | 3,250 ft |

## 11. MARKET ANALYSIS

The objectives of this section are:

1) Select an approach to analyze the business jet market
2) Analyze business jet market predictions for the years 2020 and 2022
3) Determine the most important technical aspects for the market in those years
4) Develop a competitive business strategy for the market by capitalizing on those technical aspects
5) Determine reasonable prices, market shares, and production rates based on the market analysis

The results of this section will be compared with production cost estimates to evaluate if and how the obtained price range can be achieved.

The data for the market analysis comes from publicly available business jet forecast from Jetcraft, a broker/dealer company which sells and leases aircraft [25], for the years 2016-2022. The method used in assessing the importance of technical factors is the Relative Value Index (RVI) method [26]. Price, value and demand equations are used to determine prices and market share.

## 11.1 THE RELATIVE VALUE INDEX (RVI) METHOD

The RVI aims to generate a measure of the relative value of a product in a market by comparing the value of the product based on several attributes, the goal being to value the product based on market performance. Products with a higher RVI are of more value to the market, and, if competitively priced, are expected to outperform competing products with a lower RVI. The goal, then, is to maximize the RVI of the aircraft in the respective market segments. The relationship between price and RVI is explored later in this section.

The RVI can be expressed as a product of *n* attribute functions, *v(g)*, raised to a power $\gamma$, as in Equation 1

$$RVI = v(g_1)^{\gamma_1} v(g_2)^{\gamma_2} \dots v(g_n)^{\gamma_n} \quad (1)$$

$$v(g) = \left[\frac{(g_C - g_I)^2 - (g - g_I)^2}{(g_C - g_I)^2 - (g_0 - g_I)^2}\right] \quad (2)$$

In Equation 1, $\gamma_n$ are weights for each of the functions, and in Equation 2, $g_C$ is the critical attribute level, $g_I$ is the ideal attribute level and $g_0$ is the baseline attribute level.

The critical attribute level is the level below which a product is worthless, and the ideal attribute level is the level at which improvements generate no additional value. The baseline attribute level is the average of the products in the market. Equation 2 gives a greater value to products which have attributes approaching the ideal, and a lower value to attributes approaching the critical level. Attributes can be of Larger Is Better (LIB), such as range, or Smaller Is Better (SIB) type, such as TOFL. Figure 11-1 shows the dependence of v on critical, ideal and baseline attribute values based on whether the attribute is of LIB or SIB type.

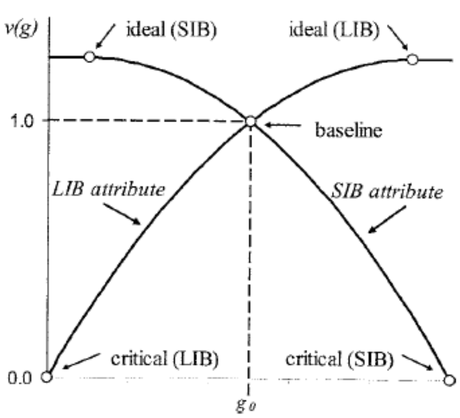



**Figure 11-1: Attributes**

The value (in monetary terms) for a product can be obtained by:

$$VI = V_0 \times RVI \quad (3)$$

$$V_0 = \frac{\overline{RV}}{\overline{RVI}} \quad (4)$$

Where $V_0$ is the baseline value for the market, taken as the average of the market segment Revealed Values (RV), divided by the average RVI of that segment. The RV can be obtained by:

$$RV = \left[\frac{D_T}{(N+1)K}\right] \ln\left(\frac{D}{\overline{D}}\right) + \frac{D_T}{K} + P \quad (5)$$

Where $D$ is product demand, $D_T$ is total segment demand, $N$ is the number of competing products in a segment, $P$ is the price of the product, and $K$ is the slope of the price/demand function and is found by:

$$K = E_p \frac{\bar{D}}{\bar{P}} \qquad (6)$$

Where $\bar{D}$ and $\bar{P}$ are average demand and price for a segment, respectively. $E_p$ is the price elasticity in percent, and is taken to be 1.5 for the business jet market [26].

Ideally, RV should equal VI. This relationship can be used to obtain the weights, γ, in Equation 1, by minimizing *J*, the sum of the squares of the error, shown in Equation 7, for the whole market, consisting of *M* segments, with *N* competitors in the segment. *N* may vary for each segment.

$$J = \sum_{s=1}^{M} \sum_{i=1}^{N} (RV_{is} - VI_{is})^2 \qquad (7)$$

Note that the γ values in Equation 1 only indicate how important each attribute is to differentiate products on the market, and do not necessarily indicate the importance of each attribute to the customer. These values also change depending on the market, so the values of γ obtained for the market in 2020 may not necessarily be the same in 2022.

## 11.2 CHOICE OF ATTRIBUTES FOR MODEL

The choice of attributes for a RVI model must be carefully considered. Attributes with high inter-correlation (r>0.85) must be avoided [26], and combined into single factors, since they cause the model to lose explanatory power. The attributes chosen are taken from [26], and one more is added, brand value, stemming from a suggestion from Cessna engineers [27]. In total, six attributes are chosen to evaluate each aircraft, and all information was obtained from Jane's [28] unless otherwise stated:

1) Operating costs – evaluated in terms of USD/hr, taken from online sources [29]. These include direct operating costs, but exclude devaluation.
2) Available passenger-miles – used to evaluate range and useful load-carrying capacity, obtained by multiplying the number of maximum occupants by maximum range.
3) Take-off field length – used to assess accessibility to different airports.
4) Maximum speed – to assess how important speed is to the market, using maximum speed Mach number.
5) Cabin volume per passenger – used to evaluate passenger comfort, by dividing cabin volume space by the maximum number of occupants in a standard configuration. Cabin volume was approximated as a cylinder with length as cabin length, and the average of cabin width and height as the diameter, since cabin volume information was not available for most jets.

6) Brand name and available customer support – evaluated by taking the normalized average of Google searches [30] for each brand. It is assumed that a brand with more searches is more popular and better known, which is assumed to correlate with better customer support availability.

Note that other important attributes, such as customer loyalty, are difficult to model and are not considered. The critical, ideal, and baseline attribute values are summarized in Table 11-1.

**Table 11-1. Critical, Baseline and Ideal Attributes**

| | Critical | Baseline | Ideal | Type |
|---|---|---|---|---|
| **Available passenger miles (pax*nmi)** | 0 | 68000 | 200000 | LIB |
| **Maximum Speed (Mach)** | 0.3 | 0.83 | 5 | |
| **Volume per passenger (ft$^3$/pax)** | 10 | 62.2 | 150 | |
| **Brand name (% average normalized Google searches 2012-2017)** | 0 | 14 | 50 | |
| **Take-off Field Length (ft)** | 15000 | 4644 | 1500 | SIB |
| **Operating costs (USD/hr)** | 10000 | 3,428.23 | 0 | |

The attributes are taken for the entire business jet market, excluding converted airliners, not only for the segments of interest. This is done for two reasons:

1) To maximize the number of data points used and evaluate the market more accurately.
2) To allow inter-segment comparisons, especially for the 600, which can fit at the top tier of the Very Light Jet segment, or the bottom of the Light Jet segment, and evaluate if the 800 could compete in the Super-Light segment.

The converted airliners segment was not analyzed as prices were hard to determine.

### 11.2.1 BRAND NAME EVALUATION

Eight aircraft brands were evaluated for their popularity, the information used and results obtained are presented here and referenced in further analysis. Brand popularity was evaluated using Google Trends [30], by taking the normalized average of worldwide searches for the terms of interest over the last five years. An effort was made to use the minimum number of words for each brand, as including additional terms, such as "aircraft", would only include English language results and would exclude other similar words such as "airplane" and "plane". Including additional terms also produced counterintuitive results, such as Cessna being more popular than Airbus. For terms which were likely to produce results for more than just the aircraft, the results were weighted accordingly, based on the aircraft-related results for the first 15 results.

The following considerations were made for each brand:

1) The term "Cessna" was used instead of "Textron", the parent company, as it is more recognizable in the aircraft world as a brand of airplanes. Specific model names, such as Citation or Latitude, were not used.
2) The term "Embraer" was used, no specific model names were used.
3) The term "Honda Jet" was used instead of "Honda", as most of these searches are assumed to be related to automobiles. However, due to the general popularity of the Honda brand, this number was adjusted using the relative market value of the company as compared to the competing companies, by 280%, using Table 11-2.
4) The term "Bombardier" was used without using specific model names, except for "Learjet". The search results were adjusted by a factor of 52%, corresponding to the revenue share of the aerospace arm of Bombardier [31] to exclude possible searches for the transportation/railway segments. This model also gave better results.
5) The term "Learjet" was searched, despite it being part of Bombardier, since it is more recognizable as a brand of small jets, and this model provided better market share approximations.
6) The term "Pilatus" was used. This is also the name of a mountain in Switzerland, and only about 58% of searches are assumed to be related to the aircraft company, based on Table 11-2.
7) The term "Gulfstream" is used, without using specific model names.
8) The term "Dassault" is used, without using specific model names. Although it is a conglomerate as well, Dassault was originally an aircraft manufacturer and is closely associated with the industry

This process is intended to provide a very rough estimate of each brand's popularity, so as to determine how it affects sales as an attribute. Figure 11-2 shows that the searches for each brand within the last five years stay relatively constant, with spikes corresponding to extraordinary events, such as crashes. All measurements are made with respect to the peak at 100%, and the straight line marks the 50% threshold, taken as the ideal value.

**Table 11-2. Market Values of Companies [42]**

| **Company** | **Market Value (Billion USD)** |
|---|---|
| Textron | 10.8 |
| Embraer | 5.8 |
| Honda | 51.5 |
| Bombardier | 3 |
| Pilatus | 3.03 |
| General Dynamics | 42.9 |
| Dassault | 10.1 |

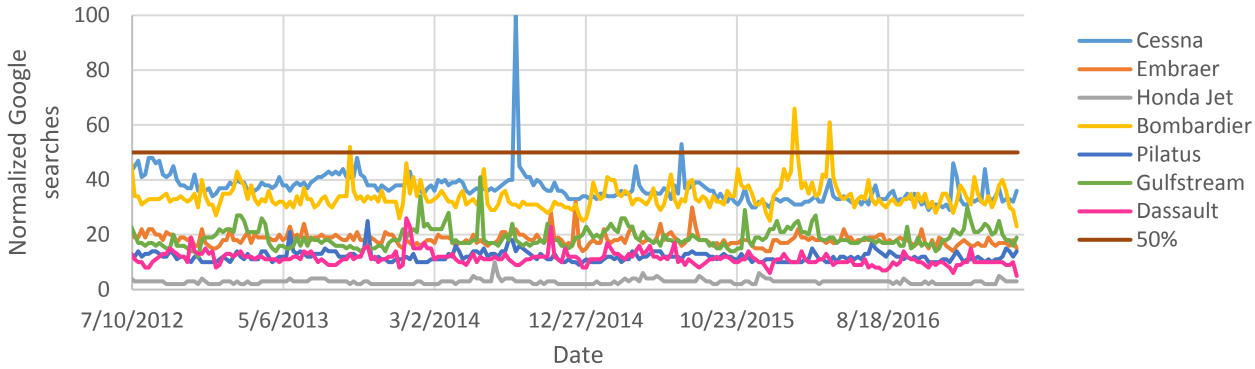



**Figure 11-2. Google Searches for the Years 2012-2017 [30]**

The data in Figure 11-2 was averaged, and used to produce the numbers in Table 11-3, where the attribute scores for each brand were obtained. These values were plotted in Figure 11-3.

**Table 11-3. Brand Attribute Adjustments and Values**

| Brand | Normalized average Google searches, 2012-2017 (%) | Traffic share adjustment (%) | Other adjustments (%) | Adjusted normalized searches (%) | Attribute score |
|---|---|---|---|---|---|
| Cessna | 37 | 95.2 | 100 | 35 | 1.87 |
| Embraer | 19 | 95.2 | 100 | 18 | 1.21 |
| Honda Jet | 3 | 95.2 | 280 | 8 | 0.60 |
| Bombardier | 34 | 93.9 | 52 | 17 | 1.13 |
| Learjet | 4 | 95.2 | 100 | 4 | 0.30 |
| Pilatus | 12 | 58.2 | 100 | 7 | 0.53 |
| Gulfstream | 19 | 77.0 | 100 | 15 | 1.02 |
| Dassault | 11 | 95.2 | 100 | 10 | 0.77 |

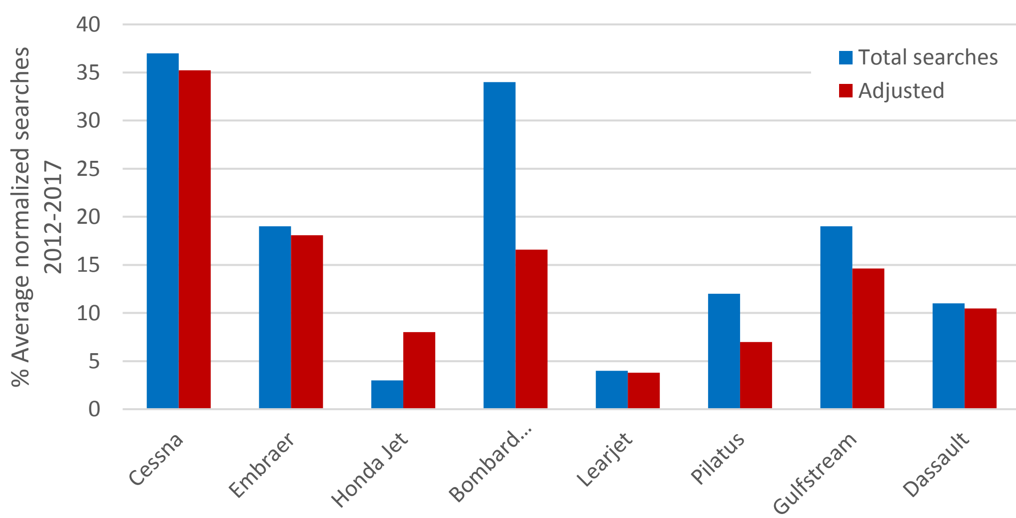



**Figure 11-3. Raw and Adjusted Data for Average Normalized Google Searches.**

## 11.3 EVALUATION OF THE BUSINESS JET MARKET IN 2020-2022

After approximating the attribute value of each brand, the business jet market is evaluated using market predictions. This is done in four steps:

1) Perform RVI analysis on the 2020 and 2022 market predictions.
2) Obtain the RVI for the 600 and the 800 using the results in the previous step.
3) Plot the RVI against the price, and estimate a good aircraft price.
4) Determine market share for both aircraft in their respective segments: Very Light Jets (600), and Light Jets (800).

Around 8000 new business jets are expected to be delivered in the years 2016-2025, according to estimates taken from publicly available business jet sales forecasts [25] [32] [33]. Of these, around 900-1000 will be Very Light Business Jets, and 1200 will be in the Light Business Jet Category. Figure 11-4 shows a breakdown of expected total business jet deliveries by market segment between 2016 and 2025.

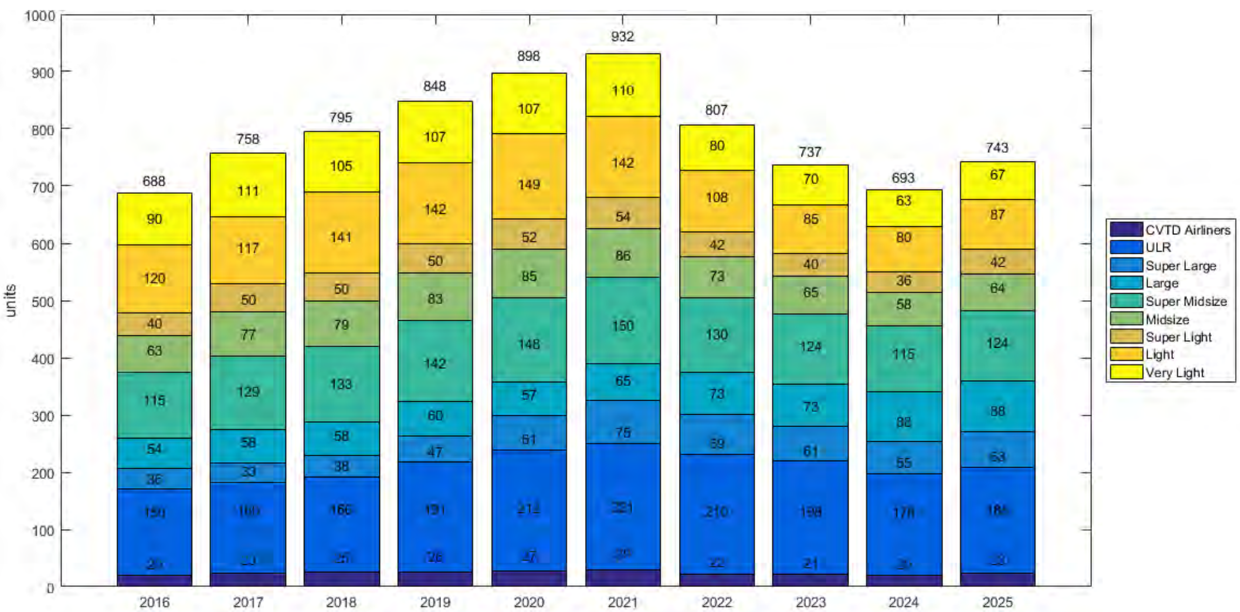



**Figure 11-4. Total Business Jet Delivery Prediction 2016-2025 [25]**

Using these market predictions and aircraft technical data from Jane's [28], the RVI method is used to evaluate the market in 2020 and 2022. This strategy will be complemented using other methods to estimate break-even production, and whether the target price can be obtained. Complementary strategies such as off sourcing and customer discounts will be considered to minimize production costs and increase market share.

### 11.3.1 VERY LIGHT JET MARKET IN 2020

The Very Light Jet market is characterized by small aircraft with a range of up to 1200 nmi and a price tag of up to 5-6 million USD [25]. They usually carry around 6 passengers. The main aircraft competing in this category in 2020, according to Jetcraft, are:

1) Honda Jet
2) Embraer Phenom 100E
3) Cessna Mustang
4) Cessna Citation M2

Some possible competitors are not considered in the market prediction and in this study, such as the Cirrus Jet. Table 11-4 summarizes the characteristics and attribute values of each of these aircraft. Brand score for the 600 is conservatively estimated at 0.038. It is set to increase to 0.38 by 2022, as aircraft are sold.

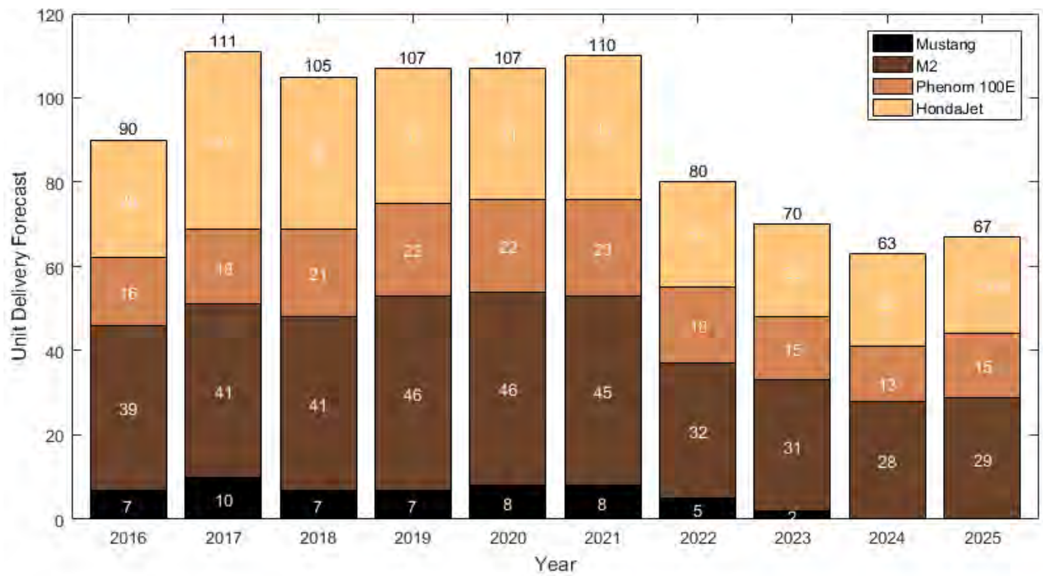



**Figure 11-5. Very Light Jet Delivery Prediction 2016-2025 [24]**

**Table 11-4. Attribute Value for the Very Light Jet Segment Competitors**

| Characteristic | Honda Jet | Phenom 100E | Mustang | Citation M2 | Tachion 600 |
|---|---|---|---|---|---|
| **Price 2016 (m. USD)** | 4.85 | 4.16 | 3.35 | 4.5 | -- |
| **Passenger miles** | 84000 | 10560 | 6900 | 12320 | 17500 |
| **Score** | 0.146 | 0.182 | 0.120 | 0.212 | 0.296 |
| **Max. Speed** | 0.72 | 0.7 | 0.63 | 0.71 | 0.85 |
| **Score** | 0.8 | 0.764 | 0.635 | 0.782 | 1.033 |
| **Vol/pax** | 40 | 27 | 26.3 | 24 | 44 |
| **Score** | 0.631 | 0.376 | 0.362 | 0.329 | 0.695 |
| **TOFL** | 3120 | 3127 | 3110 | 3120 | 3880 |
| **Score** | 1.042 | 1.042 | 1.042 | 1.042 | 1.024 |
| **Operating Costs** | 1134.90 | 1151.84 | 1015.37 | 1395.31 | 1480 |
| **Score** | 1.119 | 1.118 | 1.121 | 1.111 | 1.108 |
| **Brand score** | 0.6 | 1.21 | 1.87 | 1.87 | 0.038 |

The 6-passenger model (600) will compete in the Very Light Jet market. Table 11-5 shows the relative weight of each attribute for this year.

TOFL is valued the least, and does not affect the product relative value. This is likely due to the relative uniformity of this factor across the market. Available passenger miles, comfort, and operating costs have the greatest impact on the RVI in 2020. During a meeting with Cessna [27], it was confirmed that passenger comfort is indeed a very important aspect, however, the suggestion was made that TOFL should hold more importance, so it was adjusted slightly, also shown in Table 11-5.

**Table 11-5. Attribute Weights in 2020**

| Attribute | Weight | Adjusted weight |
|---|---|---|
| Available passenger miles | 0.37 | 0.37 |
| Speed | 0.19 | 0.19 |
| Comfort | 0.42 | 0.42 |
| TOFL | 0.00 | 0.10 |
| Operating costs | 0.76 | 0.76 |
| Brand name | 0.12 | 0.12 |

The RVI was plotted against price for all aircraft in Figure 11-6, and a logarithmic trend line was used to fit the data.

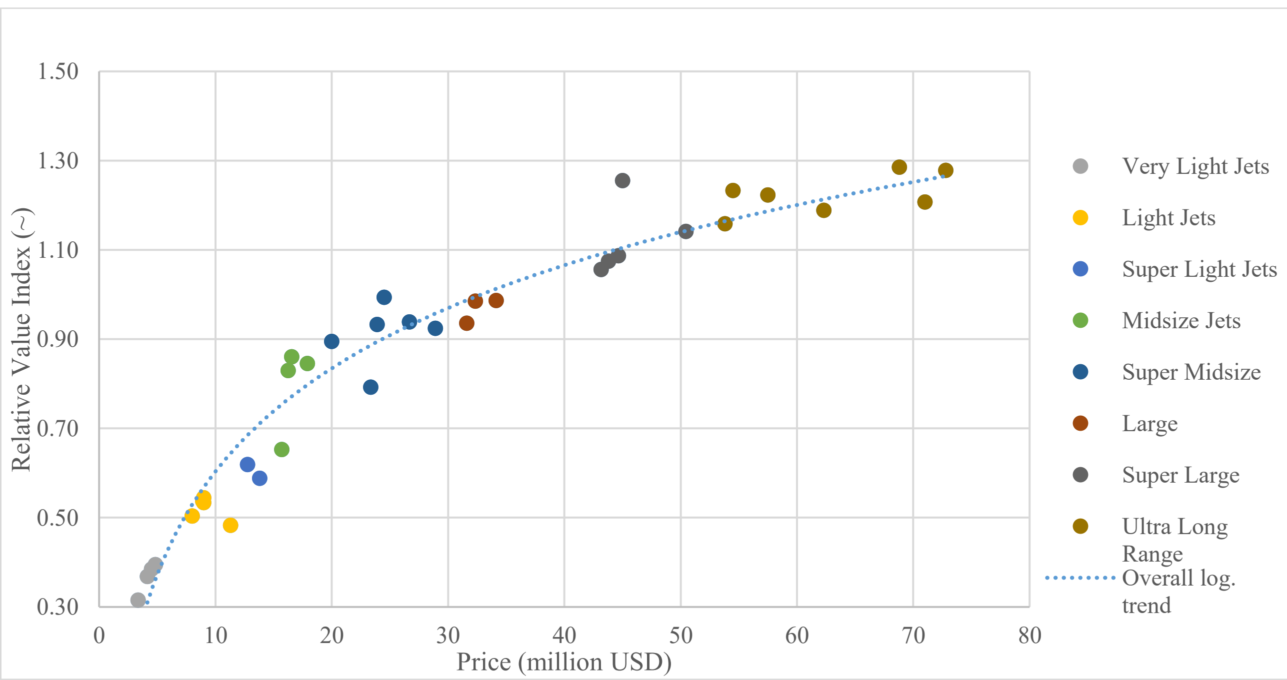



**Figure 11-6. RVI for all Business Jets in 2020**

Figure 11-7 shows a close up of the data, focusing on the small jet category. The solid blue line represents the logarithmic trend for the whole market, while the dotted blue line represents the trend only for small jets. These lines are used to compare the RVI of the design against the averages for the market.

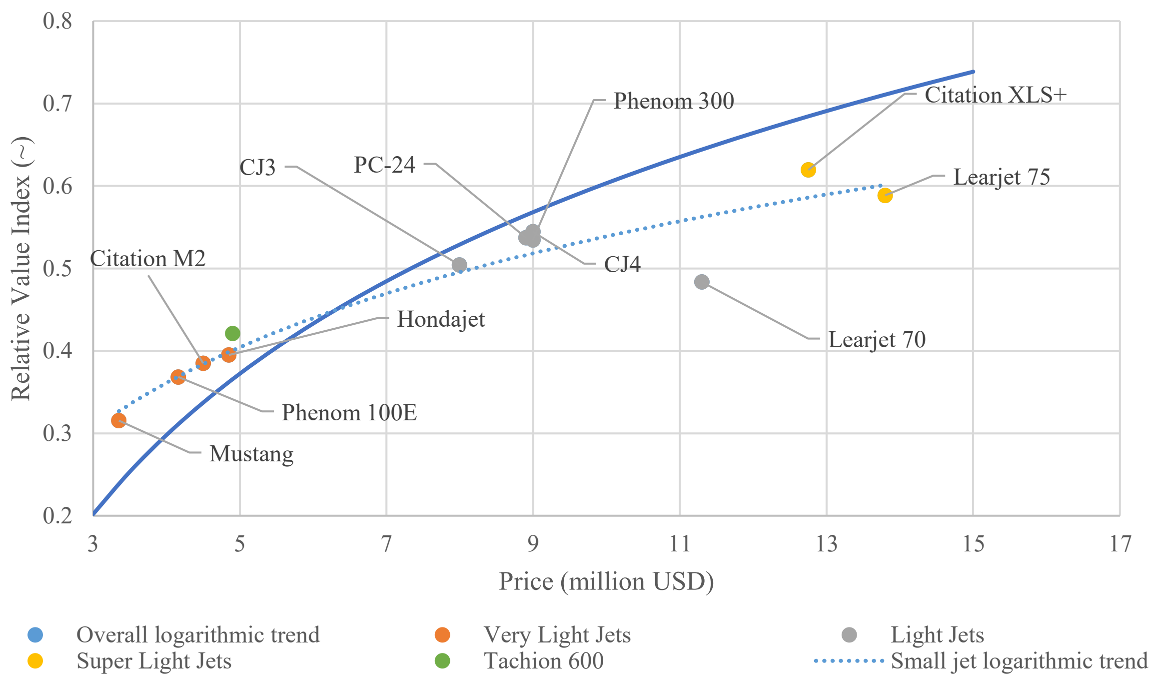



**Figure 11-7. RVI for Small Jets in 2020**

The 600 was placed in Figure 11-7 at a price of $4.95 million USD, which gives it a slight competitive edge. It's highly disadvantaged by not being produced by a recognized brand, but as the brand gains notoriety, the RVI of the aircraft is only expected to improve.

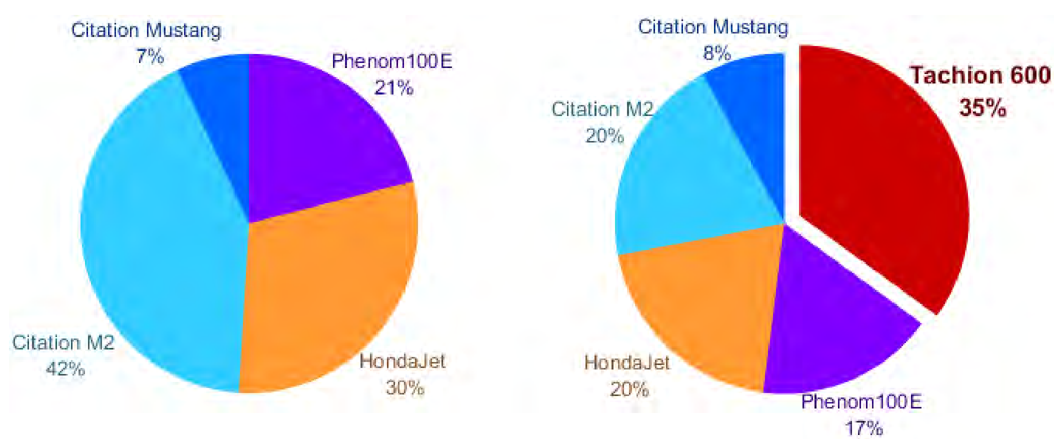



**Figure 11-8. Market Share Prediction for Very Light Jets in 2020. Jetcraft Prediction (left) and Prediction with Tachion 600 Included (right)**

Figure 11-8 shows the estimated market share of the 600 in 2020 competing in the Very Light Jet segment, priced at $4.95 million USD, which is a competitive price for the segment. This price will be verified against other possible prices to find the best price to become profitable.

It should be noted, again, that the 600 is quite heavy for the category it is in, and has a superb range. These factors may place it in a market niche of its own, between Very Light Jets and Light Jets, but to simplify market analysis, it is assumed that it competes only in the Very Light Jet market.

### 11.3.2 LIGHT JET MARKET IN 2022

The light business jet market is characterized by products which have a range of between 1700-2200 nmi, and a price of between $7.9-11.3 mil USD [25].

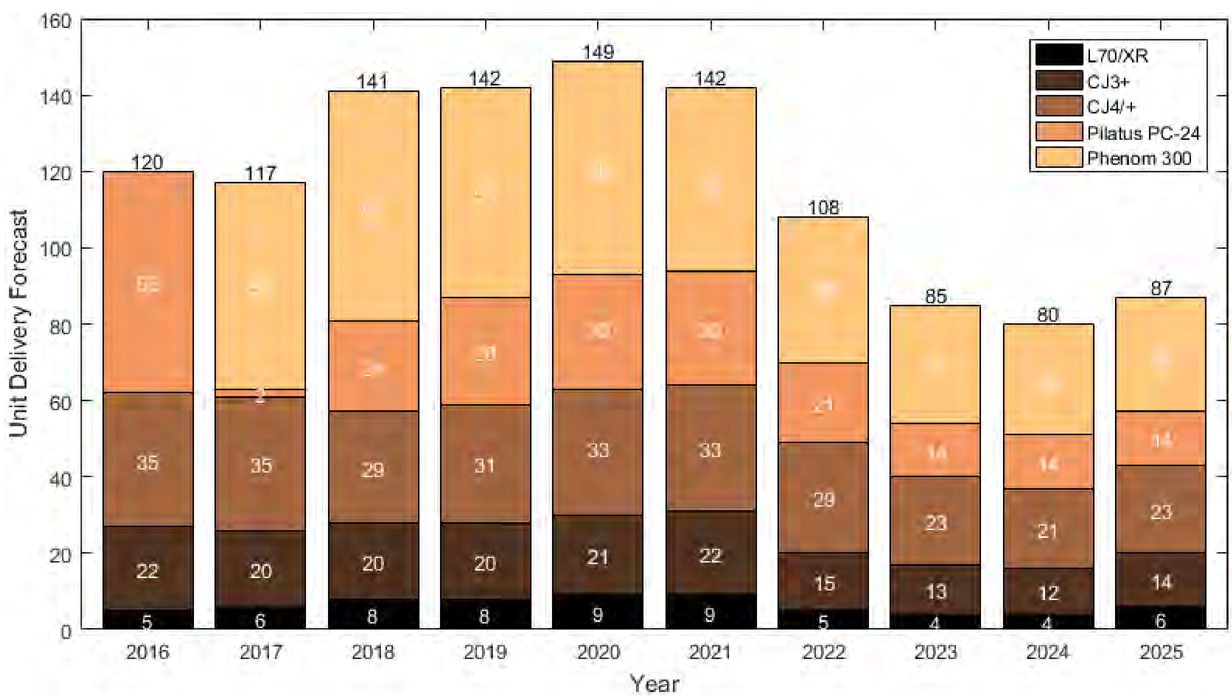



**Figure 11-9. Projected Light Jet Deliveries 2016-2025**

The main aircraft competing for buyers in the Light Jet category are seen in Figure 11-9. This list does not include the SJ30 SyberJet, as it was not included in the market prediction, but it is possible that this aircraft will be a competitor as well.

Table 11-6 summarizes the characteristics of the competing aircraft The 800 brand value score is assumed to be 0.37, an increase from 0.038 in 2020.

**Table 11-6. Light Jet Aircraft Characteristics**

| Characteristic | Phenom 300 | PC-24 | CJ3+ | CJ4 | Learjet 70 | Tachion 800 |
|---|---|---|---|---|---|---|
| **Price 2016 (m. USD)** | 8.995 | 8.9 | 7.995 | 8.995 | 11.3 | -- |
| **Passenger miles** | 19710 | 19500 | 17100 | 18018 | 18540 | 22500 |
| **Score** | 0.332 | 0.329 | 0.290 | 0.305 | 0.313 | 0.376 |
| **Max. Speed** | 0.78 | 0.73 | 0.737 | 0.77 | 0.81 | 0.85 |
| **Score** | 0.908 | 0.818 | 0.831 | 0.890 | 0.962 | 0.908 |
| **Vol/pax** | 33.7 | 41.9 | 31.4 | 34.7 | 38.8 | 44.9 |
| **Score** | 0.512 | 0.665 | 0.466 | 0.530 | 0.609 | 0.720 |
| **TOFL** | 3140 | 2691 | 3180 | 3185 | 4230 | 3880 |
| **Score** | 1.042 | 1.049 | 1.041 | 1.041 | 1.014 | 1.024 |
| **Operating Costs** | 1757.53 | 1750 (est) | 1680.03 | 1970.13 | 2166.11 | 1740 |
| **Score** | 1.210 | 1.098 | 1.101 | 1.089 | 1.080 | 1.099 |
| **Brand score** | 1.21 | 0.53 | 1.87 | 1.87 | 0.3 | 0.37 |

**Table 11-7. Attribute Weight in 2022**

| Attribute | Weight | Adjusted weight |
|---|---|---|
| Available passenger miles | 0.34 | 0.34 |
| Speed | 0.00 | 0.10 |
| Comfort | 0.39 | 0.39 |
| TOFL | 0.18 | 0.18 |
| Operating costs | 0.73 | 0.73 |
| Brand name | 0.11 | 0.11 |

Although the model weight for speed was zero initially, this was changed to reflect feedback by Learjet [34], who revealed that many business jet customers fly short routes at high speed, and therefore prefer aircraft that can fly faster. Otherwise, the weighting factors are similar to those in 2020, with the exception of TOFL being significantly higher at 0.18, instead of 0.1 (adjusted). Figure 11-10 shows a close up of the light jet market, with the solid blue line representing the overall market RVI trend, and the dotted line showing the trend only for small jets. The brand value for 800 is assumed to have increased since 2020 thanks to the good performance of the 600 in the VLJ market, so it is taken to be 0.4 instead of 0.2.

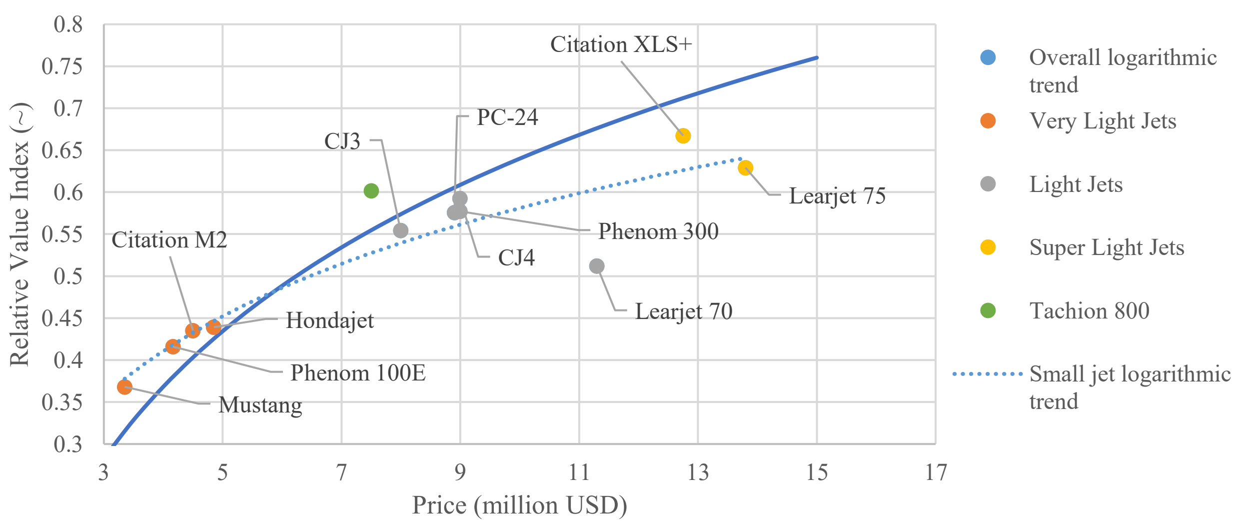



**Figure 11-10. RVI Plot, 2022, Light Jet**

The 800 was placed at a price of 7.5 million USD. The feasibility of this price is verified in the cost section. It manages to get a high RVI score due to its long range and spacious cabin, better than the competing aircraft in the Light Jet category. However, at the stage of introduction, it would have a hard time competing in the Super Light Jet

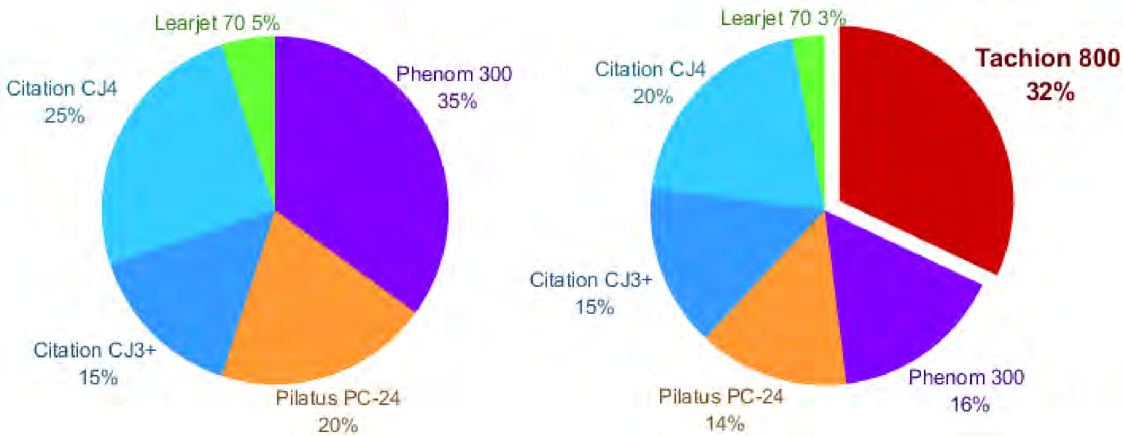



**Figure 11-11. Market Share Prediction for Light Jets, 2022. Jetcraft Prediction (left) and Prediction with Tachion 800 Included (right)**

category. The jets in this category have slightly larger cabins than the 800, and can carry more passengers. It would only be distinguished by its longer range, but due to the relatively low brand score, this advantage would be somewhat eroded. As time passes and the brand becomes more recognized, the 800 could compete in the Super Light Jet Segment, with improvements to passenger carrying capacity and perhaps a larger fuselage. This analysis will be conservative and assume that it competes only in the Light Jet market.

Figure 11-11 compares market share estimates by Jetcraft with the estimates obtained by our model for the light business jet segment in 2022, when including the 800 in the market, at a price of $8.5 million USD.

## 11.4 MARKET ANALYSIS CONCLUSION

This brief market study justifies a production rate of around 35 units per year for the 600, at a price of $4.95 million USD, and around 38 units per year for the 800, at $7.5 million USD, for a total of around 70 units yearly starting in 2022, or 5-6 units a month. These price numbers will be verified in the next section.

# 12. COSTS AND MANUFACTURING

The objectives of this section are:

1) To estimate the recurring and non-recurring costs
2) To verify whether the selling prices in the previous sections can turn a profit
3) To estimate direct operating costs
4) To establish a production strategy for the aircraft
5) To develop a manufacturing process

The Tachion 600 & 800 are expected to enter into service in 2020 and 2022, respectively. They are two members of an aircraft family separated only by two years in service entry time, and so are considered to be part of the same program, and will be analyzed concurrently. As in the market analysis section, all currency is in 2017 dollars, unless stated otherwise.

## 12.1 COSTS AFFECTING AIRCRAFT PROGRAMS

Markish [35] developed a simple model based on relating DAPCA IV costs (government cost model relating to airplanes) [36] to weight and cost fractions, and using the learning curve effect to approximate cost per pound for each aircraft. His model consists of:

1) Non-recurring costs, which include engineering, manufacturing engineering, tool design and fabrication, and support.
2) Recurring costs, which include labor, materials, and others, such as quality control.

Markish also provides estimates on the effects of commonality on cost. This model, when coupled with the Downen's RVI [26] shows the evolution of cost and revenue in time, by relating these figures through price and demand equations. This model is primarily used, as it allows to estimate the effects of commonality on cost, and checked against Roskam's [37] model.

### 12.1.1 NON-RECURRING COSTS

The non-recurring costs are calculated using Table 12-1, taken from Ref [35]. These have been adjusted from 2002 dollars to 2017 dollars, to match the currency used in the market study.

**Table 12-1. Fraction Weight Non-Recurring Costs.**

| | Cost per pound | | | | | | Weights | | NRC | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Component** | **Engineering** | **Mfg. Eng.** | **Tool Design** | **Tool Fab.** | **Support** | **Total** | **Weight 6** | **Weight 8** | **Cost 6** | **Cost 8** |
| **Wing** | 9,700 | 2,430 | 2,550 | 8,450 | 1,140 | 24,300 | 1,310 | 1,310 | 31,840,000 | 5,610,000 |
| **Empennage** | 28,600 | 7,150 | 7,500 | 24,870 | 3,360 | 71,500 | 280 | 280 | 19,740,000 | 3,480,000 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Fuselage** | 17,600 | 4,400 | 4,600 | 15,300 | 2,070 | 43,970 | 1,730 | 1,960 | 76,060,000 | 78,640,000 |
| **Landing Gear** | 1,370 | 340 | 360 | 1,190 | 160 | 3,420 | 510 | 510 | 1,750,000 | 310,000 |
| **Installed Engines** | 4,760 | 1,190 | 1,250 | 4,140 | 560 | 11,900 | 1,090 | 1,090 | 12,980,000 | 2,290,000 |
| **Systems** | 18,800 | 4,700 | 4,930 | 16,360 | 2,200 | 47,000 | 2,320 | 2,320 | 109,000,000 | 19,190,000 |
| **Payloads** | 5,900 | 1,470 | 1,550 | 5,130 | 690 | 14,700 | 980 | 980 | 14,360,000 | 3,570,000 |
| **Total** | 86,730 | 21,680 | 22,740 | 75,440 | 10,180 | 216,790 | 8,220 | 8,450 | 265,730,000 | 113,090,000 |

The non-recurring costs for the 600 using the table are estimated to be $265 million in 2017 dollars, and113 million USD for the 800, because of commonality.

### 12.1.2 EFFECTS OF COMMONALITY ON NON-RECURRING COSTS OF THE 8 PAX

For the 800, the factors in Table 12-2 are applied to non-recurring costs of each part which has already been designed, based on Ref [35] and adjusted. The fuselage adjustment factors are different since an extended (but otherwise identical) fuselage must be designed for the 800, and payload factors are different to account for different interior layout of the 800.

**Table 12-2. Non-Recurring Costs Adjustment Factors for Commonality**

| Engineering | Mfg. Eng. | Tool Design | Tool Fab. | Support | Applied to |
|---|---|---|---|---|---|
| **20%** | 50% | 5% | 5% | 50% | All except fuselage and payloads |
| **100%** | 65% | 50% | 100% | 100% | Fuselage |
| **30%** | 60% | 10% | 10% | 50% | Payloads |

### 12.1.3 RECURRING COSTS

Recurring costs are affected by the learning curve effect, where the marginal cost of each unit is reduced. This effect is approximated using Equation 8.

$$MC = TFU \times Q^{\ln(s)/\ln(2)} \quad (8)$$

Where MC is marginal cost, TFU is theoretical first unit cost, Q is quantity built to date, and s is the learning curve slope parameter [35]. The typical values for s are given in Table 12-3, as well at the percentage that each parameter is of the recurring cost.

**Table 12-3. Learning Curve and Recurring Cost Parameters**

| Parameter | Slope value | Percent of recurring cost |
|---|---|---|
| Labor | 0.85 | 41% |
| Materials | 0.95 | 33% |
| Other | 0.95 | 26% |

Table 12-4 shows the TFU costs per pound for an aircraft, adjusted from Markish to include heavier costs of payload, emulating more elaborate interiors by increasing costs by a factor of 1.5, based on Roskam [37]. The table is also adjusted for inflation.

**Table 12-4. Recurring Costs Adjustment Factors for Commonality**

| Component | Cost per pound | | | | Weights | | Total cost | |
|---|---|---|---|---|---|---|---|---|
| | Labor | Materials | Other | Total | Weight 6 | Weight 8 | Cost 6 | Cost 8 |
| **Wing** | $830 | $280 | $120 | $1,200 | 1,300 | 1310 | $ 1,610,000 | $ 1,615,000 |
| **Empennage** | $2,200 | $660 | $320 | $3,200 | 276 | 280 | $ 880,0000 | $ 881,000 |
| **Fuselage** | $930 | $260 | $130 | $1,300 | 1,730 | 1960 | $ 2,300,000 | $ 2,600,000 |
| **Landing Gear** | $140 | $130 | $21 | $300 | 510 | 510 | $ 150,000 | $ 150,000 |
| **Installed Engines** | $340 | $120 | $49 | $510 | 1,090 | 1090 | $ 558,000 | $ 560,000 |
| **Systems** | $430 | $120 | $63 | $620 | 2,320 | 2320 | $ 1,435,000 | $ 1,400,000 |
| **Payloads** | $830 | $200 | $120 | $1,160 | 970 | 970 | $ 1,127,000 | $ 1,100,000 |
| **Final Assembly** | $80 | $5 | $4 | $90 | 8,210 | 8440 | $ 731,000 | $ 750,000 |
| **Total** | $5,780 | $1,775 | $827 | $8,380 | $16,406 | $16,880 | $16,711,000 | $9,056,000 |

### 12.1.4 EFFECT OF COMMONALITY ON RECURRING COSTS

For parts which are common between aircraft, the learning curve can be inherited, as long as Q (quantity produced) for each different part is known. Thus, parts in common which have been in production for a previous aircraft will lower the marginal cost of a derivative aircraft model when compared with parts which are not common. The learning curve is inherited for all parts, except the fuselage.

By integrating Equation 8 over Q, total running cost can be estimated for the quantity produced. The evolution of these costs over time can be estimated by equating replacing Q with the average demand multiplied by the amount of time that has passed, which can be obtained from the market analysis. By starting production of the 800 two years after the 600, how many of each need to be sold at what price can be estimated to obtain a reasonable time to make 10% profit.

This simplified model does not take into account the effect of competitors' actions, fluctuations in demand, and assumes that delivery of aircraft is instantaneous. In reality, aircraft are ordered with a large lead time [35], and thus the time to make a profit will be increased as compared to the model. It also does not account for the effect of varying the price over time, which will be necessary to enter the market, since discounts are commonly given to ramp up initial production. Costs are assumed to scale up at the same rate as revenues due to inflation, so the effect of inflation over time is not modeled, but estimated after analysis has been done.

### 12.1.5 SIMULTANEOUS PROFIT PRICING STRATEGY

Cost models for the 600 and the 800 were combined to estimate the best combination of prices to make a 10 percent profit in a reasonable window of time, assuming the average demand for the market holds for the next twelve years. Many scenarios were considered, such as outsourcing production to Eastern Europe (Ukraine, Poland), Asia (China, India), and South America (Brazil, Argentina, Chile), but a quick analysis revealed Mexico, Poland, Ukraine and the USA as the best places to establish aircraft manufacturing. Since it is desirable to have the final assembly plant in the United States due to most of the business jet market (between 50% and 60% [25]) being located in North America, only two scenarios were analyzed in detail:

1) Scenario 1. Default scenario based on unadjusted model. This model assumes production is done mostly within the United States, so labor costs are not adjusted.
2) Scenario 2. This scenario assumes that the fuselage, wings, and empennage are manufactured in Mexico, so labor rates are adjusted accordingly, to approximately 25% of US rates [38], but other costs incurred, accounting for logistical, tariffs, and duty costs are increased by 312%. This is based on Ref [39], which states that Bombardier was still able to save 30% on labor despite increased logistical costs of importing parts from Mexico. Final assembly occurs in the United States.

These analyses only focus on the program cost, and do not include other costs such as setting up/building facilities. Minimizing the time to obtain profit is desirable to reduce the risk of long term uncertainty.

Figure 12-1 shows the results of the simultaneous pricing simulation based on average demand over twelve years. The model gives a minimum time to make a 10% profit as four years for both scenarios, with scenario 2 taking slightly less. The prices chosen and the time to gain ten percent profit are shown in Table 12-5. These prices are based on the market analysis, but some fluctuation in prices is allowed. These are not the prices which will generate a 10% revenue the quickest, but are more competitive.

**Table 12-5. Selected Price Ranges and Quantities to Generate 10% Profit**

| Scenario | Time (years) | 600 price ($ mil) | 800 price ($ mil) | Quantity 600 | Quantity 800 | Total Quantity |
|---|---|---|---|---|---|---|
| Scenario 1 | 4.8-5.75 | 4.5-5.0 | 7.5-9.0 | 156-211 | 98-155 | 254-366 |
| Scenario 2 | 4.4-5.2 | 4.5-5.0 | 7.5-9.0 | 142-190 | 84-131 | 226-321 |

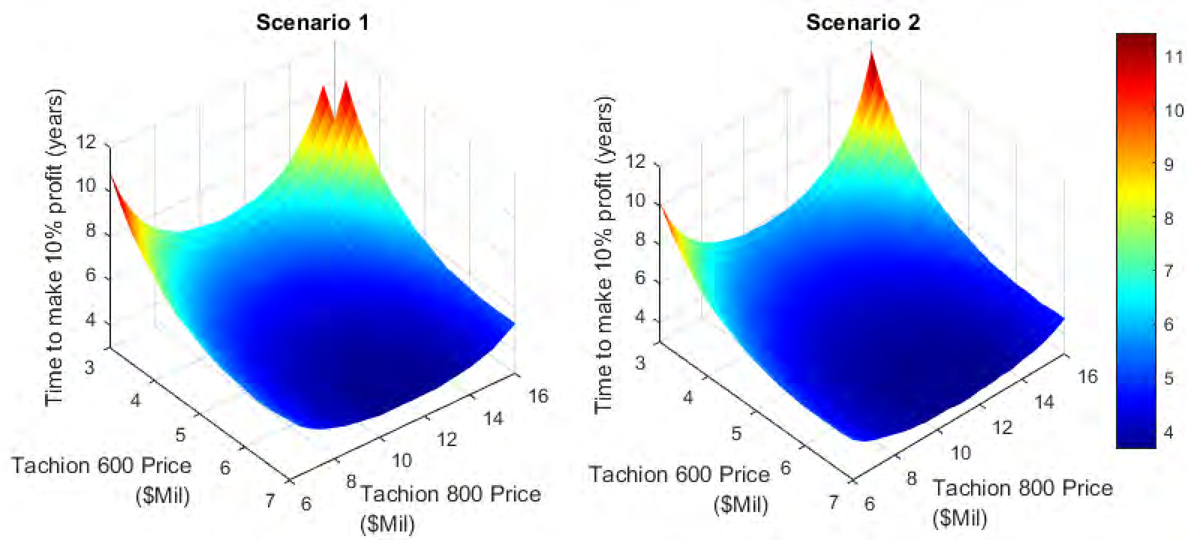



**Figure 12-1. Comparison of Time to 10% Profit, Scenario 1 (left) and Scenario 2 (right)**

Although Scenario 2 only marginally minimizes the time to be profitable, it allows reaching the 10% goal with less airplanes manufactured, and thus less costs incurred. Over a longer period of time (15 years), Scenario 2 is more profitable, generating \$2.42 billion, as compared to \$2.36 billion for Scenario 1. Such long term projection, however, may be unfeasible due to many uncertainties, and the production run of the aircraft may not reach this age. It also does not consider inflation, and the effects from political tensions that Scenario 2 may suffer from. The comparative effect of choosing different prices is shown in Figure 12-2.

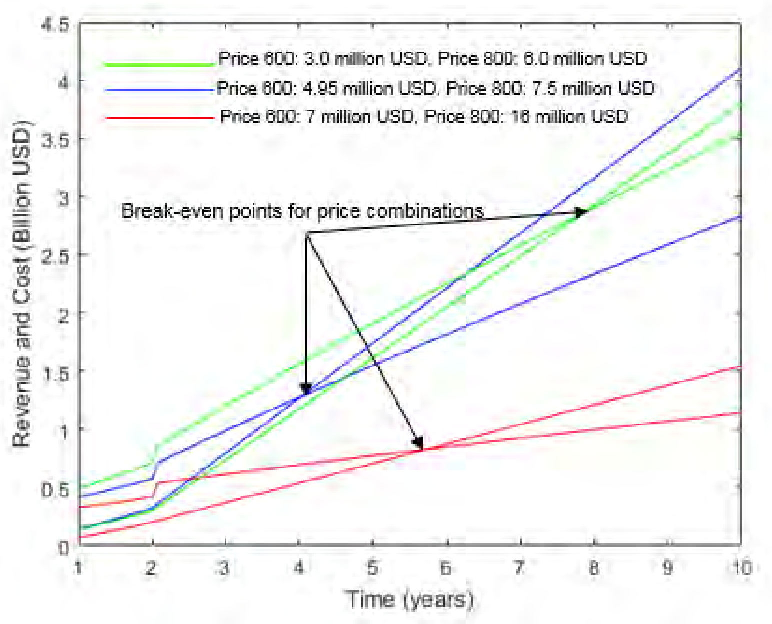



**Figure 12-2: Comparison of High Pricing, Low Pricing, and the Chosen Price**

The numbers obtained are verified using Roskam [37], where effect of commonality is simulated by using the total quantity of both models of aircraft manufactured to get a 10% revenue as the production run, with an increase of 50% in the research, design, testing and engineering (RDTE) costs simulating the burden of the 800 non-recurring costs. The resulting price for a ten percent profit was compared with the weighted average of the prices in Scenario 1, in Table 12-6. The numbers estimated by Roskam and the method used, based on Markish and Downen, are reasonably close, and thus provide a good estimate.

**Table 12-6: Comparison of Roskam with Combined Markish and Downen Method**

| Parameter | Value |
|---|---|
| Production run (total, average) | 310 |
| Roskam price (m. USD 2020) | 7.38 |
| Weighted average price, Markish and Downen (m. USD 2020) | 8.17 |
| **Difference** | 9.7% |

Based on Table 12-5, a price of 4.95 million USD is selected for the 600, and 7.5 million USD for the 800. Scenario two is chosen over scenario one, due to the requirement to minimize production costs. Table 12-7 gives the selected prices, adjusted for inflation by using a 2.5% constant inflation rate. It also provides details of the locations chosen for the manufacturing and assembly of parts, flyaway cost, and production rates. Note that the 600 runs at a loss for the estimated production rate, and would need to sell 251 units before a profit is made, seen in Figure 12-3. This is because the 600 is designed alongside the 800, with a requirement for high commonality, where the 800 drives the sizing. It is, essentially, a slightly smaller Light Business Jet being sold for a smaller price, to avoid competing against itself in the same market segment. However, the technical qualities of the 600 are very

**Table 12-7: Details of Pricing and Costs**

| Scenario | Value |
|---|---|
| Price of 600 (m. USD) | 4.95 |
| Price of 800 (m. USD) | 7.50 |
| Price of 600 (m. USD 2020) | 5.20 |
| Price of 800 (m. USD 2022) | 7.88 |
| 600 produced to 10% profit (units) | 158 |
| 800 produced to 10% profit (units) | 117 |
| Flyaway cost 600 (m. USD) | 922 |
| Flyaway cost 800 (m. USD) | 580 |
| Flyaway cost per airplane 600 (m. USD) | 5.84 |
| Flyaway cost per airplane 800 (m. USD) | 4.96 |
| Loss per airplane 600 (m. USD) | 0.89 |
| Profit per airplane 800 (m. USD) | 2.54 |
| Time to 10% profit | 4.8 years |
| Average production rate 600 (units/month) | 2.7 |
| Average production rate 800 (units/month) | 3.4 |
| Final assembly plant | Wichita, Kansas |
| Fuselage, wing, empennage manufacture | Queretaro, Mexico |

superior to those of any other plane in the VLJ category, and as brand recognition increases it is expected to take on an increasingly larger market segment.

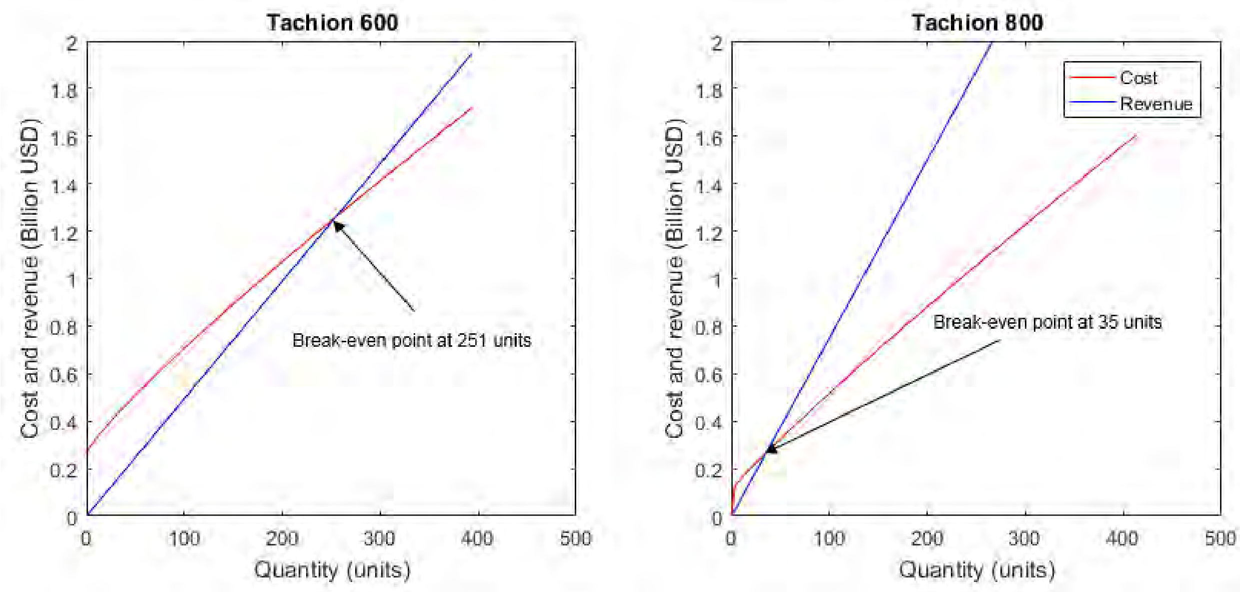



**Figure 12-3. Cost and Revenue for Each Individual of Aircraft Family as Function of Quantity of Aircraft Sold, Tachion 600 (left), 800 (right)**

### 12.1.6 OPERATING COSTS

Operating costs are estimated using Roskam [37], and a linear regression of available data [29], plotted in Figure 12-4.

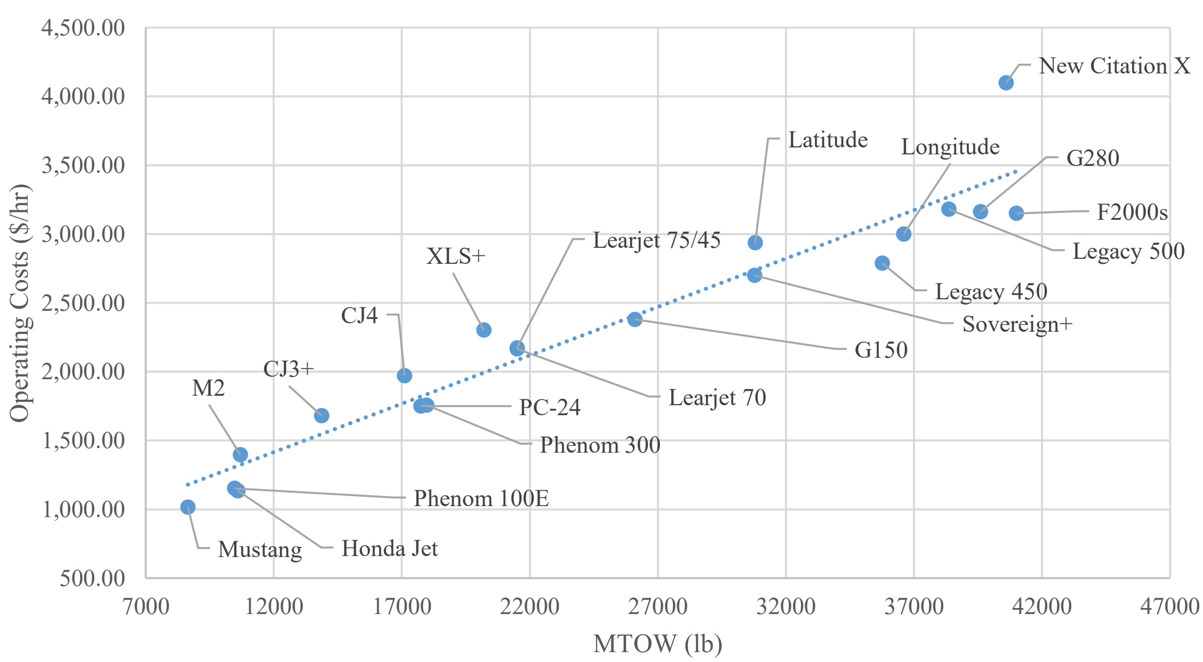



**Figure 12-4. Operating Cost as a Function of Take-Off Weight**

Table 12-8 shows the operating cost estimates for the 600 and the 800. All operating cost calculations are based on the long range cruise mission. To reduce operating costs, the aircraft allows operation with only one pilot. The hourly operation cost falls well within the range of other similar aircraft, though is on the high end for the 600.

**Table 12-8. Operating costs**

| | Chart [29] | | Roskam [37] | |
|---|---|---|---|---|
| | 6-pax | 8-pax | 6-pax | 8-pax |
| Direct operating cost ($/hr) | 1620 | 1742 | 1480 | 1560 |
| Maintenance (part of direct operating cost) ($/hr) | -- | -- | 270 | 270 |
| Depreciation ($/hr) | -- | -- | 2330 | 2330 |
| Total ($/hr) | -- | -- | 3810 | 3890 |

## 12.2 STRUCTURES

This section outlines the structural outline of the aircraft and the parameters chosen for the structure. The materials chosen and their function are listed in Table 12-9.

**Table 12-9: Materials**

| Material | Use | Parts | Fty (ksi) |
|---|---|---|---|
| **2024-T3 Aluminum, clad** | Skin and structures | Wing, Fuselage, Empennage | 68 |
| **7075 Aluminum** | Structural reinforcement, wing bottom skin | Wing, Fuselage, Empennage | 73 |
| **5052-H23 Aluminum** | Fuel tanks | Wing, fairing | 28 |
| **Countersunk rivets** | Skin and structures | All | 68 |
| **Nickel alloy fasteners** | Fasteners | Wing-fuselage joint | -- |
| **SAE 2330 Steel fasteners** | Fasteners | Wing-fuselage joint | 99 |
| **A-55 Titanium** | Leading edge deicing | Wing leading edge | -- |
| **SAE 4130 Steel** | Engine mounts | Engine pylon structure | 63 |

All preliminary structural sizing and spacing is based on Roskam [40]. The fuselage structure is outlined in Table 12-10, and shown in Figure 12-5.

The wing structural parameters are outlined in Table 12-11, and shown in Figure 12-7, which also shows the wing-fuselage interface. The wing is attached to the fuselage by eight nickel alloy and steel

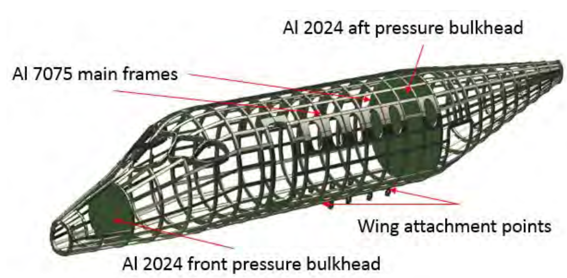



**Figure 12-5: Fuselage Structure**

**Table 12-10 - Fuselage**

| | Selected | Recommended [40] |
|---|---|---|
| Frame Spacing | 22 inches | 18 – 22 inches |
| Frame Depth | 2.5 inches | $0.02d_f$+1 inches |
| Longeron Space | 12 inches | 6 – 12 inches |

fasteners. This concept is based on the Learjet 70 design [34].

The wing empennage structural parameters are outlined in Table 12-12, and shown in Figure 12-8, which also show the engine mounts, which are made of steel.

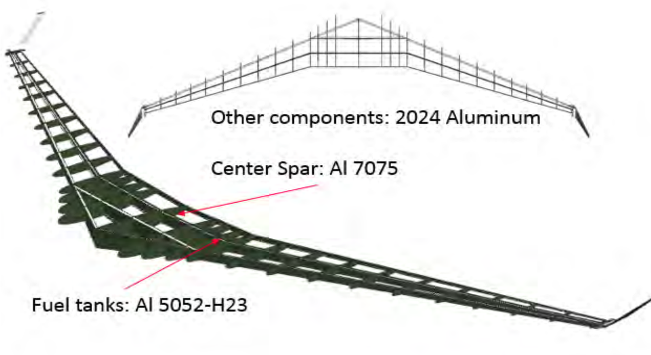



**Figure 12-6: Wing Structure**

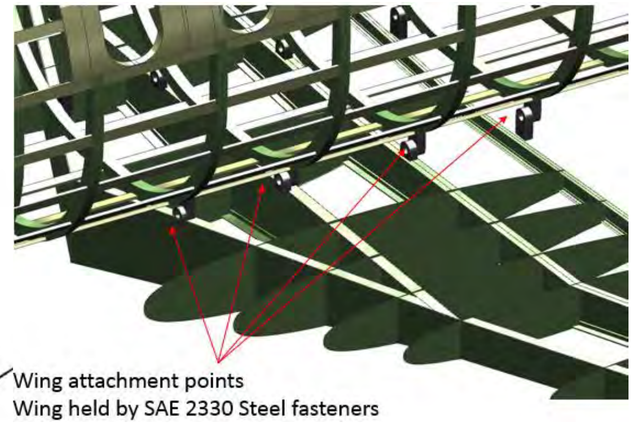



**Figure 12-7: Wing Structure and Wing Attachment Points**

**Table 12-11 - Wing**

| | Selected | Recommended [40] |
|---|---|---|
| Inboard Rib Spacing | 13 inches | 24 inches |
| Outboard Rib Spacing | 24 inches | 24 inches |
| Front Spar Location | 15% | 15-30% chord |
| Middle Spar Location | 45% | - |
| Aft Spar Location | 75% | 65-75% chord |

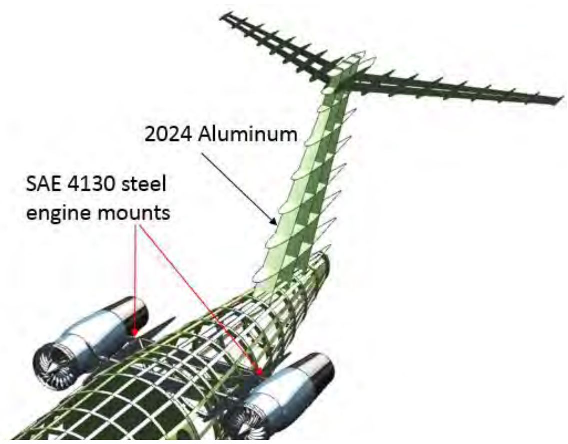



**Figure 12-8: Empennage Structure**

**Table 12-12: Empennage**

| | Horizontal Tail | Vertical Tail | Recommended [40] |
|---|---|---|---|
| Rib Spacing | 15 inches | 15 - 30 inches | |
| Front Spar Location | 25% | 20% | 15-25% chord |
| Aft Spar Location | 60% | 60% | 70-75% chord |

## 12.3 V-N DIAGRAMS

V-n diagrams were constructed using methods from Roskam's Airplane Design Part V [16]. The methods used were for FAR 23 certified aircraft, since that is the certification level chosen for both aircraft. The cruise and gust lines are calculated at Mach 0.85 at 35,000 ft, and adjusted to the equivalent airspeed at sea level to represent the flight condition represented by the RFP. Figure 12-9 shows the operational limitations for the aircraft structure. Since the same wing structure is to be used for both family members, the limit load for the 6 pax variant was not changed from that of the 8. $V_A$ represents the design maneuvering speed, $V_C$ is the design cruising speed, and $V_D$ is the design diving speed.

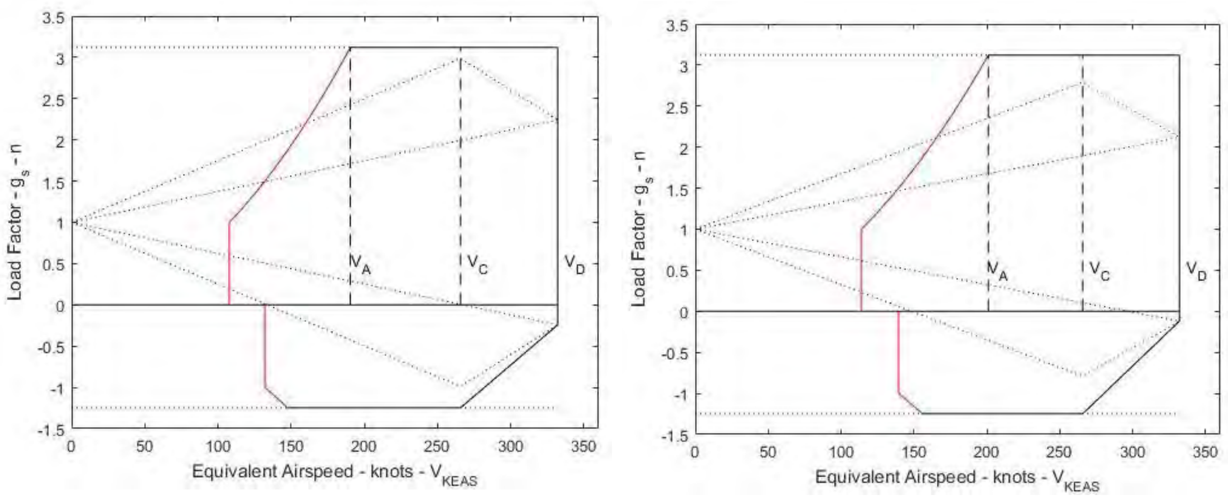



**Figure 12-9: V-n Diagram for 6 Passenger (left), 8 Passenger (right)**

**Table 12-13: Suppliers**

| Components | Supplier | Location |
|---|---|---|
| **Aircraft structures** | In-house | |
| **Avionics** | Garmin | USA |
| **Landing gear** | Safran | France |
| **Engines** | Williams International | USA |
| **Wheels** | Safran | France |
| **Control Surfaces** | Spirit Aerosystems | USA |

## 12.4 MANUFACTURING

This section outlines the manufacturing and supply process of the aircraft. The objective is to:

1) Outline the materials used and component suppliers
2) Outline the flow of manufacturing
3) Outline the required facilities

Because the EIS of the aircraft is relatively soon, in 2020 and 2022, the use of advanced materials and composites will be minimized.

The airframe will be manufactured in house, but suppliers will be used for landing gear, interiors, avionics, and engines. Table 12-13 shows the components and suppliers considered.

The manufacturing and assembly process will consist of the following steps:

1) Components manufacturing from raw materials (aluminum sheets and rods)
2) Wing, empennage, and fuselage assembly from components
3) Integration and assembly with parts from suppliers
4) Quality control and testing
5) Finishing

The wing will be assembled as a single piece, staring with the manufacturing of the required structural components (ribs, stringers, spars). Ribs will be made out of 5052 Aluminum, while the main spar will be made of the stronger 7075 Aluminum. The upper skin will be riveted first, and then sealed to create the wing fuel tank using 5052-H23 Aluminum, due to its corrosion resistance [41]. The bottom skin will then be riveted in place. After this, winglets, leading edge de-icing devices, hydraulics, actuators, and main gear will be added and tested. Figure 12-10 and Figure 12-11 show the wing manufacturing process.

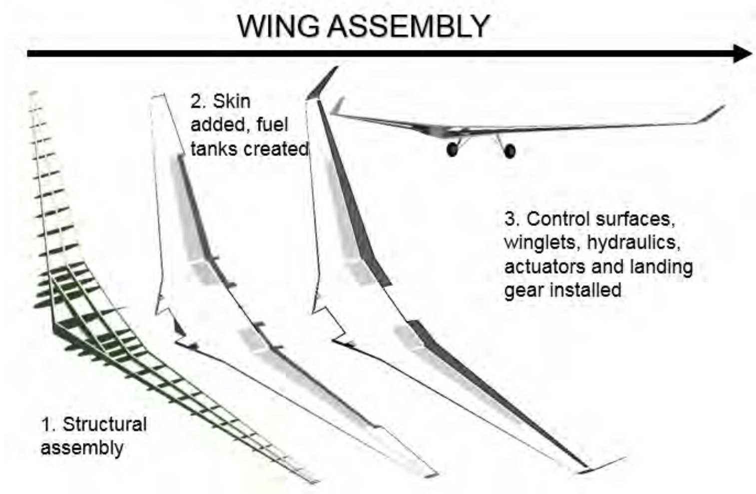



**Figure 12-10: Wing Assembly Visualization**

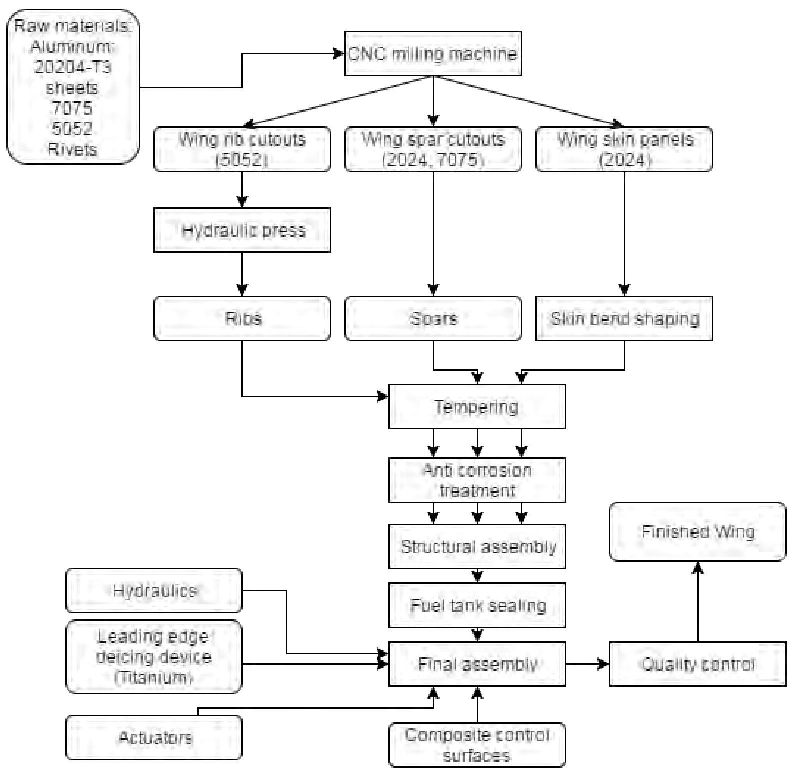



**Figure 12-11: Wing Assembly Flow Chart**

The empennage will be assembled from the vertical and horizontal tail assemblies, which follow a similar procedure to the wing. A jig and crane will be required to attach the horizontal tail to the vertical tail. Figure 12-12 and Figure 12-13 show the empennage manufacturing process.

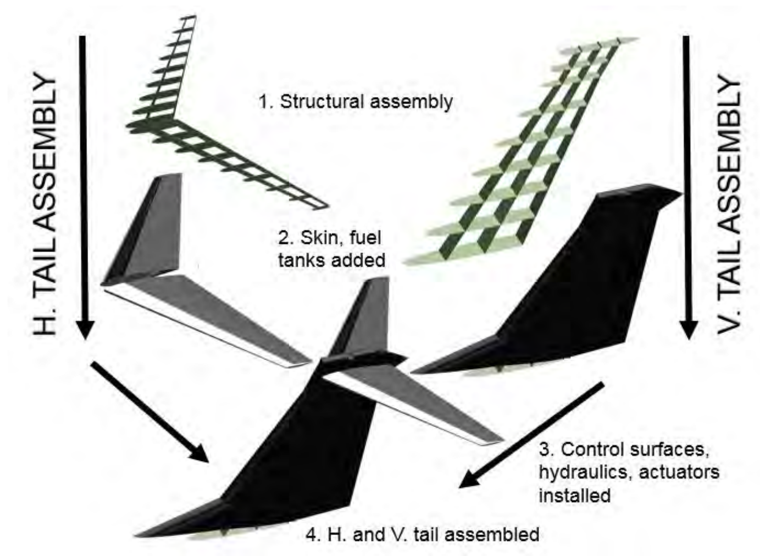



Figure 12-12: Empennage Assembly Visualization

The fuselage will be assembled from three sections, the cockpit and tail sections, which will be identical for both models, and the cabin section, which will be extended for the 800. This will minimize additional tooling design required, and allow "inheriting" most of the experience from the 600 into the 800, reducing the learning curve for the 800. Each of these sections will be built from components manufactured out of raw materials. After each section is completed, it will be mated to the neighboring sections. Once attached, the cabin and baggage doors, as well as wiring and nose gear, will be added. Figure 12-14 and Figure 12-15 show the assembly process for the fuselage.

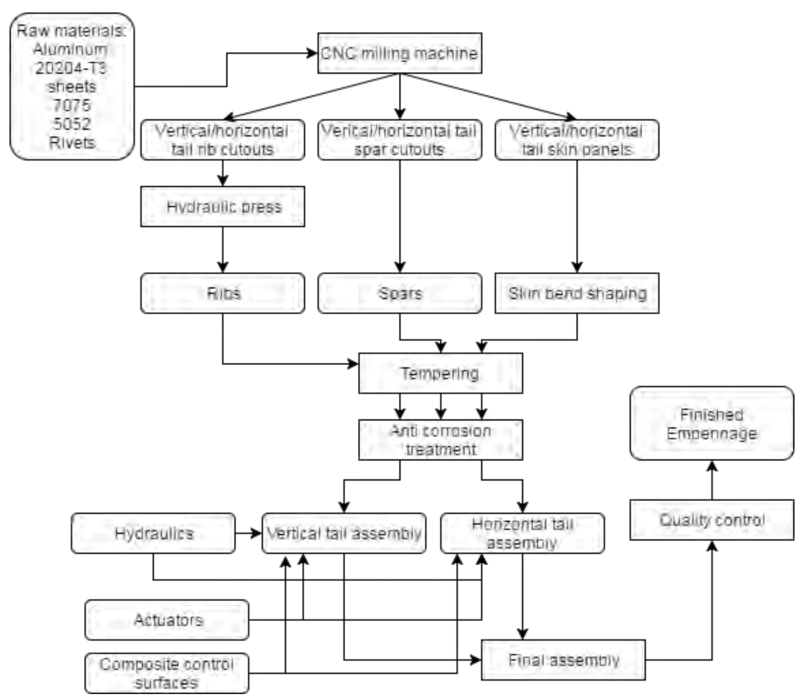



Figure 12-13: Empennage Assembly Flowchart

The final assembly will begin by adding the empennage and ventral strakes to the fuselage, for which a fixture to hold the fuselage and a crane to lift the empennage will be used.

After this, the wing will be attached under the fuselage using eight attachment points, four nickel alloy bolts, and four steel bolts. The landing gear fairing will be attached underneath the wing. Finally, the engines, in their nacelles, will be secured on the engine mounts.

When the final assembly is complete, it will undergo an inspection, followed by ground testing and flight testing. The assembly skin will then be toughened, painted, sanded, and buffed, giving it a smooth, polished finish. The interior furnishings will be installed last, based on customer choice.

The aircraft will be assembled in two main facilities, one located in Queretaro, Mexico, where the labor intensive work of manufacturing the airframe and wiring harness will be outsourced, and one in Wichita, where the final assembly testing and finishing will take place.

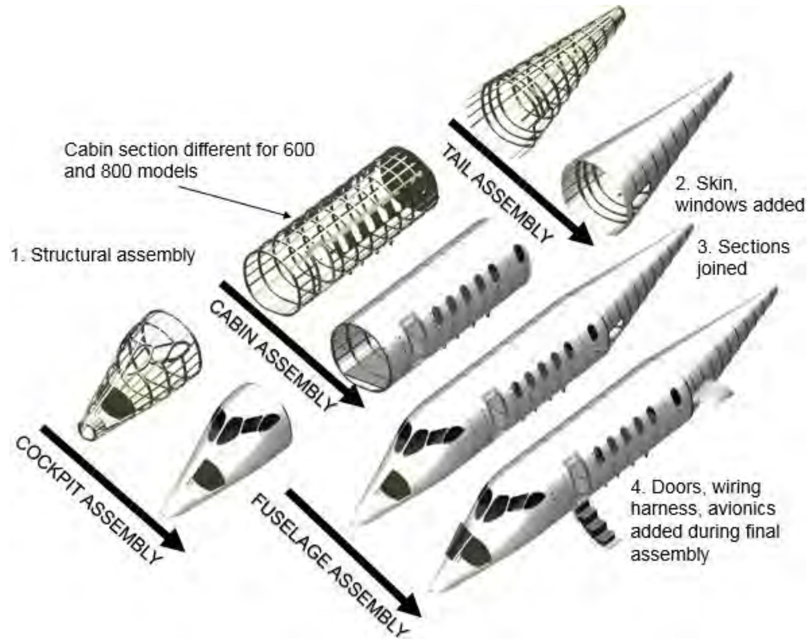



**Figure 12-14: Fuselage Assembly Visualization**

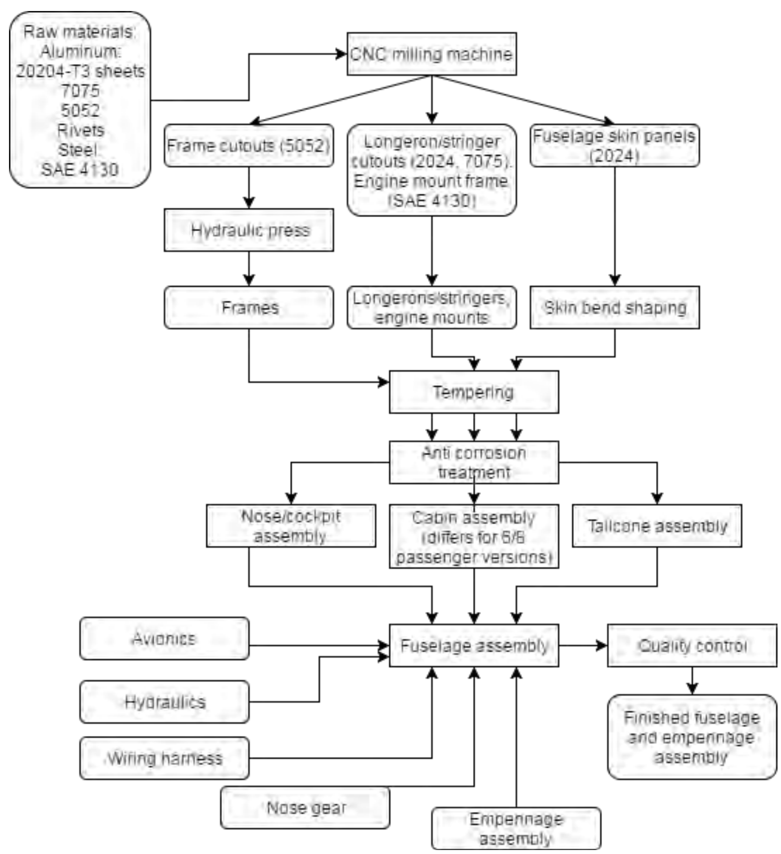



**Figure 12-15: Fuselage Assembly Flowchart**

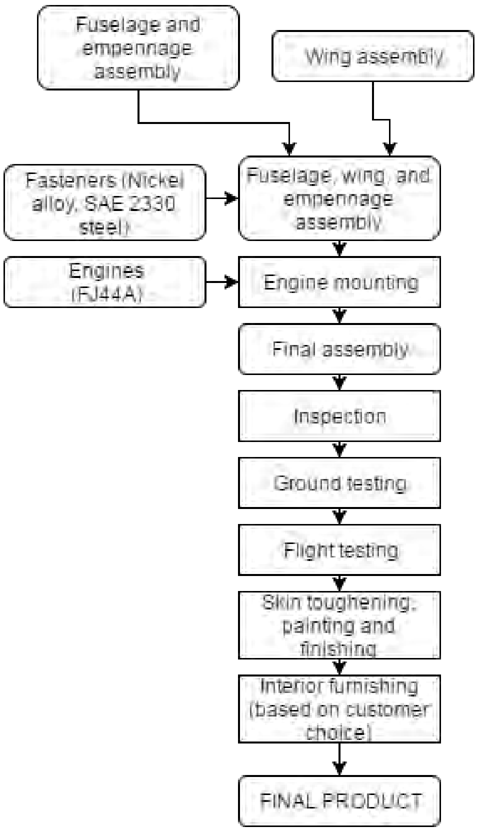



**Figure 12-16. Final Assembly Flowchart**

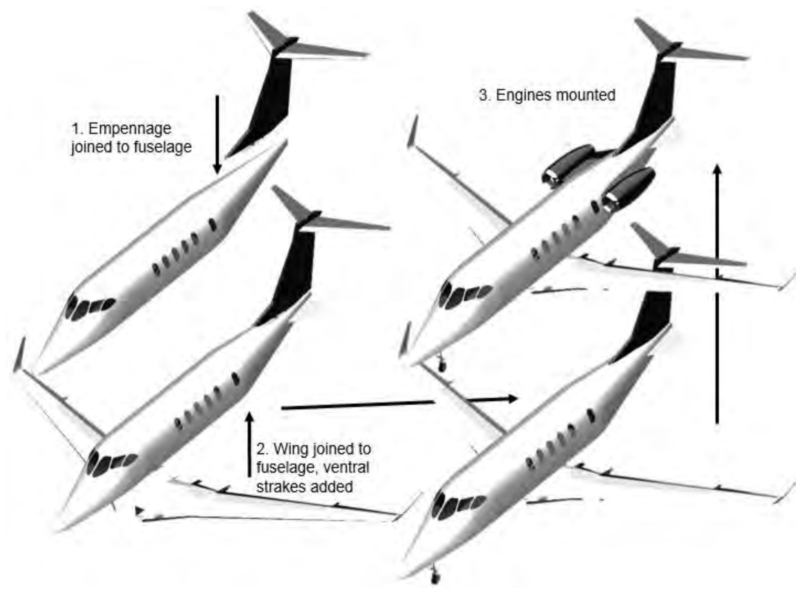
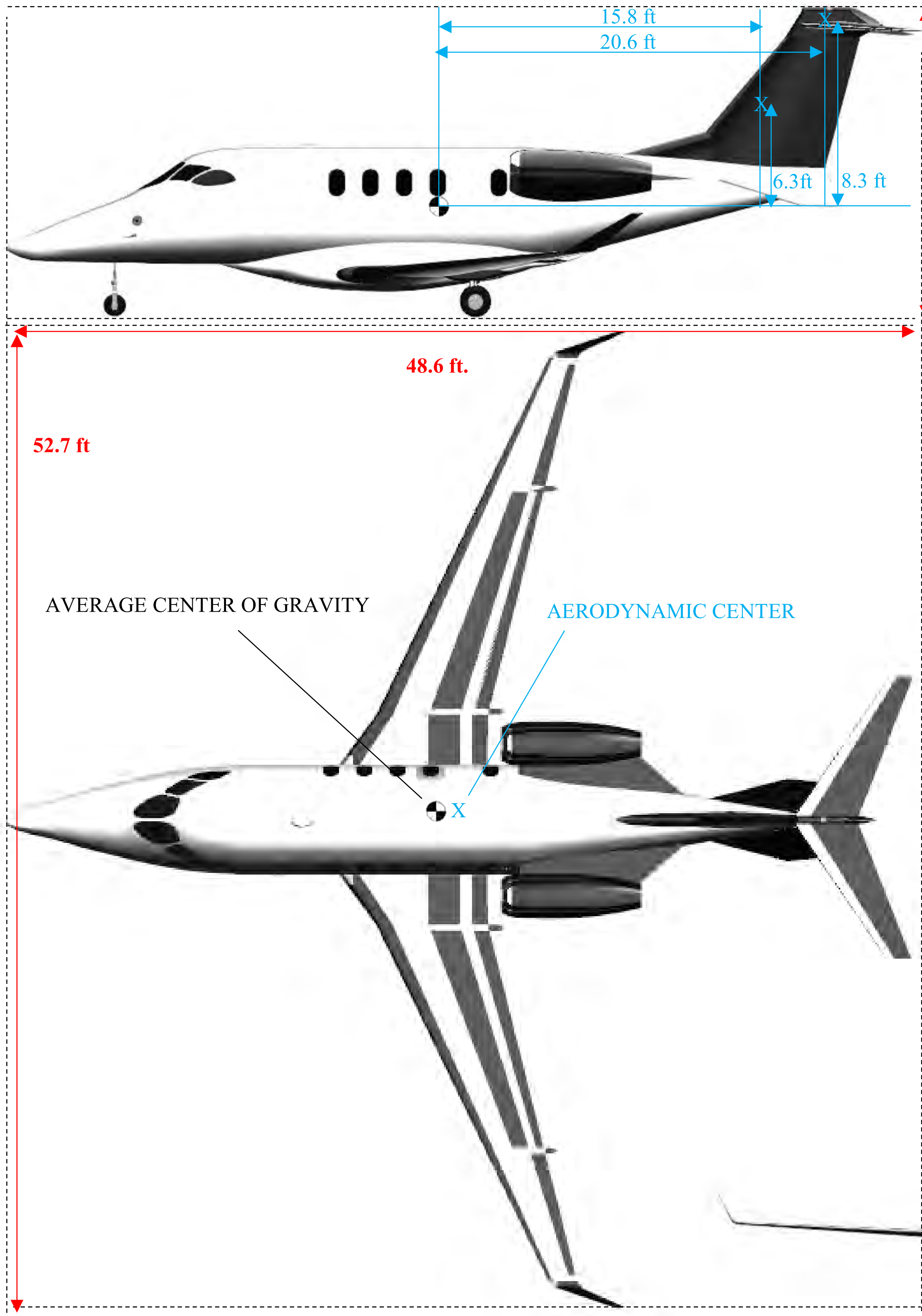



**Figure 12-17: Final Assembly Visualization**




# SCALE: 1:100

**Table 12-14: Aircraft Salient Characteristics**

| Parameter | Wing | Horiz. Tail | Vertical Tail | Fuselage (600/800) |
|---|---|---|---|---|
| Span | 52.7 ft. | 16 ft. | 7 ft. | |
| Area | 252 $ft^2$ | 40 $ft^2$ | 38.5 $ft^2$ | |
| MGC | 5.5 ft. | 2.7 ft. | 5.6 ft. | |
| Aspect Ratio | 11 | 6.4 | 1.3 | |
| Sweep Angle | 35°/25° | 35° | 40° | |
| Taper Ratio | 0.2 | 0.33 | .57 | |
| Thickness Ratio | 14%/10% | 12% | 12% | |
| Dihedral | 4°/3° | -3° | 0° | |
| Incidence | 0° | Variable | 0° | |
| Length | | | | 43.7/47.5 ft. |
| Maximum Height | | | | 6.25 ft. |
| Maximum Width | | | | 6.25 ft. |

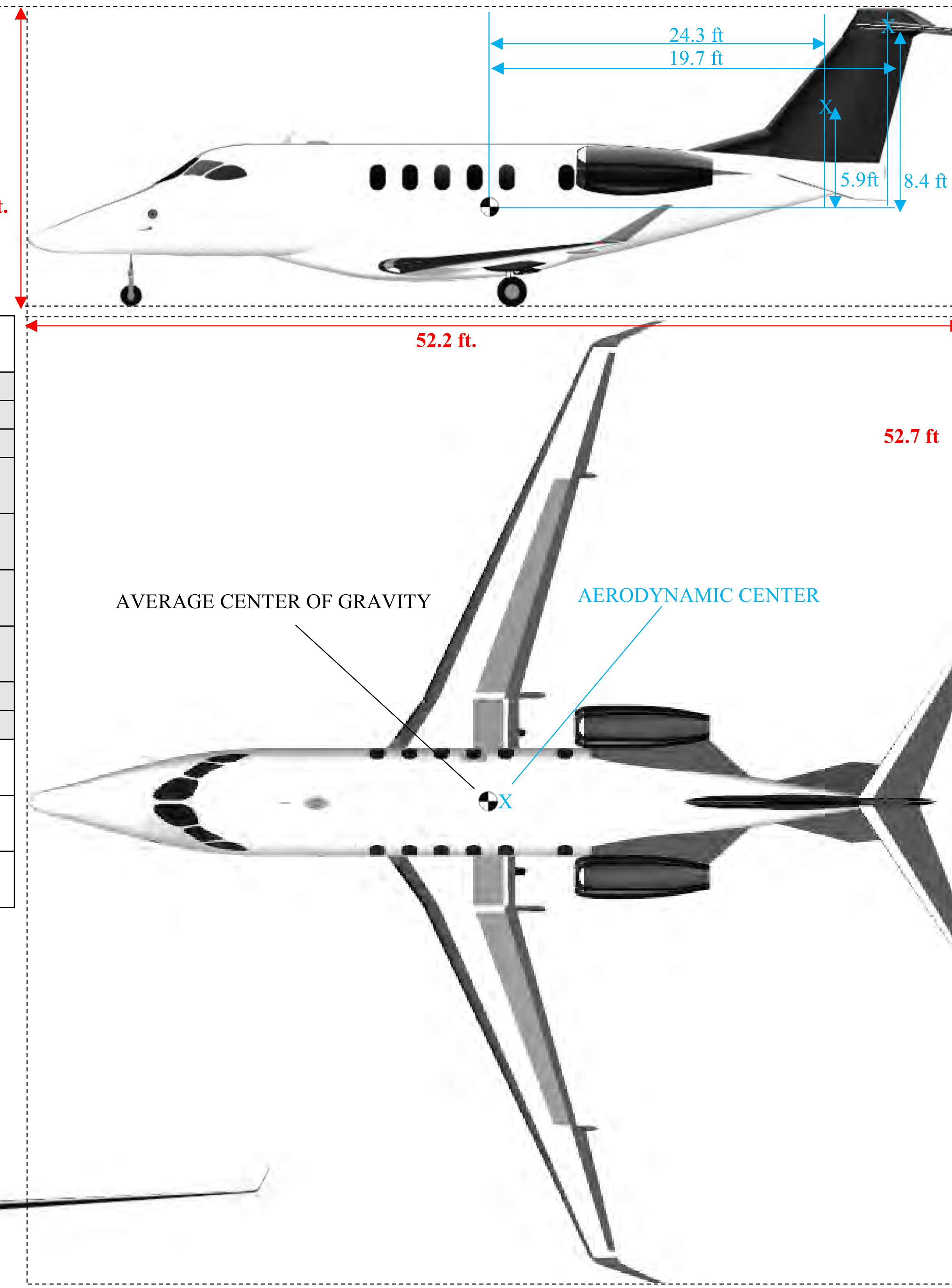



**Figure 12-18: Aircraft 3-View: Tachion 600 (left), Tachion 800 (right)**

## 13. REFERENCES


1. Wells, Douglas, *2017LightBusinessJetFamily-RFP,* American Institute of Aeronautics and Astronautics, Reston, 17 January, 2017, PDF.
2. Croft, John. "Embraer Phenom 300: bolder big brother", *Flight International*, 12 May 2008, Web, 20 January 2017.
3. Gover, Robert, "Embraer Phenom 300", *Flying Magazine"*, 14 June 2010, Web, 21 January 2017.
4. Charles, Michael, "Lear 45XR: The Swiss Army Knife of Jets: Refining and redefining the super-light jet category," *Flying Magazine*, 18 November 2010, Web, 20 January 2017.
5. Huber, Mark, "Learjet 45 & 45 XR", *Business Jet Traveler*, June 2007, Web, 21 January 2017.
6. McClellan, Mac, "SJ30-2: Trading Size for Speed", *Flying Magazine*, 11 November 2006, Web, 22 January 2017.
7. Gerzanics, Mike, "Emivest SJ30 – Long-range rocket". *Flight International,* 12 October 2009, Web, 20 January 2017.
8. Sigari, Cyrus, "Cessna CJ3+: A Plus for the CJ3", *Aircraft Owners and Pilots Association*, 5 September 2014, Web, 22 January 2017.
9. Cook, LeRoy, "Flying the Citation CJ3+", *Twin & Turbine*, 31 March 2015, Web, 20 January 2017.
10. Bergqvist, Pia, "We Fly: Honda Aircraft HA-420", *Flying Magazine*, 27 June 2016, Web, 23 January 2017.
11. Goyer, Robert "We Fly It First: HondaJet Arrives!", *Plane & Pilot*, 23 January 2017. Web. 23 January 2017.
12. Rea, Perry, *Preliminary Design Review with Perry Rea of Being*, Lawrence, KS, 6 April 2017, Interview.
13. Wells, Doug, *RFP Clarification*, 2 February 2017. Email.
14. Saarlas, Maido, *Aircraft Performance,* Whiley & Sons, Hoboken, 2007, p. 271.
15. GasTurb GmH, GasTurb 13, Aachen, GasTurb GmbH, 2017, Software.
16. Roskam, Jan, *Airplane Design Part V: Component Weight Estimation*, DARcorporation, Lawrence KS, 1985.
17. Roskam, Jan, *Airplane Design Part I: Preliminary Sizing of Aircraft*, DARcorporation, Lawrence KS, 1985.
18. Warwick, Gram. "U-tail Business Jet Shows Nosie Benefits in Clean Sky Tests", *Aviation Week Network*, 8 Dec 2016, Web, 31 January, 2017.
19. Anon, "Williams to Power New Pilatus PC-24, as Two Other Williams Turbofans Receive FAA Certification and Begin Production," *Williams International*, 21 May 2013, Web, 3 May 2017.
20. Roskam, Jan, *Airplane Design Part II: Preliminary Configuration Design and Integration of the Propulsion System*, DARcorporation, Lawrence KS, 1985.
21. Roskam, Jan, *Airplane Design Part VI: Preliminary Calculation of Aerodynamic, Thrust, and Power Characteristics*, DARcorporation, Lawrence KS, 2008.
22. Roskam, Jan, *Airplane Design Part VII: Determination of Stability, Control, and Performance Characteristics: FAR and Military Requirements,* DARcorporation, Lawrence KS, 2008.
23. Anon, "*Flying Qualities of Piloted Aircraft"*, Department of Defense, MIL-HDBK-1797, 1990.
24. Roskam, Jan, *Airplane Design Part IV: Layout of Landing Gear and Systems*, DARcorporation, Lawrence KS, 1985.
25. Fazal-Karim, Jahid. "10 Year Business Aviation Market Outlook: 2015 – 2024", *Jetcraft*, 2016 PDF, 21, April, 2017.
26. Downen, Troy D, "A multi-attribute value assessment method for the early product development phase with application to the business airplane industry" Ph.D Thesis, Engineering Systems Division, Massachusetts Institute of Technology, Cambridge, MA, 2005.
27. Anon, *Preliminary Design Review with Textron Aviation*, Wichita KS, 20, April, 2016, Presentation.
28. Buschell, Sue, Paul Jackson, Lindsay Peacock, *Jane's All the World's Aircraft: Development and Production 2017 – 2018*, 105th ed. IHS Jane's, London, 2017.
29. Marsh, Alton K, "Hourly Operating Costs of 45 Jets Compared", *Aircraft Owners and Pilots Association*, 16, November 2015, Web, 2 May 2017.
30. Google, "Google Trends", *Google*, 2 May 2017.
31. Bellemare, Alain, "Bombardier Inc. Management's Discussion and Analysis for the Fiscal Year Ended December 31, 2014", *Bombardier*, April 28, 2017.
32. Anon, "2016-2025 Bombardier Business Aircraft Market Forecast", *Bombardier*, PDF, 24 April 2017.

33. Anon, “Embraer Market Outlook 2016”, *Embraer*, Web, 24, April 2017.
34. Anon, *Preliminary Design Review with Bombardier/Learjet*, Wichita KS, 20, April, 2016, Presentation.
35. Markish, Jacob, "Valuation Techniques for Commercial Aircraft Program Design." M.S. Thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 2002.
36. Raymer, Dan, *Aircraft Design: A Conceptual Approach*, 5th ed., American Institute of Aeronautics and Astronautics, Inc., Washington D.C., 2012.
37. Roskam, Jan, *Aircraft Design Part VIII: Airplane Cost Estimation: Design, Development, Manufacturing and Operating*, Lawrence, KS: DARCorporation, 2006.
38. Anon, “International Comparisons of Hourly Compensation Costs in Manufacturing”, *United States Bureau of Labor Statistics*, 19 December 2012, PDF, 24 April 2015.
39. Andersen, Peder, Deborah McNay, “Business Jet Aircraft Industry: Structure and Factors Affecting Competitiveness”, United States International Trade Commission, No. 332-526, April 2012.
40. Roskam, Jan, *Aircraft Design Part III: Layout Design of Cockpit, Fuselage, Wing and Empennage: Cutaways and Inboard Profiles*, Lawrence, KS: DARCorporation, 2006.
41. Anon, “Aircraft Materials, Processes, & Hardware”*, Federal Aviation Administration,* FAA 3038-30, ch. 5, 3 April 2013, PDF, 22 April, 2017.
42. Anon, “Chitika Insights The Value of Google Results Positioning”, *Chitika*, 7 June 2013, Web, 1 May 2017.
43. Anon, ”America’s Top Public Companies”, *Forbes*, 2 May 2017, Web, 2 May 2017.
44. AAA, Advanced Aircraft Analysis, Software Package, Ver 3.6.2, DARcorporation, Lawrence, KS, 2016.