High Speed Mid Altitude Aircraft Project

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Abstract

This project designs aircraft that addresses the space constraint that limits airport capacity by exploiting lift created by flying aircraft at high speeds (350-500KIAS) in the mid altitudes of FL100-FL200 to increase the payload of smaller aircraft. Three solutions with the length and wingspan footprint of the Boeing 737-800 are produced using the software X-Plane, then virtually flight tested for various performance data. The results find that adoption of these designs can yield significant capacity increases, albeit at reduced fuel efficiency.
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Introduction – a problem of capacity

There are many aspects of aircraft for which continuous improvement is desirable: Speed, fuel efficiency, capacity. Speed is important as a faster aircraft will be able to complete more flights within a given time frame, resulting in happier customers and less hourly employee costs per flight. Commercial aircraft speed has been stagnating since the Concorde’s retirement, limited by a combination of bans on supersonic flights and economic factors. Fuel efficiency is an important consideration as it relates to both operating costs and larger environmental concerns. Significant improvements have been made in this area through the use of new technologies, in both lighter materials and in the case of the 787 – using an efficient electrical system in place of a pneumatic system. Capacity is an increasing concern as major airports around the globe are running out of airspace, tarmac and runway to accommodate demand. Very large aircraft such as the A380 were thought to be a solution, but fell out of favor due to the poor economics associated with logistics, and many airports cannot accommodate its unusually large footprint. Other efforts to increase airport capacity include improving air traffic control and reducing separation.

The goal of this project is to test an aircraft based solution that addresses these three concerns by designing a jet aircraft to fly at unconventional altitudes much lower than the jets currently used. A virtual prototype of the design will then be constructed and flight tested. My goal will be to support the hypothesis through comparison of my design and existing designs by obtaining performance figures for both aircraft. While this will not absolutely prove the advantage of optimizing a jet aircraft for lower altitudes, it will advance the plausibility of the idea.
The Theory

Several aviation principles work in favor of HSMA design.

1) High-bypass jet engines achieve lower specific fuel consumption\(^1\) at low altitudes.

2) Winds are weaker at lower altitudes. Cruising at lower altitudes improves consistency and predictability. Lower altitudes reduces penalties from headwinds.

3) Aircraft are limited by two speeds: Mmo (maximum mach number) and Vmo (maximum indicated airspeed). Mmo is an aerodynamic limitation that reduces aircraft top speed with increased altitude. Vmo is a structural limitation that can be increased by reinforcing the structure. Maximum airspeed is achieved at minimum altitude.

4) Cruising at low altitude reduces time and fuel spend climbing, potentially improving short distance fuel economy.

5) As lift is a function of speed, cruising at high speed will allow smaller wings to lift greater payloads.

\(^1\) Conversion of fuel flow into thrust. Lower is more efficient.
Method

This project will involve two phases: Design and testing.

Design

The first is a creative and engineering process for designing and modelling the aircraft in a software program. The design will start from an existing aircraft, to which modifications are made to optimize for an unconventional flight profile. Modifications will be made to the various aircraft parts, included but not limited to wings, the fuselage, and engine.

Wing modifications include changing the wing’s length and width (wingspan/ chord), shape (planform, airfoil). A change of wing position will also be likely. An educated estimate will be made of the resulting weight change based on knowledge of structural needs and material weights.

Fuselage modifications include changing the shape (diameter, length etc) to both accommodate added weight, and to accommodate placement of wings, engines, landing gear etcetera.

Engine modifications include a change of engine position, and a change of engine itself. Engine data regarding thrust characteristics and fuel consumption will also be obtained from reputable sources and used in the project. Such data are available on websites for various research organizations including NASA and universities. Ideally, the engine data would best come from the manufacturer. Data of engine weights will be used to estimate weight change.

The basis for these modifications will be from my knowledge of aircraft engineering and research. Design by modifying existing real aircraft rather than creating something completely
new increases chance that the results can be replicated in real life. In order for comparison to demonstrate the plausibility of the hypothesis, the design itself should not be too unconventional, and any gains in efficiency should be attributable to optimizing for lower altitudes as opposed to radically different propulsion and aircraft shape that would yield the same improvements at any altitude.

**Testing**

The second part is an experimental process where the completed aircraft is flight tested to obtain performance data. This is both for the purpose of improving the design and seeing what works, and for making a comparison to the performance of existing aircraft.

Data will be collected from testing 2 aircraft. Aircraft #1, an aircraft intended to be representative of a current commercial airliner, and Aircraft #2, the new design intended to maximize the potential of lower altitude high speed flight.

The following raw data will be collected during various tests:

1) Fuel used/ Fuel Flow

2) Distance

3) Angle of Attack

4) Climb/descent rate

5) Ground Speed

6) True Airspeed
Using screen recording and the sim’s data output function, more than 1 data point per second will be collected. The above raw data will be used to determine the following information typically included in aircraft manuals:

1) The best speed to maximize climb angle or climb rate at full power, and the resulting rate and angle of climb at each altitude.

2) The angle of attack at which the aircraft stalls, and the speed/weight combinations that it occurs

3) The amount of fuel the aircraft burns during cruise at various altitudes, weights and speeds

4) The best flap setting and rotation speed used during takeoff and the resulting takeoff distance, at various weights

5) The landing distance at various weights

6) The angle of attack at which the aircraft achieves best glide, and the speeds/weight combinations where this occurs

7) The most efficient descent profile

8) Absolute maximum range (range gliding after fuel exhaustion)

9) Operational range (including reserve fuel)

10) Fuel economy of the aircraft in 200, 500, 1000, 2000 and 3000 mile flights

Once the data for each aircraft is obtained, they can be compared with each other in metrics of time, payload, per-payload fuel economy.
This method aligns with the goals of the project as it proves plausibility that such an aircraft could work and deliver improvements. Using computer aided design and testing is the next best thing to building a scale model and doing actual flight testing.

**Simplifications**

Due to the resource constraints of a one-semester thesis, I was unable to perform tests exactly as described above. I will list the ways I simplified testing here. These methods may reduce the legitimacy of the results.

1) I did not find the actual best speed for climb, cruise and descent for each flap configuration and aircraft weight. 2° of wing Angle of Attack was assumed to deliver the best performance in normal operations (maximizes L/D), 5° of wing Angle of Attack was assumed to deliver the best performance during engine failure operations (minimize drag from dead engine, maximize performance from remaining engine(s)). Better performance may be attained by flying faster or slower.

2) Trip fuel planning is simplified to use the single hourly cruise value, instead of multi-stage climb/cruise/descent planning. The results indicate this method of fuel planning generally results in arriving with 15 minutes less fuel than planned.

3) Crosswind takeoffs and landings were not tested

4) 1000, 2000 and 3000 mile sectors were not tested. Data for these sectors can be linearly interpolated between 500 mile data and max range data.

5) Repeated tests were not made.
6) Instead of attempting complex weight estimates, aircraft weight budget is determined by: weight of the original aircraft, reduced proportionately to the amount it is shortened.

7) An added point of complexity is my decision to make 3 candidates.
The Aircraft

Figure 1 X-Plane 10 Menu in the game platform Steam

Figure 2 Wing editor in Plane Maker, wireframe view of model

In the course of this project, 4 aircraft designs were constructed in the X-Plane 10 companion program “Plane Maker”.

The first aircraft, “Aircraft #1”, is intended to be a representation of current aircraft designs, acting as control for the experiments to follow. The aircraft I chose to replicate for “Aircraft #1” was the Boeing 737-800, due to ubiquity, and it is the 2nd heaviest 737.

After replicating the control aircraft, came 3 designs for improving capacity. These designs are part of the Aircraft #2 series.
The first candidate, Aircraft #2A, maximizes capacity by combining a shortened double decker Airbus A380 fuselage with a high speed swept wing.
The second design, Aircraft #2B, improves certain performance characteristics through the adoption of an unswept, rectangular wing. The effect is improved low speed characteristics and fuel economy at a significant speed penalty.
The 3\textsuperscript{rd} Design, Aircraft #2C, is based on the Boeing 787 fuselage. This design represents minimal compromise for the smallest amount of capacity gain.

Chronologically, the order at which the aircraft were modelled/designed is #1, #2A, #2B and #2C. The following details will present the aircraft in order of capacity instead. The full spreadsheet of all test data is available in Appendix 1

\textit{Figure 6 Aircraft #2C}
Aircraft #1 is intended to be representative of a Boeing 737-800 fitted with CFM56-7B24 engines. There are a few key differences between Aircraft #1 and the Boeing 737-800.
Firstly, while the real Boeing 737 has a wing with a 2-stage planform, all aircraft modelled for this project use a single stage planform for ease of modelling and calculating average wing chord. This should have minimal impact on aircraft performance.

Secondly, Aircraft #1 has a much larger horizontal stabilizer on the aircraft rear than the Boeing 737-800. The autopilot was unable to stabilize the aircraft’s pitch with the more proportionately sized horizontal stabilizer. Engaging altitude functions would cause the aircraft to increasingly oscillate in pitch, stable flight could only be achieved through manual trim.
Tweaking the autopilot constants is the ideal solution. However, as I lack understanding in that area, increasing horizontal stabilizer size was an acceptable alternative.

In my tests, Aircraft #1 achieved a max payload range of 2873 nmi, which is just 62 nmi (2%) shy of Boeing’s quoted range of 2935 nmi\(^2\). The difference may be attributed to multiple causes: 1) Boeing may be using a slower and higher, more fuel-efficient flight profile, 2) My range estimate is based on 90 minute reserves – Boeing’s numbers may be using less, 3) increased drag from the larger horizontal stabilizer can reduce range.

Engine data for both the CFM56-7B24 using in Aircraft #1 and the CF6 80C2-B1F2 used in all Aircraft #2s come from Nathan Meier’s Jet Engine Specification Database website\(^3\). While the Boeing 737-800 comes in both the 7B24 option as well as the more powerful 7B27 option, the database only has cruise sfc data for the 7B24, hence my choice to model the 7B24 variant.


\(^3\) [http://www.jet-engine.net/index.html](http://www.jet-engine.net/index.html)
Aircraft #2C is designed to achieve capacity increase with minimal compromise.

Of the 3 candidates, 2C is the only twin-engine design. This reduces fuel consumption and maintenance costs.
By using a shortened single-deck Boeing 787 fuselage, 2C is able to use airports without double deck jet bridges – unlike the A380 based designs.

Compared to Aircraft #1, Aircraft #2C has 12% less per-passenger fuel economy, but its 10,000 gallon fuel tanks give it almost identical amount of range. In addition, 2C carries 39.6% more passengers/useful load at 11.4% more speed, for a total capacity gain of 55.5%.

Aircraft 2C requires 2 more non-pilot crew than Aircraft 1. Depending on crew pay, fuel costs and maintenance costs, 2C likely has potentially lower per-passenger-mile operating costs than Aircraft 1.

Aircraft 2C also does well in other metrics. Thanks to the use of powerful engines\(^4\), its takeoff distance is ~1000ft less than Aircraft 1, and overall it is able to make use of shorter runways.

Of all the candidates, Aircraft 2C compromises minimally on cruise altitude, this may in part be attributable to using large, possibly mis-sized wings. Fully loaded, Aircraft 2C is able to fly at all altitudes Aircraft 1 can, giving it a tremendous amount of altitude flexibility. This flexibility may be undermined if airlines choose to operate the aircraft below 25,000ft to exempt the aircraft from costly high altitude equipment and crew training regulations.

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\(^4\) A note on engine data: All 3 Aircraft 2 candidates use the CF6 80C2-B1F2 engine from the Boeing 747-400. Nathan Meier’s Jet Engine Specification Database website does not have complete data for the 57,900lbf B1F2, however it does have complete data for the B1F, which produces 57,160lbf of thrust. Given the small difference in thrust, I feel comfortable using sfc data from B1F for the B1F2.
Figure 9 Untextured 2C in testing. Green lines show lift forces
Aircraft 2B is best suited for maximizing capacity in the case of limited infrastructure, such as urban airports with relatively short runways and no room to expand.
Compared to Aircraft 1, Aircraft 2B increases capacity by 112.34% and increases raw payload by 165.12%, all the while requiring runway length just 17% more than 2C in the high altitude scenario. Unlike the other 3 aircraft that lose both useful load (range) and payload at high altitude, Aircraft 2B incurs no payload penalty operating in high altitude conditions, making it an attractive option for operators who are able to accept its comparatively low speed.

Aircraft 2B’s design philosophy can be likened to a heavy, jet powered turboprop. For short regional flights, turboprops have been recognized as the more economical alternative to regional jets, the low speed bringing negligible delay. While Aircraft 2B has the unswept wings of a typical turboprop, its 409KTAS 10,000ft cruise speed is far faster than most turboprop aircraft, its payload is also much greater.

I originally intended to equip 2B with just 2 GE90-115Bs, but due to errors on my part I underestimated the compressor frontal area. Once the corrected data was put into the model, drag from a failed engine would be too great and 2B was unable to maintain any altitude in an engine failure scenario. The solution was more engines. To simplify the design process, 4 engines producing an equivalent amount of thrust were used, although for this design the trijet is definitely an option that offers its own advantages and disadvantages.
The disadvantages of the quad jet design include acquisition cost, maintenance cost, complexity and fuel consumption. Advantages of quad jet include increased redundancy, multiple smaller engines increases the viability of a low wing configuration.
The biggest disadvantage of Aircraft 2B is the use of the NACA 65 (216)-415 laminar flow airfoil. The reason this airfoil is used is to improve the aircraft’s aerodynamic efficiency. The
downside is that the NACA 65 airfoil has a critical Mach number of 0.65, which in turn limits the aircraft’s speed. In addition, unswept wings also result in significant drag increases above M0.6.

Lift is in part a function of speed. As a result of limited speed, the aircraft’s maximum weight is also limited, which prevents it from carrying as much fuel or achieving as much range as the faster designs. Adopting the high subsonic airfoil used in the other aircraft would increase the aircraft’s maximum speed, but it would also result in a loss of lift coefficient, thus requiring the aircraft to fly faster.

Even with the limited 10,000 Gallon fuel capacity, Aircraft 2B is still capable of 1,284 nautical miles of range, making it a good fit for high density, sub 2 hour flights. Interestingly but perhaps not surprisingly, 2B’s average speed in the 200 mile sector is greater than Aircraft 1’s average speed in the 200 mile sector.
Aircraft 2A represents a peak of what you can do with a 737 sized parking space at a busy, major airport.

Thanks to its 38 ° swept wing, this aircraft is capable of 575KTAS in M0.9 maximum speed cruise, for flights up to 1873 nautical miles thanks to its 15,000 gallon fuel capacity.
Compared to aircraft 1, 2A offers a 198% increase in capacity, and a 30.36% reduction in per-passenger fuel economy.

Due to being fast and heavy, this aircraft has the worst runway performance of all the designs. Given the tremendous gain in capacity, a costly runway extension may very well be worth it.
This chart shows the per passenger fuel economy that can be expected for each sector of flight. The 200 mile sector is generally inefficient because the most inefficient portions of flight – takeoff, climb, approach and landing – occupy the biggest portion.

As sector distance increases, fuel economy also increases – up to the max economy distance. Any distance beyond the max economy distance begins to incur efficiency penalties as due to the effect of spending fuel to haul fuel. This effect is especially pronounced in Aircraft 2B.

Aircraft 2C is the only design that appears to increase in economy with range – perhaps this is because its optimal distance is greater than 500 miles. Of course, I would know for sure if I have more data points.
This bar chart shows the capacity increase that the various designs are able to deliver. Any airport “at capacity” that has 737 parking currently used by 737s will be able to nearly triple the capacity of those spots, depending on runway length available.
As I was unable to increase both capacity and economy, it would seem based on the data that there is a tradeoff in economy and capacity of aircraft designed to fit within a particular ground footprint.

15,000ft of density altitude is 10,000ft of pressure altitude on a very hot day. This chart shows the amount of payload reduction needed for an aircraft to maintain airborne with a minimum enroute density altitude of 15,000ft, in the event of an engine failure.
This chart shows the takeoff and landing distances of the various aircraft. Note that 10000ft performance numbers are attained using 15000ft payload.

Aircraft 1 has excellent landing performance due to its low weight, however it derives most of its performance from its aerodynamic efficiency. Hence, Aircraft 2B and 2C have overall better performance and can make flights from shorter runways. Even Aircraft 2A bests Aircraft 1 in high altitude runway performance.
Use of HSMA Aircraft for cargo

One of the problems of flying aircraft at low altitude is turbulent weather. For very short flights, low altitude weather is unavoidable. For longer flights, passengers may find continued turbulence throughout the entire flight to be unacceptable. Should this be the case, HSMA aircraft may still find use transporting air cargo through busy, capacity limited airports.

Markets

Overall, HSMA is suitable in any capacity limiting scenario due to limited airport real estate, or airspace capacity. Regions with high population density will benefit most from this design.

Airspace compatibility

One of the biggest barriers to HSMA aircraft may be other traffic. Without proper traffic management and accommodations allowing HSMA aircraft to fly at full potential, the minor compromise in fuel consumption could increase to disastrous levels if HSMA is forced to conduct the entire flight in an inefficient configuration.

In addition, the HSMA designs in this thesis have high minimum speeds. Aircraft 2A approaches at 200 KIAS while approach speeds of 160 KIAS (eg. used by the Concorde) are already considered high. If HSMA aircraft are unable to sequence properly in the approach queue, it would not achieve the effect of capacity gain until all aircraft are replaced with HSMA.

An effect of mass adoption of HSMA aircraft is the overcrowding of the mid altitude airspaces. From the results of this test however, the loss of fuel economy is not worth it to adopt
HSMA for airports and airspace that are not capacity constrained. Slower general aviation aircraft would still have to be extremely cautious if aircraft are flying at 400-575 kts at 10,000ft.

**Weight factors**

While I was unable to estimate the weight of my designs through sophisticated means, I can list the factors affecting the weight of HSMA aircraft:

Payload increase adds weight needed to be supported by landing gear and aircraft structure, further adding weight.

Tires would have to be able to withstand the high speeds of HSMA landing, adding weight.

Structure has to withstand the aerodynamic pressures of up to 507 KIAS, adding weight

Bigger/more powerful engines adds weight

Replacing 737 fuselage with a 787 or A380 fuselage adds weight

Fuselage only needs to be pressurized for lower altitude, which may allow for reduced weight

Fuselage may only need to be certified for lower altitude, exempting the requirement of carrying drop down oxygen systems, reducing weight.

787 and A380 are designed for ultra-long haul. Long haul specific weight such as increased food/water, as well as crew sleep areas can be removed.

Wings do not need to be significantly enlarged, saving weight.
Possible Design Improvements

Aircraft 2A and Aircraft 2C were modelled without wing incidence. Increasing the wing angle of incidence could improve efficiency.

All aircraft here use 5° of wing dihedral. Greater efficiency can be attained by reducing dihedral, up to 0° dihedral. This will result in reduced stability, which can be controlled through artificial means.

A smaller wing chord should be considered for Aircraft 2C, which currently attains optimal efficiency at 20,000+ ft.

There may be reason to shrink the dimensions of the fuselage without compromising on cabin/cargo space, as both the 787 and A380 fuselage potentially contain extra components such as fuel tanks that can be eliminated. Shrinking the fuselage reduces drag and weight, hugely improving performance and economy.
Conclusion

While there were many flaws in the design and testing process, I’ve found that HSMA aircraft are plausible. In my tests, HSMA aircraft achieved stable flight and huge capacity gains, but did not achieve fuel economy increase.

I’ve also found that there are many roadblocks to their eventual adoption, but it is a viable solution in the face of increasingly constrained airport capacity. It is possible for HSMA aircraft to reduce per-passenger operating costs in spite of lower fuel economy.

The viability of HSMA aircraft depends – in a large part – on the viability of the weight estimates. A best-case scenario would be finding my weight estimates to be overly pessimistic, and that HSMA aircraft are able to meet or exceed fuel economy of current aircraft.
Resources Used/Works Cited

Software:

X Plane 10 by Laminar Research

737NG, 747-400, 787-8 by X-Plane Freeware Project

X737-800 by EADT

Information:


Wikipedia entries for: Boeing 737NG, Boeing 787, Airbus A380, which cite:


## Appendix 1 – Test Data Spreadsheet

<table>
<thead>
<tr>
<th>Item/Aircraft Designation</th>
<th>1</th>
<th>2A</th>
<th>2B</th>
<th>2C</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1. General capacity information</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exit Limit</td>
<td>189</td>
<td>470</td>
<td>470</td>
<td>264</td>
<td>Maximum amount of people the aircraft can contain.</td>
</tr>
<tr>
<td>Multi class configuration</td>
<td>142</td>
<td>353</td>
<td>353</td>
<td>198</td>
<td>&quot;Typical” multi class capacity about 75% of Exit limit</td>
</tr>
<tr>
<td>Required Crew</td>
<td>6</td>
<td>12</td>
<td>12</td>
<td>8</td>
<td>Required crew: 2 pilots + 1 attendant per 50 passengers</td>
</tr>
<tr>
<td>Payload (lb)</td>
<td>43,610</td>
<td>115,620</td>
<td>115,620</td>
<td>64,944</td>
<td>weight budget for occupants and cargo (exit limit<em>200lb</em>1.23)</td>
</tr>
<tr>
<td>Max Takeoff Weight</td>
<td>174,200</td>
<td>549,859</td>
<td>516,359</td>
<td>306,816</td>
<td>Empty weight budget, based on exit weight of base aircraft adjusted by shortening factor</td>
</tr>
<tr>
<td>Empty Weight (lb)</td>
<td>91,300</td>
<td>333,739</td>
<td>333,739</td>
<td>174,872</td>
<td></td>
</tr>
<tr>
<td>Specified Max Landing Weight</td>
<td>146,300</td>
<td>485,359</td>
<td>470,539</td>
<td>254,816</td>
<td>Empty weight + payload + guestimated 90 min reserve fuel. The 737-800's weight is manufacturer specified, and reverse engineered to produce the exit limit to payload ratio (takes into account pax weight, baggage, misc supplies) used in the other aircraft</td>
</tr>
<tr>
<td>Calculated max landing weight</td>
<td>142,770</td>
<td>483,049</td>
<td>472,279</td>
<td>254,126</td>
<td>Max landing weight based on tested fuel use data</td>
</tr>
<tr>
<td>Max useful load on takeoff</td>
<td>82,900</td>
<td>216,120</td>
<td>182,620</td>
<td>131,944</td>
<td></td>
</tr>
<tr>
<td>Max useful load on landing</td>
<td>55,000</td>
<td>151,620</td>
<td>136,800</td>
<td>79,944</td>
<td></td>
</tr>
<tr>
<td>Fuel Capacity (lb)</td>
<td>46,063</td>
<td>100,500</td>
<td>67,000</td>
<td>67,000</td>
<td></td>
</tr>
<tr>
<td><strong>2. Shape and dimensions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuselage Length</td>
<td>130</td>
<td>126</td>
<td>126</td>
<td>130</td>
<td>length of fuselage only</td>
</tr>
<tr>
<td>Fuselage Drag coefficient</td>
<td>0.055</td>
<td>0.060</td>
<td>0.060</td>
<td>0.050</td>
<td>Circular front = more aerodynamic. Shorter/teardrop = more aerodynamic.</td>
</tr>
<tr>
<td>Length (ft)</td>
<td>133</td>
<td>142.7</td>
<td>129</td>
<td>135</td>
<td>Length of the aircraft, including rear control surfaces</td>
</tr>
<tr>
<td>Wingspan (ft)</td>
<td>112.4</td>
<td>112</td>
<td>112</td>
<td>112</td>
<td>Width of the aircraft</td>
</tr>
<tr>
<td>Wing sweep</td>
<td>25°</td>
<td>38°</td>
<td>0°</td>
<td>27°</td>
<td>Higher wing sweep allows for higher speeds at the cost of low speed efficiency</td>
</tr>
<tr>
<td>Wing Chord (ft)</td>
<td>12</td>
<td>22.5</td>
<td>20</td>
<td>17</td>
<td>average of the front-to-back length of each cross section of the main wing</td>
</tr>
<tr>
<td>Wing Aspect Ratio</td>
<td>9.37</td>
<td>4.98</td>
<td>5.60</td>
<td>6.59</td>
<td>Ratio of average chord to wingspan. Higher aspect ratios are more efficient.</td>
</tr>
<tr>
<td>Wing incidence</td>
<td>1°</td>
<td>0°</td>
<td>2°</td>
<td>0°</td>
<td></td>
</tr>
<tr>
<td>Wing dihedral</td>
<td>5°</td>
<td>5°</td>
<td>5°</td>
<td>5°</td>
<td>Angle of wing &quot;v&quot; shape as viewed from front/rear</td>
</tr>
<tr>
<td>Wing airfoil</td>
<td>Boeing Mid high subsonic</td>
<td>Boeing Mid high subsonic</td>
<td>NACA 65 (216)-415</td>
<td>Boeing Mid high subsonic</td>
<td>Shape of the wing as viewed from the side</td>
</tr>
<tr>
<td>Fuselage Base</td>
<td>737-800</td>
<td>A380-800</td>
<td>A380-800</td>
<td>787-8</td>
<td>The fuselage the aircraft is based on</td>
</tr>
<tr>
<td>Shortening Factor</td>
<td>1</td>
<td>0.55</td>
<td>0.55</td>
<td>0.7</td>
<td>The amount the original aircraft is proportionately shortened to</td>
</tr>
<tr>
<td>Pax Ceiling (ft)</td>
<td>41,000</td>
<td>25,000</td>
<td>25,000</td>
<td>25,000*</td>
<td>This is the highest the aircraft will fly with passengers, limited by cabin pressurization</td>
</tr>
<tr>
<td>------------------</td>
<td>--------</td>
<td>--------</td>
<td>--------</td>
<td>---------</td>
<td>------------------------------------------------------------------</td>
</tr>
<tr>
<td>500fpm Ceiling @ MTOW (ft)</td>
<td>31,000</td>
<td>17,000</td>
<td>28,000</td>
<td>33,000</td>
<td>This is the highest altitude the aircraft can reach on a full load</td>
</tr>
<tr>
<td>500fpm ceiling min crew, full fuel (ft)</td>
<td>40,000</td>
<td>31,000</td>
<td>35,000</td>
<td>39,500</td>
<td>highest altitude aircraft can reach with full fuel and minimum crew. (ferry flight using oxygen)</td>
</tr>
<tr>
<td>500fpm cig min crew, min fuel (ft)</td>
<td>52,000</td>
<td>37,000</td>
<td>38,000</td>
<td>46,500</td>
<td>highest altitude aircraft can reach, minimally loaded.</td>
</tr>
<tr>
<td>VMo (KIAS)</td>
<td>340</td>
<td>513</td>
<td>362</td>
<td>480</td>
<td>Aircraft Indicated Airspeed Limit</td>
</tr>
<tr>
<td>Mmo</td>
<td>0.82</td>
<td>0.91</td>
<td>0.65</td>
<td>0.85</td>
<td>Aircraft speed limit as a proportion of the speed of sound</td>
</tr>
<tr>
<td>Mmo/Vmo Intersect altitude (ft)</td>
<td>26,000</td>
<td>10,000</td>
<td>10,000</td>
<td>10,000</td>
<td>Altitude at which maximum true airspeed is achieved</td>
</tr>
<tr>
<td>Max KTAS</td>
<td>491</td>
<td>581</td>
<td>415</td>
<td>544</td>
<td>Maximum true airspeed</td>
</tr>
<tr>
<td>Max TAS cruise KIAS</td>
<td>330</td>
<td>507</td>
<td>356</td>
<td>470</td>
<td>Maximum cruise true airspeed (small margin of safety lower than Max KTAS)</td>
</tr>
<tr>
<td>Max TAS cruise KTAS</td>
<td>479</td>
<td>575</td>
<td>409</td>
<td>534</td>
<td></td>
</tr>
<tr>
<td>Max TAS cruise Mach Number</td>
<td>0.80</td>
<td>0.90</td>
<td>0.64</td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>Max TAS cruise fuel flow (lb/hr)</td>
<td>5,240</td>
<td>22,460</td>
<td>15,280</td>
<td>9,540</td>
<td></td>
</tr>
<tr>
<td>Max TAS cruise altitude (ft)</td>
<td>26,000</td>
<td>10,000</td>
<td>10,000</td>
<td>10,000</td>
<td></td>
</tr>
<tr>
<td>Cruise Capacity (passenger-knots)</td>
<td>90,531</td>
<td>270,250</td>
<td>192,230</td>
<td>140,976</td>
<td>Passengers * speed, higher is better</td>
</tr>
<tr>
<td>Cruise fuel economy (per passenger nmpg)</td>
<td>115.76</td>
<td>80.62</td>
<td>84.29</td>
<td>99.01</td>
<td>passenger nautical miles per gallon, higher is better</td>
</tr>
<tr>
<td>Cruise px-knots per gph</td>
<td>17.277</td>
<td>12.033</td>
<td>12.580</td>
<td>14.777</td>
<td>combined efficiency of fuel economy and capacity</td>
</tr>
<tr>
<td>FL200 cruise KIAS</td>
<td>330</td>
<td>424</td>
<td>295</td>
<td>393</td>
<td></td>
</tr>
<tr>
<td>FL200 cruise KTAS</td>
<td>438</td>
<td>553</td>
<td>394</td>
<td>516</td>
<td></td>
</tr>
<tr>
<td>FL200 cruise Mach</td>
<td>0.71</td>
<td>0.90</td>
<td>0.64</td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>FL200 cruise fuel flow</td>
<td>4,980</td>
<td>25,360</td>
<td>19,280</td>
<td>10,000</td>
<td></td>
</tr>
<tr>
<td>FL250 cruise KIAS</td>
<td>330</td>
<td>384</td>
<td>266</td>
<td>356</td>
<td></td>
</tr>
<tr>
<td>FL250 cruise KTAS</td>
<td>472</td>
<td>543</td>
<td>386</td>
<td>506</td>
<td></td>
</tr>
<tr>
<td>FL250 cruise Mach</td>
<td>0.78</td>
<td>0.90</td>
<td>0.64</td>
<td>0.84</td>
<td></td>
</tr>
<tr>
<td>FL250 cruise fuel flow</td>
<td>5220</td>
<td>27,920</td>
<td>23,000</td>
<td>10,584</td>
<td></td>
</tr>
<tr>
<td>FL250 500fpm weight restriction (lb)</td>
<td>174,200</td>
<td>549,859</td>
<td>516,359</td>
<td>306,816</td>
<td></td>
</tr>
<tr>
<td>Payload/fuel ratio</td>
<td>1.110</td>
<td>1.150</td>
<td>1.726</td>
<td>0.969</td>
<td></td>
</tr>
<tr>
<td>est. Range with max payload, rem. fuel and 90 min reserves (nmi)</td>
<td>2,873</td>
<td>1,710</td>
<td>1,180</td>
<td>2,949</td>
<td></td>
</tr>
<tr>
<td>est. endurance with reserves (hrs)</td>
<td>6.00</td>
<td>2.97</td>
<td>2.88</td>
<td>5.52</td>
<td></td>
</tr>
<tr>
<td>est. range with max fuel, rem. payload and 90 min reserves (nmi)</td>
<td>3,492</td>
<td>738 can only hold 36837lb payload at full fuel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>endurance with reserves (hrs)</td>
<td>7.29</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum range with full payload and fuel, 90min reserves as tested (nmi)</td>
<td>3,170</td>
<td>1,873</td>
<td>1,284</td>
<td>3,397</td>
<td>Based on trip iii range minus 1.5 hours</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>enduranc with reserves as tested</td>
<td>6.79</td>
<td>3.37</td>
<td>3.31</td>
<td>6.58</td>
<td></td>
</tr>
<tr>
<td>Max range avg speed as tested</td>
<td>467</td>
<td>556</td>
<td>388</td>
<td>516</td>
<td></td>
</tr>
<tr>
<td>Max range pax nmpg as tested</td>
<td>106</td>
<td>85</td>
<td>88</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>Engine and lbf each</td>
<td>CF6 80C2-B1F2</td>
<td>CF6 80C2-B1F2</td>
<td>CF6 80C2-B1F2</td>
<td>CF6 80C2-B1F2</td>
<td><a href="http://www.jet-engine.net/civtfspec.html">http://www.jet-engine.net/civtfspec.html</a></td>
</tr>
<tr>
<td>Reverse Thrust</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
<td></td>
</tr>
<tr>
<td>100% N1</td>
<td>5,175</td>
<td>3,854</td>
<td>3,854</td>
<td>3,854</td>
<td></td>
</tr>
<tr>
<td>Bypass ratio</td>
<td>5.3</td>
<td>5.2</td>
<td>5.2</td>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td>Compressor Area</td>
<td>20.27</td>
<td>47.17</td>
<td>47.17</td>
<td>47.17</td>
<td></td>
</tr>
<tr>
<td>Engine sea level sfc</td>
<td>0.370</td>
<td>0.316</td>
<td>0.316</td>
<td>0.316</td>
<td>Specific fuel consumption data (conversion of fuel flow to thrust) - lower is more efficient</td>
</tr>
<tr>
<td>Engine FL350 sfc</td>
<td>0.627</td>
<td>0.564</td>
<td>0.564</td>
<td>0.564</td>
<td></td>
</tr>
<tr>
<td>Number of engines</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Total thrust (lbf)</td>
<td>48,000</td>
<td>231,600</td>
<td>231,600</td>
<td>115,800</td>
<td></td>
</tr>
<tr>
<td>4. Runway information</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tailstrike pitch</td>
<td>7°</td>
<td>10°</td>
<td>10°</td>
<td>8°</td>
<td></td>
</tr>
<tr>
<td>Takeoff speeds (KIAS)</td>
<td>130</td>
<td>170</td>
<td>160</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Takeoff ground roll</td>
<td>5,800</td>
<td>7,200</td>
<td>4,800</td>
<td>4,860</td>
<td></td>
</tr>
<tr>
<td>Distance over 50ft obstacle</td>
<td>6,800</td>
<td>8,000</td>
<td>5,700</td>
<td>5,500</td>
<td></td>
</tr>
<tr>
<td>Approach speed</td>
<td>145</td>
<td>200</td>
<td>180</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td>Landing ground roll</td>
<td>1,916</td>
<td>3,822</td>
<td>3,131</td>
<td>2,704</td>
<td></td>
</tr>
<tr>
<td>Landing 50ft obstacle</td>
<td>3,398</td>
<td>7,343</td>
<td>4,743</td>
<td>4,304</td>
<td></td>
</tr>
<tr>
<td>1 engine out 50fpm ceiling (ft)</td>
<td>9,000</td>
<td>13,000</td>
<td>24,000</td>
<td>9,000</td>
<td></td>
</tr>
<tr>
<td>1 engine out procedure</td>
<td>clean, 250 KIAS</td>
<td>flaps 20, 250KIAS,</td>
<td>flaps 10, 250 KIAS</td>
<td>flaps 5, 250KIAS</td>
<td></td>
</tr>
<tr>
<td>5. High Altitude Operations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 engine out 50fpm @ 15000ft gross weight limit</td>
<td>140,000</td>
<td>533,000</td>
<td>516,359</td>
<td>255,000</td>
<td>15000ft density altitude is 10,000ft @39c</td>
</tr>
<tr>
<td>15000ft useful load</td>
<td>48,700</td>
<td>199,261</td>
<td>182,620</td>
<td>80,128</td>
<td></td>
</tr>
<tr>
<td>15000ft gross weight penalty</td>
<td>19.63%</td>
<td>3.07%</td>
<td>0.00%</td>
<td>16.89%</td>
<td></td>
</tr>
<tr>
<td>15000ft Useful load penalty</td>
<td>41.25%</td>
<td>7.80%</td>
<td>0.00%</td>
<td>39.27%</td>
<td></td>
</tr>
<tr>
<td>Takeoff ground roll @10000ft density</td>
<td>10,700</td>
<td>9,900</td>
<td>8,450</td>
<td>6,700</td>
<td><a href="http://www.jet-engine.net/civtfspec.html">KDEN 29.92, 5433ft @ 47c = 10,000ft density altitude. Takeoff distance @ 15000ft weight</a></td>
</tr>
<tr>
<td>Distance over 50ft obstacle @10000ft</td>
<td>12,000</td>
<td>11,900</td>
<td>10,000</td>
<td>8,300</td>
<td></td>
</tr>
</tbody>
</table>
1 engine out procedure above 10000ft

<table>
<thead>
<tr>
<th></th>
<th>clean, 250 KIAS</th>
<th>clean, 350KIAS/AoA 5°</th>
<th>clean, M0.64</th>
<th>clean, 300Kias/AoA 5°</th>
</tr>
</thead>
</table>

6. Complete Trip Data

i. 200 mile sector

<table>
<thead>
<tr>
<th>Planned fuel (lb)</th>
<th>10048</th>
<th>41502</th>
<th>30392</th>
<th>17883</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (hours)</td>
<td>0.65</td>
<td>0.55</td>
<td>0.62</td>
<td>0.57</td>
</tr>
<tr>
<td>Actual distance (nnmi)</td>
<td>206.9</td>
<td>206.7</td>
<td>206.8</td>
<td>206.6</td>
</tr>
<tr>
<td>Fuel used (lb)</td>
<td>3329</td>
<td>13385</td>
<td>11364</td>
<td>5503</td>
</tr>
<tr>
<td>Reserves on touchdown (lb)</td>
<td>6658</td>
<td>28443</td>
<td>18814</td>
<td>12427</td>
</tr>
<tr>
<td>Reserves on touchdown (hrs)</td>
<td>1.27</td>
<td>1.27</td>
<td>1.23</td>
<td>1.30</td>
</tr>
<tr>
<td>Effective kts</td>
<td>304.62</td>
<td>360.00</td>
<td>319.35</td>
<td>347.37</td>
</tr>
<tr>
<td>Effective pax nmpg</td>
<td>75.32</td>
<td>46.58</td>
<td>54.87</td>
<td>63.64</td>
</tr>
</tbody>
</table>

Approximates enough fuel to make the flight and land with 1.5 hour reserves.

KEWR 22R - IZUMI - KIAD 19L 198nmi 10z

ii. 500 mile sector

<table>
<thead>
<tr>
<th>Planned fuel (lb)</th>
<th>13330</th>
<th>53220</th>
<th>41600</th>
<th>23243</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (hours)</td>
<td>1.26</td>
<td>1.05</td>
<td>1.35</td>
<td>1.18</td>
</tr>
<tr>
<td>Actual distance (nnmi)</td>
<td>501.6</td>
<td>502.3</td>
<td>499.6</td>
<td>503.3</td>
</tr>
<tr>
<td>Fuel used (lb)</td>
<td>5979</td>
<td>24368</td>
<td>21120</td>
<td>11103</td>
</tr>
<tr>
<td>Reserves on touchdown (lb)</td>
<td>7526</td>
<td>28819</td>
<td>20524</td>
<td>12261</td>
</tr>
<tr>
<td>Reserves on touchdown (hrs)</td>
<td>1.44</td>
<td>1.28</td>
<td>1.34</td>
<td>1.29</td>
</tr>
<tr>
<td>Effective kts</td>
<td>392.06</td>
<td>470.48</td>
<td>365.93</td>
<td>418.64</td>
</tr>
<tr>
<td>Effective pax nmpg</td>
<td>104.62</td>
<td>63.84</td>
<td>73.66</td>
<td>78.70</td>
</tr>
</tbody>
</table>

KSJC 30R - HANAH - KPDX 28L 494nmi 16z

iii. Range @ max payload+fuel, max speed

| Time (hours)      | 8.29  | 4.87  | 4.81  | 8.08  |
| Effective kts     | 466.83| 556.24| 387.94| 516.21 |
| Effective pax nmpg | 93.55 | 63.61 | 65.78 | 82.59 |

(738 only) max fuel+payload range

| 4,639 |
| 9.85 |

iv. Ferry Range

<table>
<thead>
<tr>
<th>Ferry Range</th>
<th>545</th>
<th>2,972</th>
<th>1,960</th>
<th>4,429</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferry Range with reserves</td>
<td>4851</td>
<td>2,161</td>
<td>1,378</td>
<td>3683</td>
</tr>
<tr>
<td>Ferry Altitude (ft)</td>
<td>30,000</td>
<td>21,000</td>
<td>20,000</td>
<td>26,000</td>
</tr>
<tr>
<td>Time (hours)</td>
<td>11.98</td>
<td>5.50</td>
<td>5.05</td>
<td>8.90</td>
</tr>
</tbody>
</table>

No reserves.

9z start, full power takeoff to touch down.

No Reserves.
Appendix 2 – Demo videos and models download Links

i. Test Videos Playlist:

https://www.youtube.com/playlist?list=PLAMjsD8Gfr4B6COrkIKTGDSWdXxDBYQYI

This playlist contains the following:

1. Demo video showcasing takeoffs, cruise and landings from multiple angles (3 minutes each)

2. Approach and landing tests (4 minutes each)

3. Full length recording of 200 mile sector flight (50 minutes each)

ii. Aircraft models download:

https://drive.google.com/open?id=1_k_QnJA4z8UbPNtY6yohgjQVa9CCAXZ6

(May not be fully compatible with X-Plane 11)
Appendix 3 – Flight Procedures

Flight procedure - Aircraft 1

1) Full flaps.

2) Apply brakes, apply full power. Release brakes.

3) At 130 kts – rotate. Climb out at 145 kts.

4) Out of runway - raise gear.

Clear of obstacles –

5) Maintain +1000fpm. When AoA approaches 1°, raise 1 notch of flaps.

Repeat until speed is 250KIAS.

6) Climb out at 250KIAS using minimum flaps needed to maintain 4° or less AoA

At 10,000ft, reduce climb to +1000fpm

7) Allow aircraft to accelerate. Raise flaps at 1° AoA. Repeat until flaps are up and aircraft is at 1° AoA.

8) Climbout at 1° AoA

Once Mach = 0.8

9) level off at next altitude, engage altitude hold and speed hold.

10) cruise climb as necessary

At top of descent -
11) power idle, glide at 1° AoA

12) at 13000ft, reduce descent to -1000fpm. Allow aircraft to slow to 250KIAS, increase flaps to stay at less than 4° AoA

Continue descent.

13) Approach at 145 KIAS, full flaps, braking mechanisms armed

14) land. Use brakes, spoilers and reversers.

   Engine failure procedure

All altitudes: Max power, establish 250KIAS, flaps up, rudder and aileron trim.

Land ASAP
Flight procedures - Aircraft 2A

1) Full flaps.

2) Apply brakes, apply full power. Release brakes.

3) At 170 kts – rotate. Climb out at 190 kts.

4) Out of runway - raise gear.

Clear of obstacles –

5) Maintain +1000fpm. When AoA approaches 2°, raise 1 notch of flaps.

Repeat until speed is 250KIAS.

6) Climb out at 250KIAS using minimum flaps needed to maintain 5° or less AoA

At 10,000ft, reduce climb to +1000fpm

7) Allow aircraft to accelerate. Raise flaps at 2° AoA. Repeat until flaps are up and aircraft is at 2° AoA.

8) Climbout at 2° AoA

Once Mach = 0.89

9) level off at next altitude, engage altitude hold and speed hold.

10) cruise climb as necessary

At top of descent -

11) power idle, glide at 2° AoA
12) at 13000ft, reduce descent to -1000fpm. Allow aircraft to slow to 250KIAS, increase flaps to stay at less than 5° AoA

Continue descent.

13) Aim approach at 200 KIAS, full flaps, braking mechanisms armed

14) At threshold: do not pull power to idle. Instead, flare with approach power and allow aircraft to rest.

15) Brake, spoiler and reverse upon touchdown.

**Engine failure procedure**

Below 10,000ft: Max power, establish 250KIAS, flaps 20°, rudder and aileron trim.

Above 10,000ft: Max power, clean, 350KIAS or AoA 5°

Land ASAP
Flight procedures - Aircraft 2B

1) Full flaps.

2) Apply brakes, apply full power. Release brakes.

3) At 160 kts – rotate. Climb out at 180 kts.

4) Out of runway - raise gear.

Clear of obstacles –

5) Maintain +1000fpm. When AoA approaches 0°, raise 1 notch of flaps.

Repeat until speed is 250KIAS.

6) Climb out at 250KIAS using minimum flaps needed to maintain 3° or less AoA

At 10,000ft, reduce climb to +1000fpm

7) Allow aircraft to accelerate. Raise flaps at 0° AoA. Repeat until flaps are up and aircraft is at 0° AoA.

8) Climbout at 0° AoA

Once Mach = 0.63

9) level off at next altitude, engage altitude hold and speed hold.

At top of descent -

10) power idle, glide at 0° AoA

11) at 13000ft, reduce descent to -1000fpm. Allow aircraft to slow to 250KIAS, increase flaps to stay at less than 3° AoA
Continue descent.

12) Aim approach at 180 KIAS, full flaps, braking mechanisms armed

13) At threshold: flare with half of approach power and allow aircraft to rest.

14) Brake, spoiler and reverse upon touchdown.

**Engine failure procedure**

Below 10,000ft: Max power, establish 250KIAS, flaps 10°, rudder and aileron trim.

Above 10,000ft: Max power, clean, M0.64

Land ASAP
Flight procedures - Aircraft 2C

1) Full flaps.

2) Apply brakes, apply full power. Release brakes.

3) At 150 kts – rotate. Climb out at 170 kts.

4) Out of runway - raise gear.

Clear of obstacles –

5) Maintain +1000fpm. When AoA approaches 2°, raise 1 notch of flaps.

Repeat until speed is 250KIAS.

6) Climb out at 250KIAS using minimum flaps needed to maintain 5° or less AoA

At 10,000ft, reduce climb to +1000fpm

7) Allow aircraft to accelerate. Raise flaps at 2° AoA. Repeat until flaps are up and aircraft is at 2° AoA.

8) Climb out at 2° AoA

Once Mach = 0.83

9) level off at next altitude, engage altitude hold and speed hold.

10) cruise climb as necessary

At top of descent -

11) power idle, glide at 2° AoA
12) at 13000ft, reduce descent to -1000fpm. Allow aircraft to slow to 250KIAS, increase flaps to stay at less than 5° AoA

Continue descent.

13) Aim approach at 160 KIAS, full flaps, braking mechanisms armed

14) At threshold: flare with half of approach power and allow aircraft to rest.

15) Brake, spoiler and reverse upon touchdown.

**Engine failure procedure**

Below 10,000ft: Max power, establish 250KIAS, flaps 5°, rudder and aileron trim.

Above 10,000ft: Max power, clean, 300KIAS or AoA 5°

Land ASAP