Multidisciplinary Design Optimization of a Medium Range Transonic Truss-Braced Wing Transport Aircraft

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ABSTRACT

This study utilizes Multidisciplinary Design Optimization (MDO) techniques to explore the effectiveness of the truss-braced (TBW) and strut-braced (SBW) wing configurations in enhancing the performance of medium range, transonic transport aircraft. The truss and strut-braced wing concepts synergize structures and aerodynamics to create a planform with decreased weight and drag. Past studies at Virginia Tech have found that these configurations can achieve significant performance benefits when compared to a cantilever aircraft with a long range, Boeing 777-200ER-like mission. The objective of this study is to explore these benefits when applied to a medium range Boeing 737-800NG-like aircraft with a cruise Mach number of 0.78, a 3,115 nautical mile range, and 162 passengers.

Results demonstrate the significant performance benefits of the SBW and TBW configurations. Both configurations exhibit reduced weight and fuel consumption. Configurations are also optimized for 1990's or advanced technology aerodynamics. For the 1990's technology minimum TOGW cases, the SBW and TBW configurations achieve reductions in the TOGW of as much as 6% with 20% less fuel weight than the comparable cantilever configurations. The 1990's technology minimum fuel cases offer fuel weight reductions of about 13% compared to the 1990's technology minimum TOGW configurations and 11% when compared to the 1990's minimum fuel optimized cantilever configurations. The advanced aerodynamics technology minimum TOGW

configurations feature an additional 4% weight savings over the comparable 1990's technology results while the advanced technology minimum fuel cases show fuel savings of 12% over the 1990's minimum fuel results. This translates to a 15% reduction in TOGW for the advanced technology minimum TOGW cases and a 47% reduction in fuel consumption for the advanced technology minimum Fuel cases when compared to the simulated Boeing 737-800NG. It is found that the TBW configurations do not offer significant performance benefits over the comparable SBW designs.

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Chapter 1: Introduction

Since the beginning of the modern era of commercialized air travel, the industry has been dominated by a common tube and wing, cantilever aircraft configuration. This cantilever wing design is used in nearly every aircraft application from fighter jets to cargo planes. Over the years, the development of advanced technologies has allowed the cantilever planform to become consistently more efficient; however, they still look very much like they did 50 years ago. It seems that there is only so much room for improvement, thus many alternative aircraft configurations have been explored such as the Blended Wing Body (BWB), the Joined Wing, and the Truss-Braced Wing (TBW). The objective of this study is to further investigate the performance benefits of the Truss-Braced Wing aircraft configuration now for a medium range, transonic transport.

The TBW concept for a long range transport has been studied at Virginia Tech in the late 1990's and then again for the last three years[1]. Based on the vision of Werner Pfenninger shown below[2],

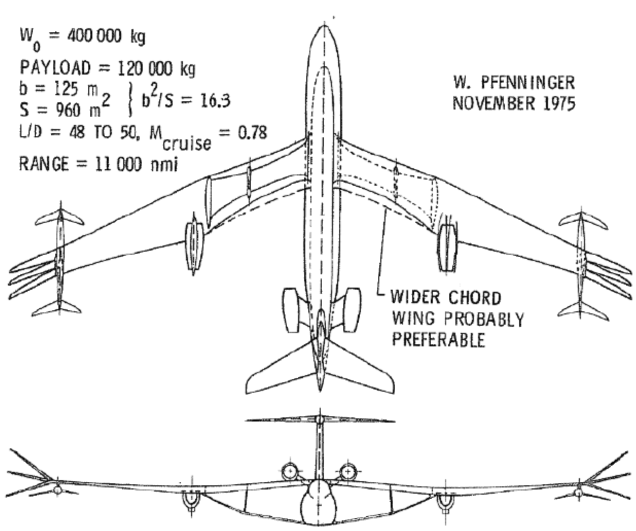


Figure 1.1: Pfenninger's 1970's Truss-Braced Wing Concept[2]

the TBW configuration utilizes additional members below the main wing to stiffen the wing structure. These members reduce the bending moment in the wing thus allowing both for a reduced t/c as well as reduced skin thickness. This allows the main wing spar and skin to become thinner and lighter with reduced chord and thus reduced Reynolds number. The reduced wing thickness results in decreased wave drag. This also allows the wing to unsweep, thereby reducing span-wise cross flow disturbances. The combined effect of decreased cross flow and the reduced chord Reynolds number result in increased laminar flow. The expansive inboard wing areas with laminar flow experience reduced skin friction drag. These benefits synergize to reduce wing structural weight, drag and fuel consumption. This is the main motivation of the TBW concept. The Strut-Braced Wing (SBW) configuration, the TBW without the vertical truss member, will also be studied.

In recent years at Virginia Tech, the TBW has been studied using a long-range Boeing 777-200ER-like mission. This consisted of a 7,730 nautical mile (nm) range with a cruise Mach number of 0.85 and 305 passengers. This study examines the benefits of the TBW for a Boeing 737-800NG medium range mission shown below[3] because the bulk of passenger miles and fuel consumption occur for such aircraft.

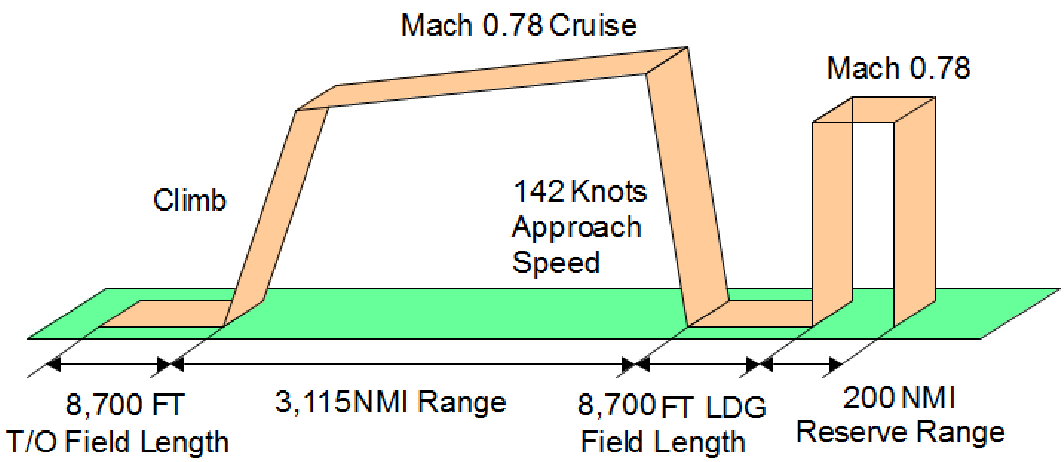


Figure 1.2: Boeing 737-800NG-like Mission Profile[3]

This means a cruise Mach number of 0.78, a range of 3,115 nm and 162 passengers. The maximum balanced field length of 8,700 feet and approach speed of 142 knots are used so that the aircraft is consistent with current Boeing 737-800NG performance. A reserve range of 200 nm is also added to ensure additional fuel is stored in case of a missed approach or an emergency detour to an alternate airport.

In addition to the medium range mission, other assumptions are made to accurately model Boeing 737-like performance. The wing structure is completely aluminum. The wing is the only part of the aircraft that changes during optimization so the tail areas and fuselage size and weight remain constant. All SBW and TBW configuration have a high wing. A T-tail is used for all braced wing configurations as well as the high-wing cantilever. The T-tail horizontal stabilizer is approximately the same size as a Boeing 737-800NG's with a Boeing 737-800 sized vertical stabilizer. A larger vertical stabilizer tip chord is used to accommodate the higher horizontal tail attachment point similar to the Boeing 717. A conventional tail is used on the low-wing cantilever with dimensions similar to the Boeing 737-800NG. The Boeing 737-800NG CFM 56-

7B engine is also assumed as the reference engine in the "rubber engine" model discussed in Chapter 2.

The motivation of the study is the application of the significant performance benefits of the TBW configuration to the medium range transonic transport such as the Boeing 737 or other comparable aircraft. The TBW concept takes advantage of many synergistic effects of aerodynamic and structural optimization in an effort to improve aircraft performance and efficiency. It also easily scales to any aircraft mission unlike comparable BWB designs. This allows seamless application of TBW ideas to a medium range aircraft such as the Boeing 737-800NG. Further, the Boeing 737 is the most successful transport in history with more sales than any other aircraft model[4]. The Boeing 737-800NG variant accounts for 3,696 of the 5,754 Boeing 737 orders since April 2011[5]. The July 2011 issue of Aerospace America shows that the Boeing 737-like, single aisle class will have approximately 50% of the total market deliveries as shown in Figure 1.3[6].

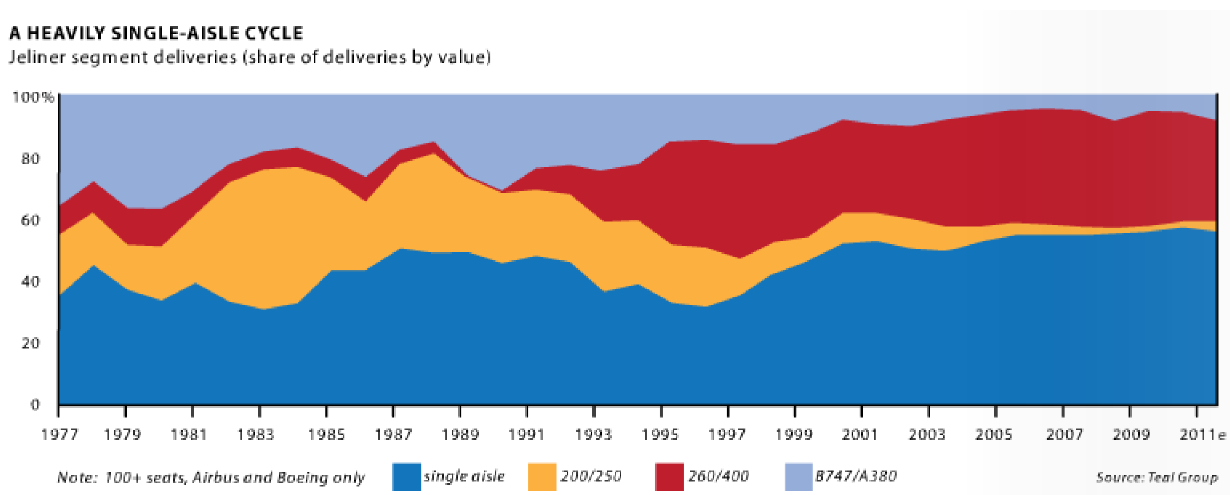


Figure 1.3: Jetliner Segment Deliveries[6]

The extensive use of the medium range transonic transport demonstrates the possible large scale impact of the performance gains of the TBW configuration.

Using the mission discussed above, Multidisciplinary Design Optimization (MDO) techniques are used to analyze the synergistic benefits of the SBW and TBW configurations for a medium-range, transonic aircraft when compared to conventional cantilever configurations. The study involves minimizing either the takeoff gross weight (TOGW) or the fuel weight for each configuration. Each configuration is also designed for "current" or 1990's technology and "advanced technology" aerodynamics. The 1990's technology configurations use aerodynamics similar to current aircraft. The advanced technology accounts for improved airfoil design with an improved Korn factor for reduced wave drag and aggressive laminar flow. Engine location and its impact on performance are also discussed. The following section discusses the MDO framework and the TBW problem formulation.

Chapter 2: Methodology

2.1 Framework

The multidisciplinary analysis of the SBW and TBW configurations requires the use of many different codes and software packages. Phoenix Integration's ModelCenter™ allows full integration of all internal codes and software packages into one environment. Figure 2.1 is a screenshot of the TBW formulation as an N^2 diagram in ModelCenter. The TBW framework used for these studies is adapted from that used for the long-range TBW studies at Virginia Tech[7]. A simple flowchart is given in Figure 2.2.

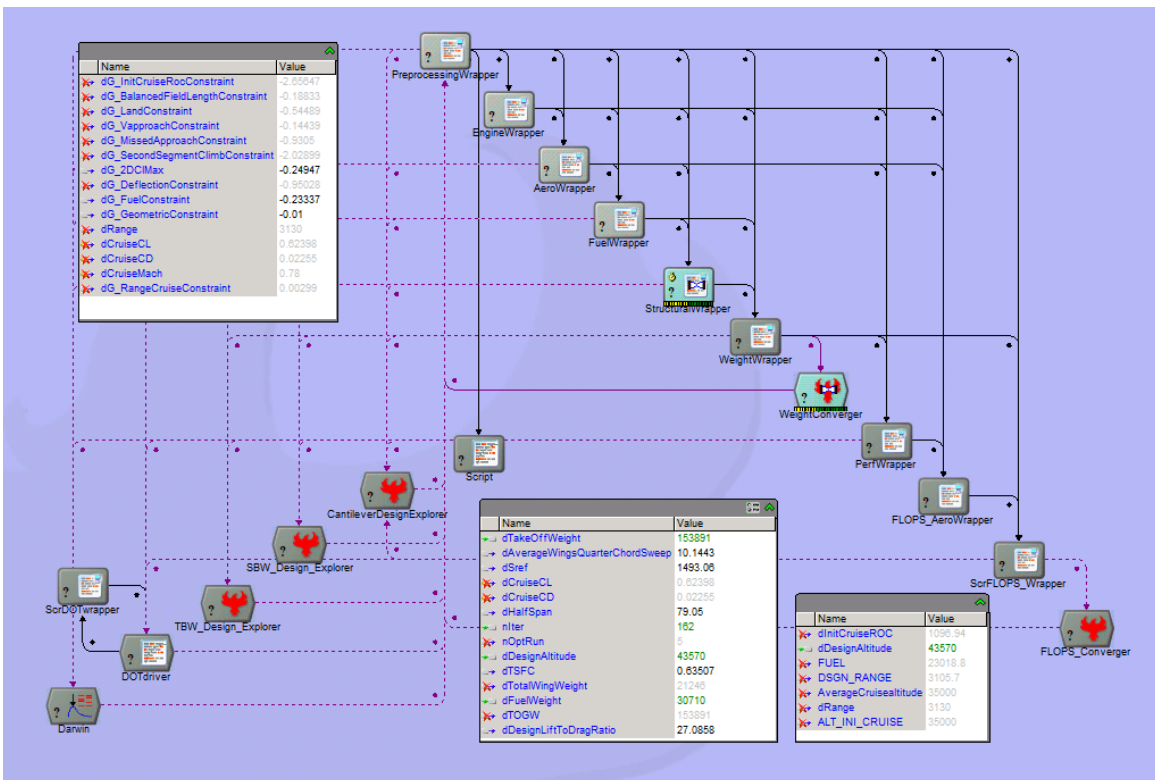


Figure 2.1: ModelCenter TBW N^2 diagram

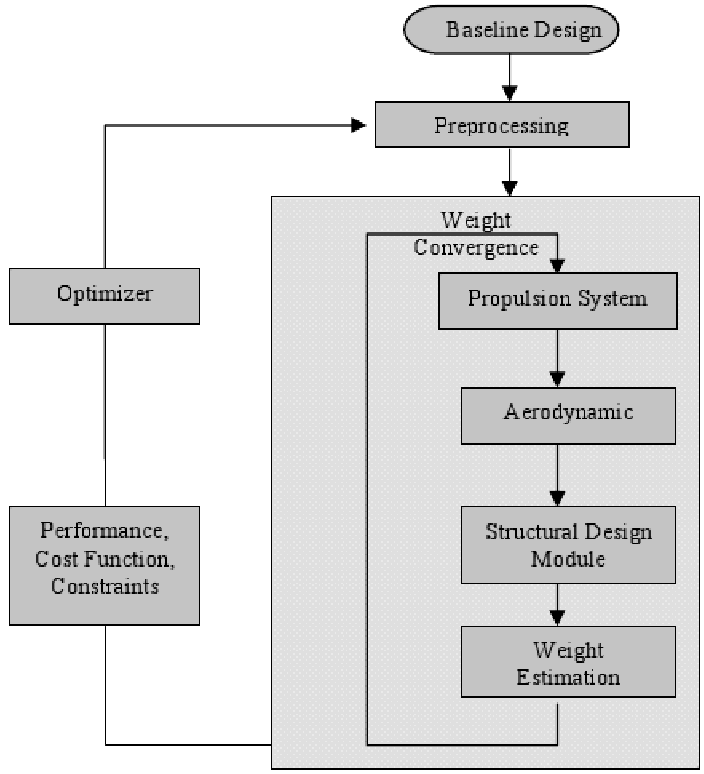


Figure 2.2: The Flow Of Calculations Within The ModelCenter N^2 Diagram

The ModelCenter interface consists of analysis nodes and optimization nodes. These are all connected via links which show the flow of information from one node to another. The analysis nodes include the preprocessing wrapper, engine wrapper, aerodynamics wrapper, fuel wrapper, structures wrapper, weight wrapper, and performance wrapper. The analysis nodes are referred to as wrappers because they are linked to C++ scripts which are connected to ModelCenter by a Python file called a Script wrapper. The optimization nodes include DOT, Design Explorer, and Darwin[8]. The analysis nodes are briefly discussed below. Additional details regarding the problem formulation within ModelCenter can be found in [8]. The optimization nodes are discussed later in this chapter.

The preprocessing wrapper mainly initializes analysis information including the aircraft geometry and other specifications required by the later analysis nodes. One of the primary tasks is to calculate the mission load cases. All of the aircraft configurations are designed with respect to seventeen load cases. The seventeen load cases shown below in Table 2.1 are representative of the aircraft mission, but the computational impact is small enough for the loads to be incorporated into the MDO architecture.

Table 2.1: Design Load Cases[7]

*Loading	Cases	Definition*				
No.	Alt[ft]	Mach	N-Aero	N-Inertia	%fuel	%Cargo
1	31000	0.78	2.5	2.5	100	100
2	31000	0.78	2.5	2.5	50	100
3	31000	0.78	-1	-1	100	100
4	31000	0.78	-1	-1	50	100
5	0	0.2	0	2	100	100
6	0	0.2			100	100
7	0	0.2			0	0
8	0	0.5			100	100
9	0	0.5			0	0
10	10000	0.531			100	100
11	10000	0.531			0	0
12	20000	0.668			100	100
13	20000	0.668			0	0
14	30000	0.78			100	100
15	30000	0.78			0	0
16	35000	0.78			100	100
17	35000	0.78			0	0

The first 5 load cases are the principal design cases. These loads tend to directly impact the wing structural design. All of the load cases are satisfied with a factor of safety of 1.5, thus the maximum load factor to satisfy is 3.75g and the minimum is -1.5g. The remaining twelve cases are gust loadings subject to FAR 25 structural load requirements.

The engine analysis consists of two parts: engine sizing and engine performance. The engine sizing uses a standard "rubber engine" model. The following equations are used to determine the weight, length and diameter of the engines during the analysis[9],

$$W_{engine} = W_{ref} \frac{T_{max,req}}{T_{ref}}$$

$$L_{nacelle} = L_{ref} \sqrt{\frac{T_{max,req}}{T_{ref}}}$$

$$D_{nacelle} = D_{ref} \sqrt{\frac{T_{max,req}}{T_{ref}}}$$

where W_{ref} is the weight of a reference engine, T_{ref} is the reference thrust, L_{ref} is the reference nacelle length, D_{ref} is the reference nacelle diameter, and $T_{max,req}$ is the minimum thrust the engines must produce to complete the mission. The CFM 56-7B24 is used as the reference engine for this study. The reference values used are included in Table 2.2.

Table 2.2: CFM 56-7B24 Engine Reference Values[10]

Specifications	CFM 56-7B24
Dry Weight (lb):	5,216
Nacelle Length (ft):	10.14
Nacelle Diameter (ft):	6.76

The engine performance part calculates the thrust specific fuel consumption (TSFC) and the thrust available at sea level and at cruise. The following equations shows how the TSFC is found[7],

$$TSFC_{SLS} = 2.472 \cdot 10^{-11} \cdot T_{\max,\mathrm{req}}{}^{2} - 4.851 \cdot 10^{-6} \cdot T_{\max,\mathrm{req}} + 0.5175$$

$$TSFC_{cr} = \left(TSFC_{SLS} + 0.4021 \cdot M_{cr}\right) \cdot \left(OAT_{cr} / OAT_{SL}\right)^{0.4707}$$

where $T_{max,req}$ is the maximum thrust required to complete the mission, SLS refers to static sea level, "cr" refers to the cruise condition, M_{cr} is the cruise Mach number, and *OAT* is the operating altitude temperature[7]. The thrust available is a function of the cruise Mach number and the density ratio, σ, shown below.

$$T_{\mathrm{available}} = T_{\max,\mathrm{req}} \cdot \left[0.60685 + 0.5344216 \cdot \left(0.9001142 - M_{cr}\right)^{2.7981}\right] \cdot \sigma^{0.8851778}$$

These performance values are used by the performance wrapper.

The aerodynamics wrapper performs an aerodynamic analysis using the updated aerodynamics analysis as discussed in [1]. The analysis starts with the lift coefficient values required to maintain steady, level flight at each load case calculated by the preprocessing wrapper. Then the analysis uses the discrete vortex method to find an initial optimum span-wise lift distribution that satisfies the lift coefficient constraint internally. The induced and wave drag are calculated and minimized iteratively as discussed in [1]. The wave drag calculation is based on a Korn factor that reflects the supercritical performance of the airfoil design. The resulting interference drag is then calculated. These together with the friction and form drag form the total drag which is used to calculate the L/D later used by the performance wrapper.

The fuel wrapper calculates the fuel loads. It uses the seventeen load cases from the preprocessing wrapper to find the fuel load distributions for each case. These loads are then sent to the structures wrapper along with the aerodynamic loads.

The structures wrapper uses the aerodynamic and fuel loads to calculate the minimum amount of material required. The structure is modeled as finite beam elements with the Euler buckling criteria applied to the truss and wing members with the strut span. The stiffness is calculated using a rectangular wing box with variable thickness upper, lower, and webs. The wing structural thicknesses are found using a fully-stressed design. This means that each member is designed to be fully stressed for one of the 17 static load cases based on the von Mises stress[7]. The final result is a structural wing weight which is sent to the weight wrapper.

The weight wrapper uses the weights calculated in the previous wrappers to determine the takeoff gross weight (TOGW) of the aircraft. The fuel weight, engine weight and structural wing weight come from the previous analyses. The systems weights and payload weights come from a FLOPS weight calculation[11]. The aircraft configurations with wing spans larger than 118ft have a wing fold at the 59.5 ft half span and include a penalty to account for the folding mechanism[7].

The performance wrapper takes the designed aircraft and calculates the performance parameters. The performance analysis calculates the approach velocity, balanced field length, initial cruise rate of climb, 2nd segment climb gradient, missed approach climb gradient, range and their constraints. The Breguet range equation is used to calculate the range as shown in [7]. The nature of the constraints will be discussed in the following section.

All of these nodes mentioned above complete the analysis of each configuration. As shown in Figure 2.2, the analysis is repeated until the TOGW is converged. Each analysis also calculates constraint values which are used in the outer optimizer loop. The optimization problem and the optimizer are discussed below.

2.2 The Optimization Problem

The optimization problem is to minimize or maximize some function with respect to some variables. The unique solution is a vector x in which the objective function is minimized or maximized. This x vector is an array of design variables. The general objective function is expressed as:

$$f(x^*) = min\, f(x)$$

assuming that x is within a given feasible domain and x^* is the optimum solution vector. However, the objective function must be properly constrained to avoid unrealistic solutions. The constraints come in the form of equalities and inequalities. The constraints can be written as:

$$h(x) = 0$$

$$g(x) \leq 0$$

where h is the equality constraint and g is the inequality constraint[12]. Throughout this study, only inequality constraints are used.

The design variables mentioned above are different for each aircraft configuration. Figure 2.4 shows a layout for the TBW with wing engines. All SBW and TBW configurations have a high wing.

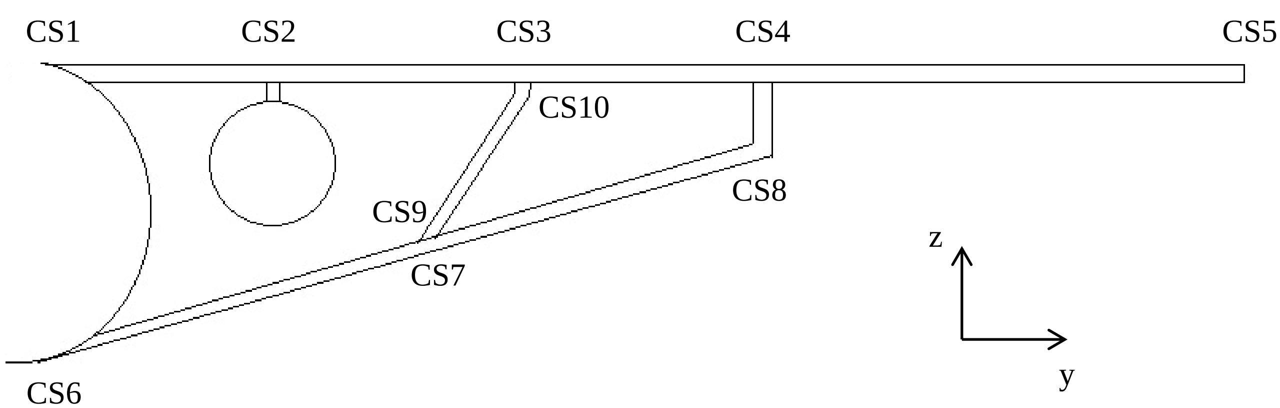


Figure 2.3: TBW Configuration with Wing Engines

The geometric design variables are defined at the wing cross sections and interpolated in-between, where CS1 is cross-section 1. The configuration consists of one jury between CS3 and CS7 and one strut between CS6 and CS8, so this is called the TBW with wing engines. The SBW with wing engines is similar but does not have the jury member. The member between CS4 and CS8 is a connector which is used to avoid a large interference drag penalty from the strut hitting the wing at a sharp angle. This member also helps to increase the moment of inertia of the wing cross-section to resist bending in the vertical plane. All design variables are interpolated at the engine locations. The thickness and thickness to chord ratios (t/c) are interpolated at the jury locations. This includes the engine spanwise location. Fixing the engine location for wing mounted engines allows the horizontal and vertical tail sizes to remain the same for each configuration to ensure there is enough rudder control authority to counter the yaw moment created if one engine fails. Table 2.3 below shows the distribution of geometric design variables for all of the cross-sections.

Table 2.3: Geometric Design Variables for the TBW with Wing Engines

	Design Variables
1	Cross Section 1 Chord
2	Cross Section 1 t/c
3	Cross Section 3 Y-coordinate
4	Cross Section 4 Chord
5	Cross Section 4 t/c
6	Cross Section 4 Y-coordinate
7	Cross Section 5 X-coordinate
8	Cross Section 5 Y-coordinate
9	Cross Section 5 Chord
10	Cross Section 5 t/c
11	Cross Section 6 X-coordinate
12	Cross Section 6 Chord
13	Cross Section 6 t/c
14	Cross Section 7 Y-coordinate
15	Cross Section 8 Z-coordinate
16	Cross Section 9 Chord
17	Cross Section 9 t/c

These design variables are representative of the TBW planform with wing engines however there are some assumptions that allow design variable linking to reduce the overall number of design variables. First, the wing is assumed to have constant quarter chord sweep. The upper surface of the wing is completely planar. The strut is assumed to be linear. There is also interpolation of design variables at engine and jury locations (except for span-wise location). These assumptions greatly reduce the number of design variables but also reduce the design space.

There are additional non-geometric design variables such as the design cruise altitude, the maximum thrust required and the fuel weight which are allowed to vary throughout the optimization. The maximum thrust required is the minimum amount of thrust the aircraft must produce to satisfy performance requirements. The fuel weight design variable is used because the fuel loads are required to calculate the TOGW.

There are eleven main constraints applied to all of the aircraft configurations. There are also side constraints or ranges on the design variables. These are used to ensure convergence to a solution. Table 2.4 lists all of the constraints used in each optimization problem.

Table 2.4: Constraints

	Constraints
1	Cruise Range Constraint
2	Initial Cruise Rate of Climb Constraint
3	2D Design Lift Coefficient Constraint
4	Fuel Capacity Constraint
5	Wing Tip Deflection Constraint
6	Second Segment Climb Constraint
7	Missed Approach Constraint
8	Approach Velocity Constraint
9	Balanced Field Length Constraint
10	Landing Constraint
11	Geometric Constraint

Each constraint makes sure that the current aircraft configuration during the optimization can satisfy the physical requirements of the mission. Each constraint is briefly discussed below.

1.) The Cruise Range Constraint checks that the range of the current aircraft is greater than the required range of 3,115 nm.

2.) The Initial Cruise Rate of Climb Constraint ensures that there is sufficient thrust at the cruise altitude.

3.) The Two Dimensional Lift Coefficient Constraint checks that the current lift coefficient is physically possible. The maximum two-dimensional lift coefficient allowed is 0.8.

4.) The Fuel Capacity Constraint ensures that the fuel required to complete the mission can be stored on the aircraft. For this study, all fuel is stored in the wing and strut.

5.) The Wing Tip Deflection constraint does not allow the wing tip to deflect past the bottom of the fuselage.

6.) The Second Segment Climb, Missed Approach and Landing Constraints are used to check that the aircraft satisfies FAR requirements.

8.) The Balanced Field Length Constraint validates that the calculated balanced field length is less than the required distance of 8,700 feet.

9.) The Geometric Constraint is used to penalize configurations that are not possible or not supported by the current analysis methods.

2.3 Optimization Techniques

Now that the optimization problem has been formulated, it is necessary to understand the nature of the problem in order to find the best aircraft configuration. Within ModelCenter, there are numerous analysis nodes or optimizers available, each with different advantages and disadvantages. Three different techniques were used in an effort to efficiently find the best solution. These methods include DOT, Design Explorer, and Darwin. Design Optimization Tools (DOT) by Vanderplatt R&D uses a suite of gradient based optimization algorithms such as MFD (modified feasible directions), SLP (sequential linear programming) and SQP (sequential quadratic programming). MFD was used throughout this study. Design Explorer is a hybrid technique developed by Boeing to search complex design spaces. This method uses a stochastic Latin Hypercube sampling of the design space and then chooses the best design points to start SQP. The final method, Darwin, is a genetic algorithm which uses large populations of points to search the design space. Each of these methods is quite different and some work better on different types of problems, so it is important to explore the performance of each.

DOT is a gradient based optimization routine. This means it requires the gradients of the objective function which are usually supplied analytically or by finite difference. Since gradients are used, the objective function must be smooth. DOT also requires a starting point, so for the modal objectives of this study the optimum is dependent on the first design point. Thus, this method is good for low order functions however the optimizer can have difficulty searching higher order, nonlinear objective functions or constraints with many minima. Therefore, optimizing with complex functions can delay or even prevent convergence, and one can find suboptimal solutions. For simple, convex, unconstrained design problems, DOT is independent of the starting point so it can find the same optimum from any location in the design space. For highly nonlinear problems, there are many minima that satisfy the gradient based convergence criteria, so the optimizer may find some different minima depending on the starting location. This minimum is a local optimum and, unless the whole design space is searched, it may or may not be the global optimum solution. This is a significant disadvantage of DOT.

Design Explorer is a hybrid optimization technique included in ModelCenter. Developed in industry by Boeing, this technique was designed to tackle some of the difficult problems related to global optimization[5]. It samples the entire design space using Latin Hypercube Sampling (LHS). These design points are used to start local gradient based searches using SQP. These sample points give the optimizer a rough feel of the design space making it easier to find a global solution however with extremely large design spaces Design Explorer still has trouble finding the global optimum.

Darwin is a genetic algorithm included in ModelCenter. Genetic algorithms are based on sampling the design space with populations of design points. These methods do not use gradients, so they are good for discontinuous or highly nonlinear objectives. The main idea is to generate a population of design points and to select the best objectives for each population to influence the next generation. The objective used to quantify the fitness of each design point is modified to account for the constraint values. This merit function thus penalizes design points with violated constraints as less fit when compared to a feasible design. The many details that go into Darwin's analysis can be found in Modelcenter[8]. In general, the genetic algorithm is independent of the starting point, since populations are generated randomly. It also does not require derivative information so does not fall into suboptimal minima, but the run time is significantly longer than Design Explorer or DOT.

Each of the methods previous mentioned greatly vary in computational time. The gradient based methods like DOT are very quick, running in as little as 7 hours for a TBW case on a six-core machine. Design Explorer takes considerably longer on the order of 1-2 days. Darwin, the genetic algorithm, runs on the order of 1 to 3 days on a comparable computer. The size of the problem is determined by the number of design variables and constraints. But all of the optimizations require the same number of constraints. Thus, the runtimes for the TBW optimizations take more time than the SBW and Cantilever configurations due to the increased number of geometric design variables.

Throughout this study, it was determined that the genetic algorithm is the best way to get the global optimum. This means that each optimization takes on the order of 3-4 days on a six-processor computer. However, Darwin allows simple application of the multiple objective genetic algorithm (MOGA). MOGA has been used create two and three dimensional Pareto fronts (non-dominated points) and can be used to find designs that compromise between competing objective functions.

The final method used here is a hybrid technique that uses Darwin and DOT, a stochastic method and a gradient based method. Darwin is run until a sufficient number of generations without improvement are achieved. Then, DOT is used to verify that Darwin has found a minimum. Darwin does not use gradients so it has no way of checking the convergence besides the improvement in each design generation. DOT uses the Kuhn-Tucker first order necessary conditions for constrained optimization to monitor convergence[12]. Since Darwin is already close to the presumably global optimum, DOT converges quickly and verifies that a minimum was found.

Chapter 3: Results

The objective of this study is to investigate the performance benefits of the SBW and TBW configurations for a Boeing 737-800NG-like mission. This involves first modeling a baseline 737-800NG configuration for validation with the current analysis architecture. Once validation was complete, six different configurations were studied. These include the low-wing, cantilever with wing engines, the high-wing cantilever with wing engines, the SBW and TBW with fuselage engines, and the SBW and TBW with wing engines. These models are optimized using the hybrid optimization technique using Darwin and DOT with respect to different cost functions. The primary cost functions for minimization include the TOGW and the fuel weight. Each configuration is minimized with either a baseline 1990's technology aerodynamics or an advanced technology with an improved Korn factor and aggressive laminar flow.

3.1 Analysis Validation

The validation required modeling a current Boeing 737-800NG. The current 737-800NG information was collected to create a graphical model. Figure 3.1 is an orthographic and isometric view of the Baseline 737-800NG model.

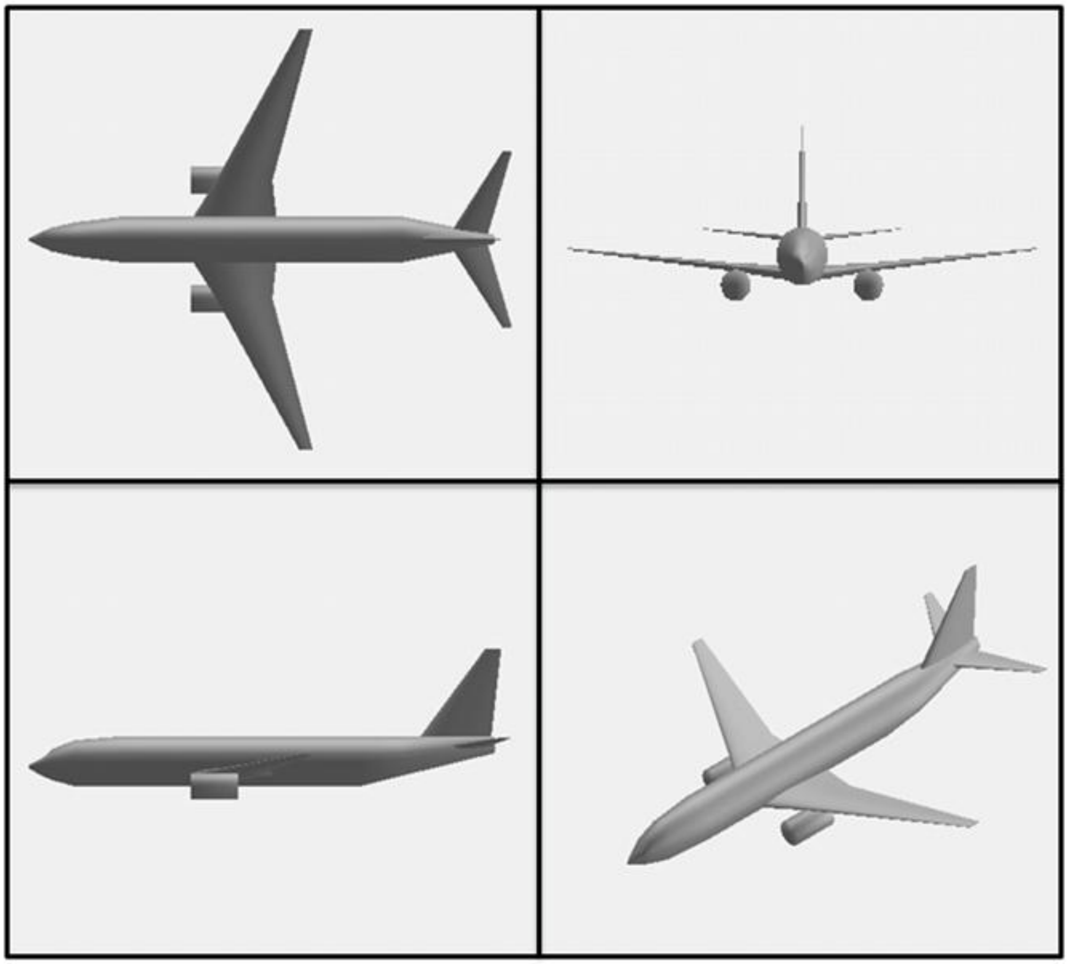


Figure 3.1: Baseline Boeing 737-800NG Model

The aircraft was modeled to be within inches of the reference Boeing 737-800NG dimensions. A full analysis was completed to estimate the TOGW, empty weight, and wing structural weight. The performance and geometric characteristics of this model are displayed in the Table 3.1.

Table 3.1: Baseline Boeing 737-800NG Model Characteristics

Characteristics	1990's Technology Baseline Boeing 737-800NG Model: 189 passengers (Analysis)
TOGW(lb):	175,379
Fuel Weight (lb):	46,000
Payload Weight (lb):	44,909
Wing Weight (lb):	17,057
Structural Wing Bending Weight (lb):	6,635
Design L/D:	17.9
Maximum Thrust Required (lb):	27,300
Wing/Strut Half-span(ft):	56.29
Wing ¼ chord sweep (deg):	25.08
Design Altitude (ft):	35,000
Wing Area (ft):	1,413
Range (nm):	3,069
Centerline Chord (ft):	26.73
Chord at Engine Location (ft)	15.03
Tip Chord (ft):	3.38
Root t/c:	0.14
t/c at Engine Location (ft):	0.13
Tip t/c :	0.115

The predicted TOGW is 175,379 pounds compared to 174,200 pounds TOGW reported for the Boeing 737-800NG with a maximum single class payload of 189 passengers. The resulting error is well under 1%. For the purposes of this study, another Baseline Boeing 737-800NG simulation was created with a reduced passenger load to better compare with current 737-800 performance information. Table 3.2 below compares both configurations with a single class of 189 passengers and two classes of 162 passengers.

Table 3.2: Baseline Boeing 737-800NG Model Comparison

Characteristics	1990's Technology Baseline Boeing 737-800NG Model: 189 passengers (Analysis)	1990's Technology Baseline Boeing 737-800NG Model: 162 passengers (Analysis)
TOGW(lb):	175,379	168,683
Fuel Weight (lb):	46,000	46,000
Payload Weight (lb):	44,909	39,145
Wing Weight (lb):	17,057	16,571
Structural Wing Bending Weight (lb):	6,635	6,370
Design L/D:	17.9	17.9
Maximum Thrust Required (lb):	27,300	27,300
Wing/Strut Half-span(ft):	56.29	56.29
Wing ¼ chord sweep (deg):	25.08	25.08
Design Altitude (ft):	35,000	35,000
Wing Area (ft):	1,413	1,413
Range (nm):	3,069	3,263
Centerline Chord (ft):	26.73	26.73
Chord at Engine Location (ft)	15.03	15.03
Tip Chord (ft):	3.38	3.575
Root t/c:	0.14	0.14
t/c at Engine Location (ft):	0.13	0.13
Tip t/c :	0.115	0.115

The table above shows the effect of varying the passenger load on the aircraft weight based on a single analysis. The difference in payload is 5,764 pounds. The difference in the TOGW is 6,696 pounds. Even though the aircraft geometry is the same, the larger passenger load case results in an increase in the lift required in each load condition. This causes the structure to be heavier to withstand the higher bending stress. Note that even though the fuel weights are the same, the 162 passenger version has 7% more range.

3.1.1 Wing Weight Validation

The wing weight calculated in the analysis is compared to the wing weight curve created by Shevell[13] shown in Figure 3.2.

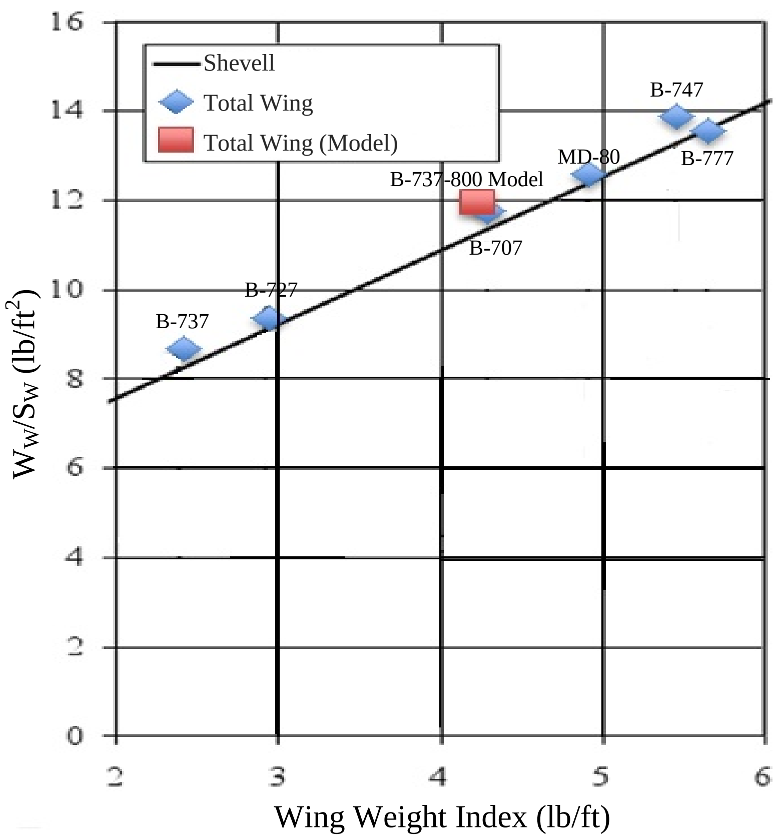


Figure 3.2: Wing Weight Comparison[13][14]

Figure 3.2 above shows the correlation of many aircraft with the Shevell curve for the Wing weight/ Wing Area ratio versus the Shevell Wing Weight Index. The wing weight index is given by the following equation,

$$\text{Wing Weight Index} = \frac{N_{ULT} \cdot b^3 \cdot \sqrt{TOGW \cdot ZFW} \cdot (1 + 2 \cdot \lambda)}{t/c_{avg} \cdot \cos^2 \Lambda_{\text{Elastic Axis}} \cdot S_W{}^2 \cdot (1 + \lambda)} \cdot 10^{-6} \quad lb/\ ft$$

where N_{ULT} is the maximum load factor, b is the wing span, *ZFW* is the zero fuel weight, λ is the wing taper ratio, $\Lambda_{elastic}$ is the wing sweep along the elastic axis, and S_W is the wing area[13]. The Boeing 737-800 Model analysis correlates well with the Shevell curve and the other aircraft. The other aircraft component weights are calculated using NASA's FLOPS weight estimation. Since only the wing structure varies during the optimization, this is a good validation of the analysis accuracy.

3.2 The effect of storing fuel in the strut

In the recent years, the TBW studies at Virginia Tech led to the use of larger struts for the Boeing 777-200ER-like mission. These larger struts not only contribute to the structural rigidity of the wing structure, but they also carry lift. For the "777-like" mission, fuel tanks are available in the wings and fuselage, but the 737-800 only stores fuel in the wings. This caused many of the wing planforms to grow to accommodate the fuel weight required to complete the mission. Below are results of a study comparing the SBW with and without the option of fuel stored in the strut.

Table 3.3: SBW with and without Strut Fuel Storage Characteristics

Characteristics	**1990's Technology Optimized SBW with Fuselage Engines: Minimum TOGW**	**1990's Technology Optimized SBW with Fuselage Engines Without a Strut Fuel Tank: Minimum TOGW**
TOGW(lb):	151,600	153,700
Fuel Weight (lb):	31,300	29,900
Wing Weight (lb):	15,200	19,200
Structural Wing Bending Weight (lb):	6,500	9,000
Design L/D:	25.9	28.4
Cruise C_D	0.027	0.021
Maximum Thrust Required (lb):	22,700	19,900
Wing/Strut Half-span(ft):	70.2/38.2	80.1/41.9
Wing ¼ chord sweep (deg):	15.2	15.5
Design Altitude (ft):	41,710	44,300
Wing Area (ft):	1,266	1,640
Root Chord (ft):	10.72	11.685
Strut Junction Wing Chord (ft):	10.66	12.99
Strut Chord (ft):	9.88	10.48
Tip Chord (ft):	3.38	2.88
Root t/c:	0.0757	0.0656
Strut Junction Wing t/c:	0.0759	0.0870
Strut t/c:	0.1042	0.0927
Tip t/c :	0.0675	0.0732

SBW with Strut Fuel Tanks SBW without Strut Fuel Tanks

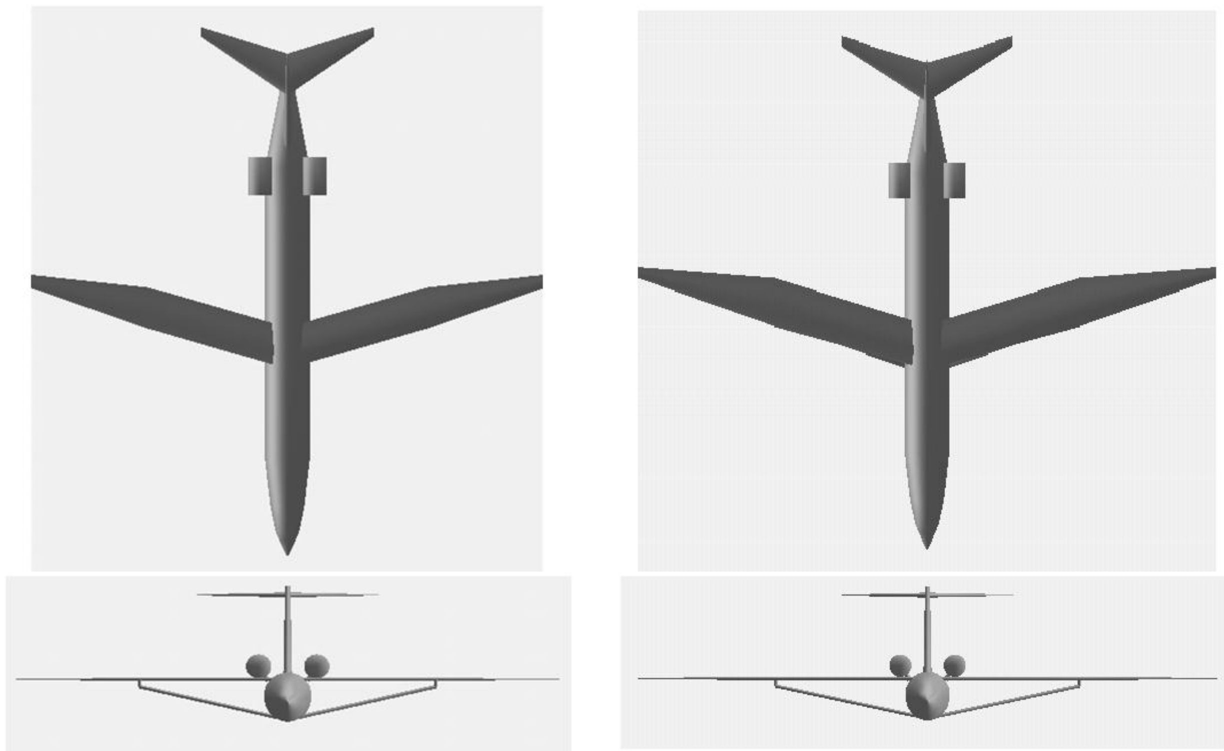


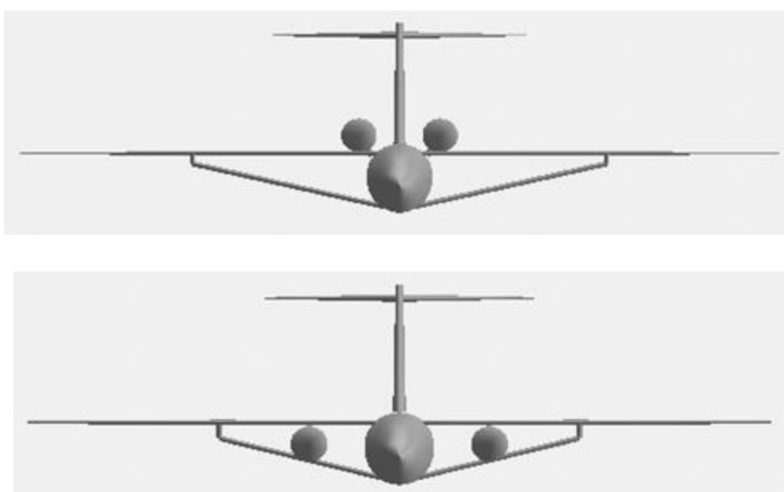
Figure 3.3: SBW configurations with Strut Fuel and SBW without Strut Fuel

Table 3.3 and Figure 3.3 above compare the SBW with and without fuel stored within the strut. The SBW with fuel stored in the strut has a TOGW about 2,000 pounds less than the other. It is important to note that the SBW with no strut tank ends up with an active fuel constraint along with the balanced field length and cruise range constraints which are usually active for these minimum weight cases. This active fuel constraint means that the wing grew to accommodate the required fuel. This usually happens for these strut-braced wing concepts due to their thin wings. In some ways, this SBW without fuel in the strut is an improvement, since fuel consumption is less due to the reduced Cruise C_D. This smaller C_D is a result of a higher cruise altitude and thinner wings. The final result is that the SBW with fuel in the strut is lighter than the comparable wing fuel configuration. Thus, configurations of the following studies store fuel in the wing and strut.

3.3 Engine Location

The engine location is extremely important to consider when designing an aircraft. Both the engine thrust and weight impact the feasible engine locations. This study involves comparing the effects of engine location choice on the optimized aircraft planforms. The engines are attached to the fuselage in one configuration and the engines hang from the wings in the other. Both of these configurations have the same tail. So the only thing changing is the engine location. Figure 3.4 shows the resulting SBW in both cases optimized for minimum TOGW.

a) Front View



b) Top View

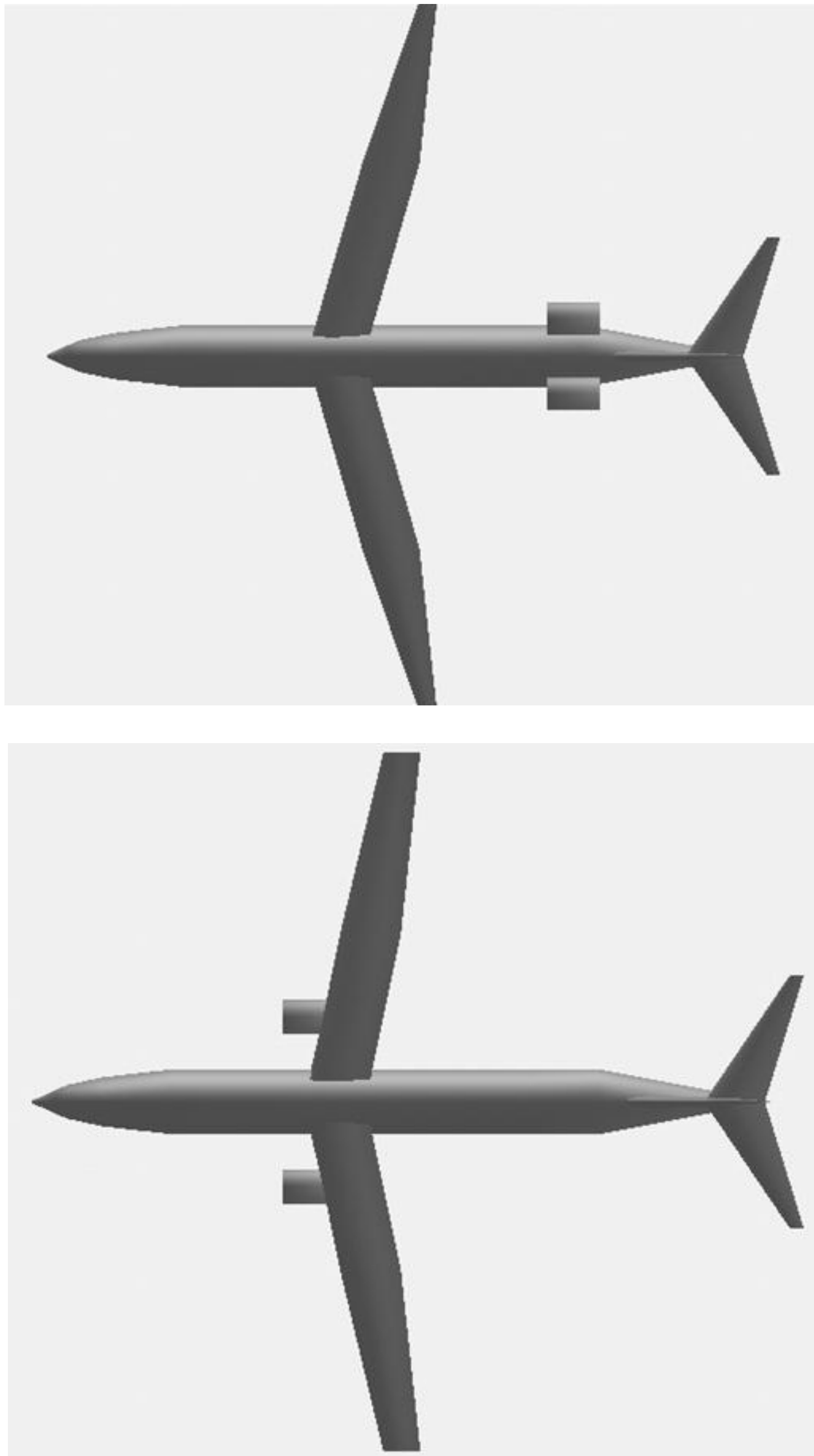


Figure 3.4: SBW with Fuselage Engines and SBW with Wing Engines

Optimized for minimum TOGW

These configurations are quite similar but the TOGW is lower for the SBW with wing engines. Table 3.4 shows the basic characteristics of both SBW configurations.

Table 3.4: Optimized SBW with Fuselage Engines and SBW with Wing Engines Characteristics

Characteristics	**1990's Technology Optimized SBW with Fuselage Engines: Minimum TOGW**	**1990's Technology Optimized SBW with Wing Engines: Minimum TOGW**
TOGW(lb):	151,600	148,400
Fuel Weight (lb):	31,300	31,500
Wing Weight (lb):	15,200	13,800
Design L/D:	26	25
Maximum Thrust Required(lb):	22,700	22,400
Wing Half-span(ft):	70.2	65.3
¼ chord sweep (deg):	15.2	11.0
Design Altitude (ft):	41,700	43,700

The table shows that the SBW with wing engines has a total wing weight nearly 10% less than its counterpart. The SBW with fuselage engines has a minimum TOGW of 151,640 pounds versus the SBW with wing engines minimum TOGW of 148,352 pounds. This weight difference is primarily due to the reduction in wing weight, but the SBW with wing engines has a lower wing sweep and wing span also contributing to the overall TOGW reduction. The wing weight reduction mainly comes from the wing engines. The engines help to counter the large aerodynamic forces generated by the upper wing. Similar to the fuel loading effect mentioned earlier, the engine weight helps to alleviate some of the load due to the lift.

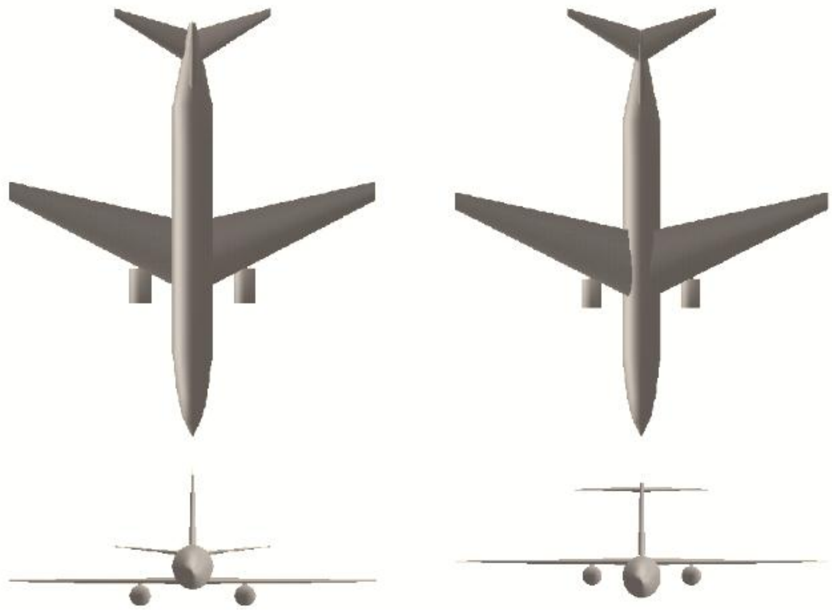
Besides the structural benefits of wing engines, there are other things to consider that often lead aircraft designers to place engines on the wings. Fuselage engines are located towards the rear of the fuselage causing the aircraft center of gravity to shift rearward when compared to configurations with wing mounted engines. This causes the aircraft to become less longitudinally stable. Fuselage engines also tend to be next to the cabin increasing cabin noise. There are also performance losses due to inlet flow distortions from turbulent flow generated by the wing. Alternatively, wing engines are forward on the wing causing the center of gravity to shift forward, but in high angles of attack the engines tend to interrupt flow approaching the wing. This is usually alleviated by using large vortex generators on the engine nacelles. Throughout this study, the configurations with wing engines tend to have lower TOGW, but this is not always helpful when designing for the minimum fuel case. This will be discussed in the following sections.

3.4 Minimizing TOGW

The minimum TOGW objective is fully explored in this section. Consisting of the fuel weight, engine weight, wing weight and other fixed structural and payload weights, the minimum TOGW case gives an overall reduction in weight. It is important to note that only the wing weight, fuel weight and engine weight are free to vary. Thus, most of the weight improvement is due to the reduction in wing weight or fuel consumption. The minimum TOGW objective function tends to be more difficult to optimize when compared to minimizing fuel weight. The following includes a comparison of all of the aircraft configurations for minimum TOGW with both 1990's and advanced technology.

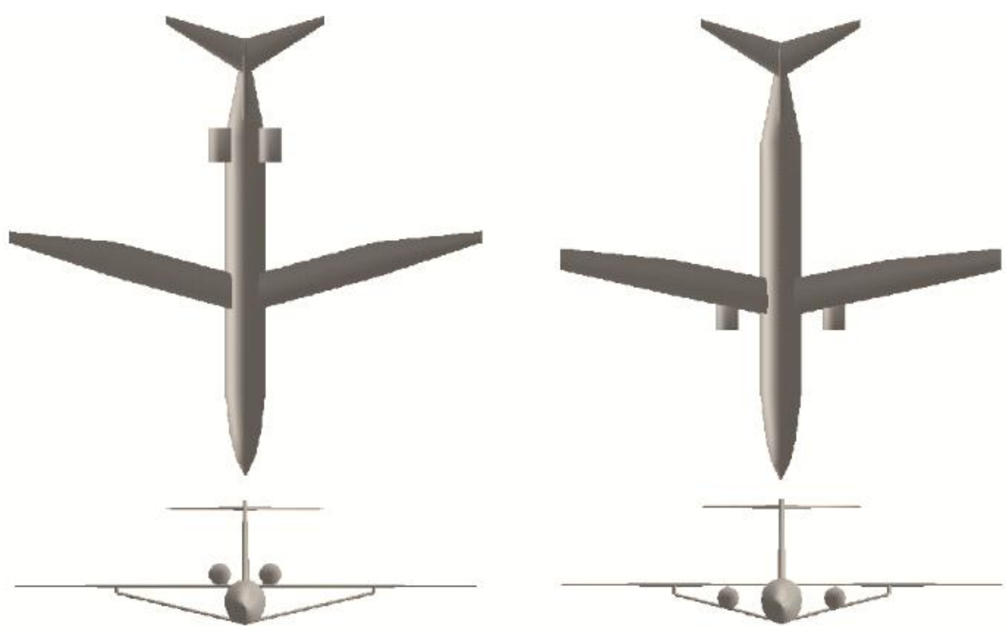
Due to the number of designs, the presentation is split by technology level. The first designs discussed are the 1990's technology configurations. All of the 1990's technology configurations assume a Korn factor of 0.9 and no aggressive laminar flow. Figure 3.5 shows each of the 1990's technology minimum TOGW aircraft configurations.

a) Cantilever Configurations



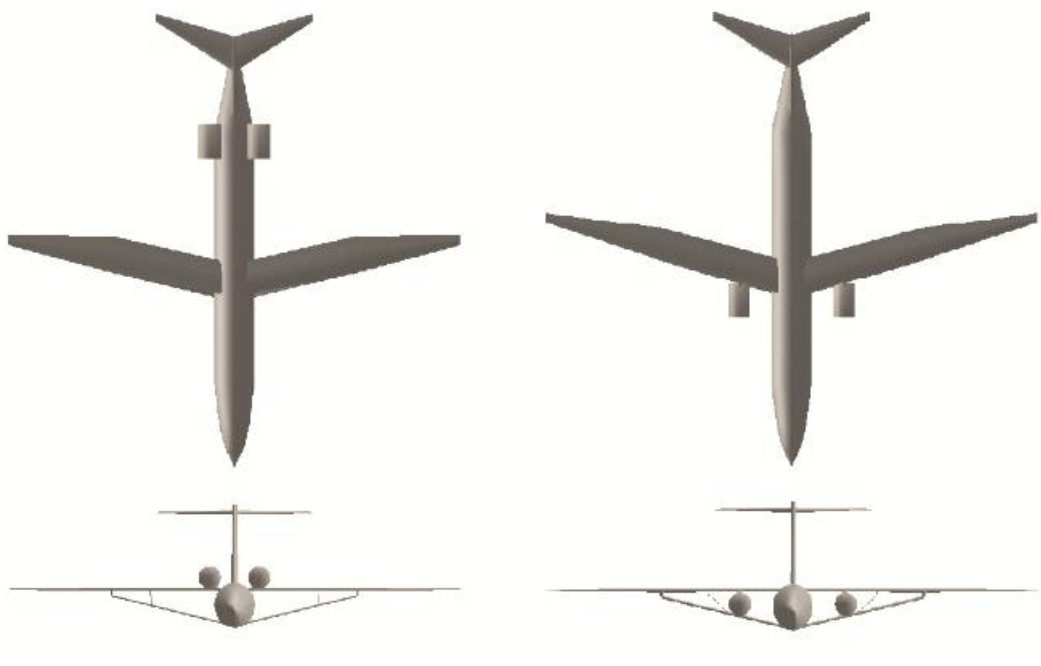
Low-Wing, Conventional tail High-Wing, T-tail

b) SBW Configurations



Fuselage Engines Wing Engines

c) TBW Configurations



Fuselage Engines Wing Engines

Figure 3.5(a-c): 1990's Technology Minimum TOGW Optimized Configurations

Table 3.5: 1990's Technology Minimum TOGW Optimized Configurations Characteristics

Characteristics	Low Wing Cantilever	High Wing Cantilever	SBW with Fuselage Engines	SBW with Wing Engines	TBW with Fuselage Engines	TBW with Wing Engines
TOGW(lb):	**159,400**	**160,700**	**151,600**	**148,400**	**154,300**	**149,000**
Fuel Weight (lb):	38,300	37,400	31,300	31,500	33,100	31,600
Wing Weight (lb):	18,000	20,500	15,300	13,800	14,900	14,400
Structural Wing Bending Weight (lb):	7,590	9,550	6,500	5,200	6,400	6,250
Design L/D:	20.9	22.1	25.9	25.0	22.9	24.8
Maximum Thrust Required (lb):	21,900	20,510	22,690	22,430	24,400	22,760
Wing/Strut Half-span(ft):	55.4	59.5	70.2	65.3	68.0/37.0	73.6/39.0
Wing ¼ chord sweep (deg):	23.9	23.3	15.2	11.0	11.4	15.3
Design Altitude (ft):	38,200	38,000	41,710	43,680	42,130	41,420
Wing Area (ft):	1,540	1,660	1,270	1,260	1,220	1,225
Root Chord (ft):	22.09	22.4	10.72	10.62	9.87	10.54
Jury Chord (ft):	-	-	-	-	3.278	3.234
Strut Junction Wing Chord (ft):	-	-	10.66	10.75	11.28	9.73
Strut Chord (ft):	-	-	9.88	9.69	11.07	10.09
Tip Chord (ft):	5.68	5.55	3.38	6.54	3.15	2.81
Root t/c:	0.099	0.104	0.0757	0.0678	0.0985	0.0518
Jury t/c :	-	-	-	-	0.0626	0.0753
Strut Junction Wing t/c:	-	-	0.0759	0.0935	0.0932	0.0927
Strut t/c:	-	-	0.1042	0.102	0.0583	0.0857
Tip t/c :	0.094	0.085	0.0675	0.0683	0.0684	0.0857

Table 3.5 above shows the performance and geometric characteristics of each of the configurations shown in Figure 3.5.

First, the cantilever configurations are discussed. Both the high-wing and low-wing configurations have a similar TOGW. But, there are some different results in terms of the weight breakdown. The most noticeable difference is the wing weight. The structural wing weight of the high-wing cantilever is about 2,000 greater than the low-wing arrangement. It seems that the higher span and greater L/D of the High-wing case result in greater aerodynamic loads. This causes the wing thickness to increase. However, both configurations are still similar based on current analyses.

The optimized SBW with fuselage engines and the SBW with wing engines are significantly lighter than the comparable optimized cantilever configurations. These configurations not only have a lower TOGW, but they also have much lower fuel weights when compared to the optimized cantilevers and the Baseline. There are some noticeable differences between the SBW and cantilever aircraft characteristics. First, the SBW spans and wing areas are larger. This results in higher L/Ds for the SBW configurations due to decreased drag. Second, the load capacity of the strut helps to reduce the wing bending moment resulting in a lower wing weight. These effects combine to reduce the TOGW and increase aircraft performance.

The optimized TBW with fuselage engines and the TBW with wing engines are also lighter than the comparable cantilever configurations. However, they are not any better than the SBW configurations in terms of TOGW. There appears to be little advantage to the additional jury member (TBW versus SBW) in reducing the TOGW, which was not the case for the 777-like studies.

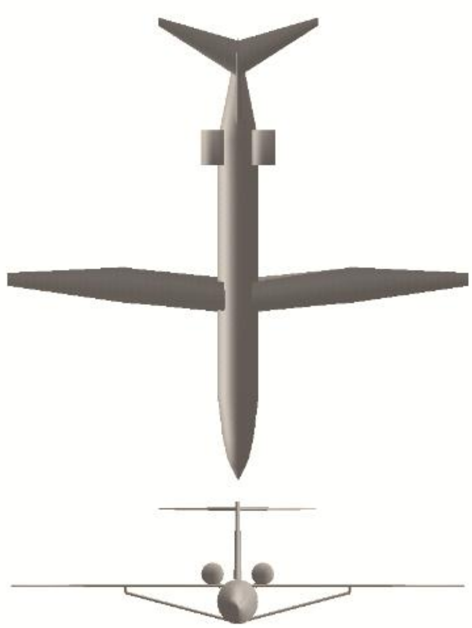
The six configurations are also optimized for minimum TOGW with advanced technology. Advanced technology refers to enhanced aerodynamics consisting of a higher Korn factor of 0.95 and aggressive laminar flow[1]. The advanced technology configurations tend to have lower drag and sweep. The reduced wing sweep results in lower wing weights. The following figures show the advanced technology minimum TOGW configurations.

a) Cantilever Configurations

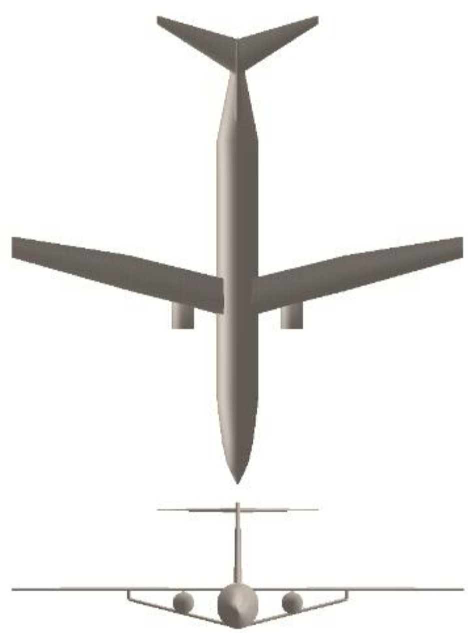
Low-Wing, Conventional tail

High-Wing, T-tail

b) SBW Configurations

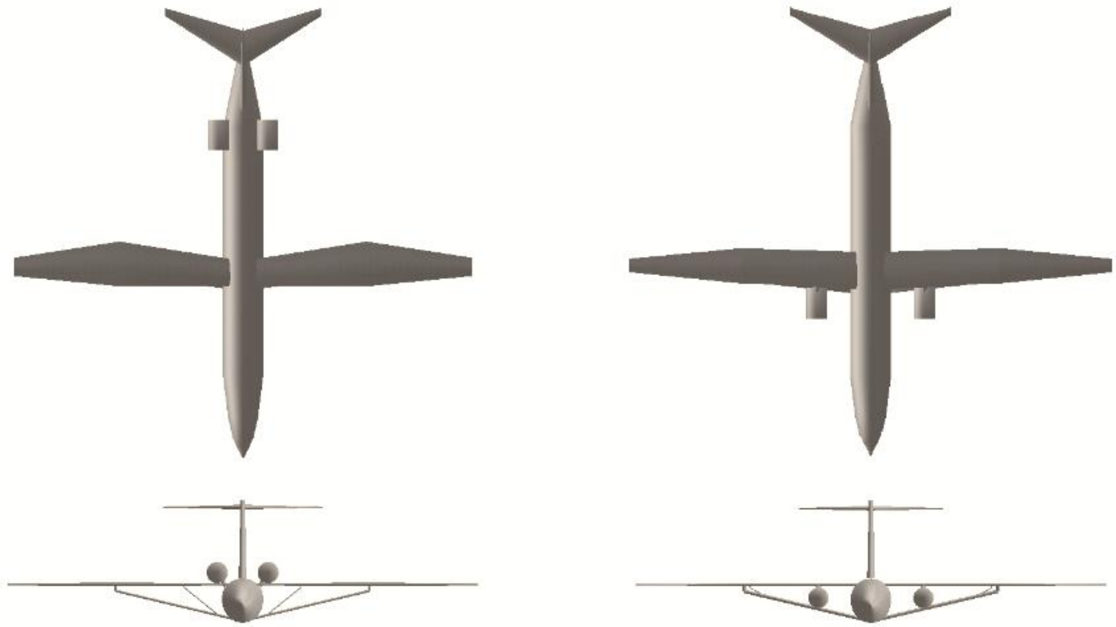


Fuselage Engines



Wing Engines

c) TBW Configurations



Fuselage Engines | Wing Engines

Figure 3.6(a-c): Advanced Technology Minimum TOGW Optimized Configurations

Table 3.6: Advanced Technology Minimum TOGW Optimized Configurations

Characteristics	Low Wing Cantilever	High Wing Cantilever	SBW with Fuselage Engines	SBW with Wing Engines	TBW with Fuselage Engines	TBW with Wing Engines
TOGW(lb):	**149,300**	**151,600**	**146,700**	**142,900**	**149,900**	**143,900**
Fuel Weight (lb):	30,700	31,900	28,200	28,100	30,500	28,200
Wing Weight (lb):	17,400	16,800	13,300	12,900	15,100	14,100
Structural Wing Bending Weight (lb):	7,400	7,300	5,200	4,900	5,600	5,400
Design L/D:	26.4	25.2	28.4	27.9	26.7	28.2
Cruise C_D:	0.019	0.022	0.025	0.024	0.024	0.021
Maximum Thrust Required (lb):	18,900	21,600	24,100	21,200	20,800	20,100
Wing/Strut Half-span(ft):	61.1	58.4	67.9/33.5	65.7/31.7	69.4/37.4	71.1/38.2
Wing ¼ chord sweep (deg):	2.9	5.9	5.5	9.9	1.9	3.1
Design Altitude (ft):	39,500	38,300	40,240	41,040	42,490	39,970
Wing Area (ft):	1,520	1,360	1,120	1,220	1,400	1,330
Root Chord (ft):	21.84	17.89	8.11	10.51	7.48	11.73
Jury Chord (ft):	-	-	-	-	4.08	4.23
Strut Junction Wing Chord (ft):	-	-	10.53	10.34	13.62	10.57
Strut Chord (ft):	-	-	10.23	9.60	6.68	9.74
Tip Chord (ft):	3.08	5.44	3.83	6.18	5.57	3.88
Root t/c:	0.115	0.127	0.097	0.503	0.082	0.069
Jury t/c :	-	-	-	-	0.094	0.089
Strut Junction Wing t/c:	-	-	0.097	0.096	0.093	0.10
Strut t/c:	-	-	0.094	0.107	0.118	0.116
Tip t/c :	0.105	0.087	0.083	0.114	0.115	0.088

The advanced technology minimum TOGW configurations result in further reductions in the TOGW compared to the 1990's optimizations. One of the most significant changes is the reduced sweep. This unsweeping is mostly attributed to the increased Korn factor. This increased aerodynamic performance also allows larger wing thicknesses with lower drag penalties. Note that the TBW with fuselage mounted engines features a decreasing chord towards the root and a thicker wing at the wing-strut junction as suggested by Pfenninger in Figure 1.1. Below is a discussion of the results for each configuration.

The cantilever configurations have a TOGW around 150,000 pounds. The wings are drastically upswept with quarter chord sweeps between 2-6 degrees even though the wings have a higher root t/c than the 1990's technology configurations. The wing weight has decreased due to the unsweeping, but not significantly due to the increase in wing span. The results show that the low wing cantilever is approximately equivalent to the TBW TOGW. This is an unexpected result of the TBW's larger drag coefficient. In these results, the TBW is generating a large fraction of the lift from the strut. Overall, the cantilever configurations showed greater sensitivity to aerodynamic technology than comparable SBW and TBW configurations, resulting in greater performance gains when compared to the 1990's technology configurations.

The SBW configurations appear to be the best configurations for obtaining minimum TOGW. Both SBW configurations have a lower TOGW than the comparable TBW configurations and the cantilever designs. However, within the fidelity of this analysis, the SBW and TBW configuration are approximately equivalent in performance. The SBW improvement in performance due to advanced aerodynamics is smaller than for the comparable cantilevers, but still results in a more efficient aircraft.

The TBW configurations experience relative performance gains similar to the SBW configurations. Relative to the 1990's technology, advanced aerodynamics results in a decrease of about 6,000 pounds in the TOGW. This is primarily due to the reduction in fuel consumption. In terms of the performance of each TBW, there is a large difference in performance of the wing engine versus fuselage engine configurations. The fuselage engine TBW results in a higher wing weight as predicted previously. However, the drag is also larger due to the increased wing thicknesses compared to the TBW with wing engines. The jury members do not appear to significantly improve the SBW's performance. In fact, the TBW with wing engines has a jury nearly parallel to the strut near the strut wing junction. Assuming this is the global optimum, this could mean that the jury is not needed when the engines are placed on the wing.

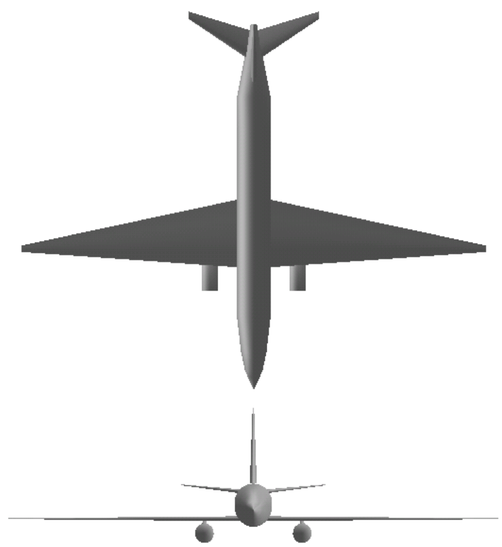
From the previous results for minimum TOGW configurations with 1990's and advanced aerodynamics, the SBW with wing engines appears to be the best configuration when considering the minimum TOGW. However, these results can be interpreted in different ways. Noisy constraint or objective functions could also be affecting the optimum solutions. Thus within the fidelity of this analysis, there are some observations. First, the SBW and TBW configurations result in similar performance in terms of minimum TOGW. Second, in nearly every case, the braced wing configurations are significantly more efficient than the cantilevers. Third, many of the SBW and TBW configurations exhibit unusual wing planforms similar to Pfenninger's TBW concept.

3.5 Minimizing Fuel Weight

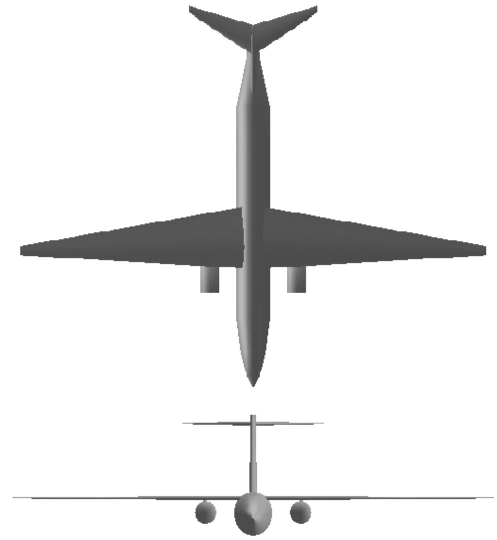
This section investigates minimizing the required fuel weight. Since the fuel weight is indicative of the fuel consumption, this is also considered a minimum emissions case. This section includes an analysis of results for six configurations optimized for minimum fuel with both 1990's and advanced technology aerodynamics.

The first results discussed are for the 1990's technology minimum fuel configurations. Figure 3.7 shows all of the optimized aircraft configurations followed by Table 3.7 summarizing the geometric and performance characteristics.

a) Cantilever Configurations

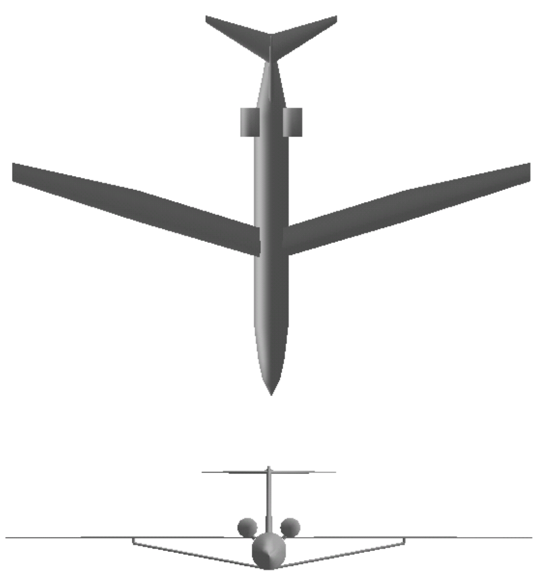


Low-Wing, Conventional Tail

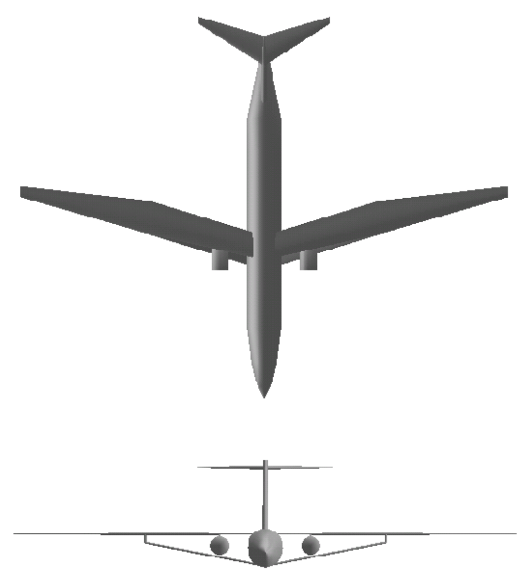


High-Wing, T-tail

b) SBW Configurations

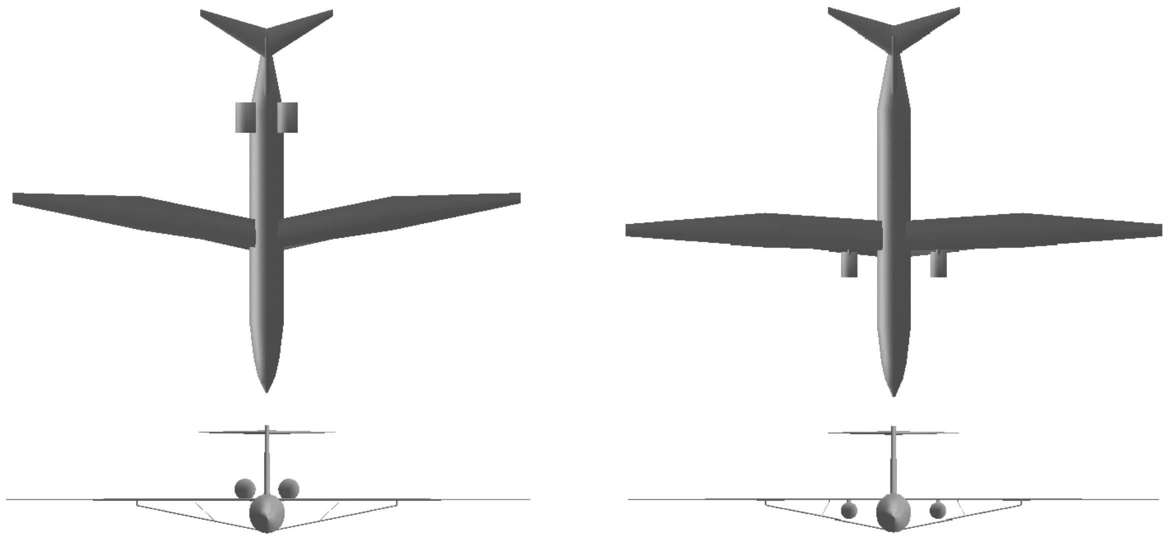


Fuselage Engines



Wing Engines

c) TBW Configurations



Fuselage Engines   Wing Engines

Figure 3.7(a-c): 1990’s Technology Minimum Fuel Optimized Configurations

Table 3.7: 1990's Technology Minimum Fuel Optimized Configurations

Characteristics	Low Wing Cantilever	High Wing Cantilever	SBW with Fuselage Engines	SBW with Wing Engines	TBW with Fuselage Engines	TBW with Wing Engines
TOGW(lb):	175,400	183,800	164,400	159,100	169,600	161,800
Fuel Weight (lb):	**31,300**	**32,200**	**28,100**	**28,600**	**29,000**	**27,900**
Wing Weight (lb):	40,200	44,400	28,100	26,900	31,400	31,000
Structural Wing Bending Weight (lb):	29,500	43,600	17,500	16,900	21,600	21,400
Design L/D:	32.2	32.3	33.2	31.7	32.9	34.1
Cruise C_D:	0.015	0.015	0.020	.022	.020	0.018
Maximum Thrust Required (lb):	19,200	23,900	25,600	21,300	27,800	18,900
Wing/Strut Half-span(ft):	83.5	85.9	92.4/47.5	87.6/40.9	90.5/44.5	94.9/45.5
Wing ¼ chord sweep (deg):	0	0	16.6	13.9	9.3	2.1
Design Altitude (ft):	42,900	41,100	46,300	45,100	43,800	45,300
Wing Area (ft):	2,260	2,250	1,840	1,590	1,700	1,800
Root Chord (ft):	24.79	22,88	10.54	8.81	9.74	10.11
Jury Chord (ft):	-	-	-	-	2.00	2.045
Strut Junction Wing Chord (ft):	-	-	11.24	11.93	12.09	12.11
Strut Chord (ft):	-	-	10.53	12.12	8.91	9.47
Tip Chord (ft):	2.23	3.26	6.66	3.87	3.69	4.13
Root t/c:	0.0643	0.066	0.050	0.058	0.075	0.051
Jury t/c :	-	-	-	-	0.084	0.061
Strut Junction Wing t/c:	-	-	0.063	0.084	0.058	0.057
Strut t/c:	-	-	0.089	0.064	0.050	0.050
Tip t/c :	0.060	0.055	0.062	0.072	0.062	0.076

The minimum fuel cases tend to have low sweep, high aspect ratio wings compared to the simulated 737 model. Even without the advanced aerodynamic technology, there are significant reductions in fuel consumption relative to current aircraft configurations.

The 1990's technology minimum fuel cantilever configurations shows fuel reductions of nearly 32% relative to the simulated 737 when comparing the above results and Table 3.2. This reduction comes from a synergy of structures and aerodynamics. These minimum fuel cases tend to reduce the drag so the wings become thinner and longer with increased wing area and lower wing loadings. This means a larger TOGW, but lower fuel weight. The results show low t/cs of about 6% on both cantilever configurations. It is also found that with the current analysis methods, there is no significant difference in the performance of the High-wing or Low-wing cantilever configurations.

The SBW configurations show reductions in fuel consumption on *the order of 38% compared to the simulated 737* shown in Table 3.2. Consistent with the trends mentioned above, the SBW configurations result in wing spans even larger than the cantilevers due to the wing stiffening from the strut. There is a small difference in sweeps between the two SBW configurations. The SBW with wing engines has the inertia relief of the engines allowing the wing structure to be slightly lighter and thinner because the bending moment has decreased. This results in less wave drag so the configurations with wing engines have less quarter chord wing sweep.

The TBW configurations show fuel reductions similar to the SBW. Both configurations have similar characteristics to the SBW and Pfenninger's concept. These results show that the TBW with wing engines is the best configuration for minimizing the fuel weight. However, the SBW and TBW results have nearly equivalent performance within the fidelity of the analysis. Because of this similarity, further analysis is used to determine the skin thickness distributions in order to fully understand the results.

The figures below show the different predicted structural thickness distributions for each configuration. The low-wing and high-wing cantilever skin and spar thickness distributions are shown below in Figure 3.8.

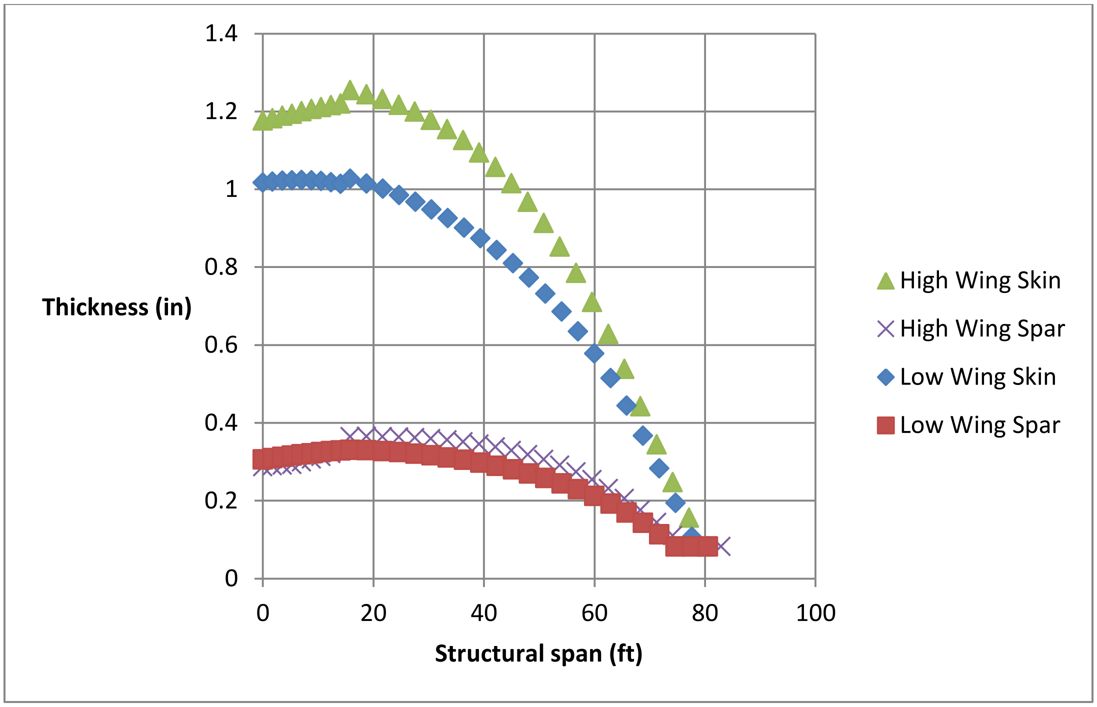


Figure 3.8: 1990's Minimum Fuel: Low-Wing and High-Wing Cantilever Structural Thickness Distributions

The results show that both the skin and spar thicknesses peak at the engine location and then decrease towards the tips. These results are consistent with common cantilever thickness distributions.

Figure 3.9 shows the thickness distributions for the SBW configuration.

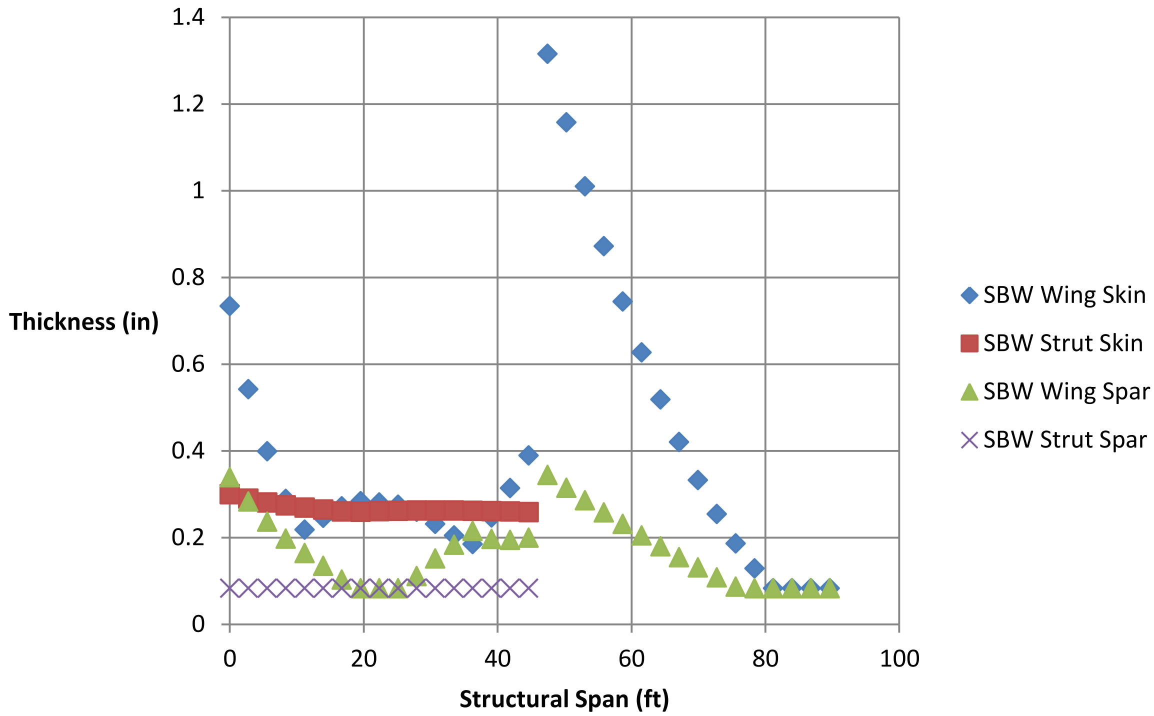


Figure 3.9: 1990's Minimum Fuel SBW with Fuselage Engines Structural Thickness Distributions

The SBW results show a near constant strut skin and spar thickness. One can note a wing with a decreasing and increasing wing skin and spar thickness within the strut span. There is a sharp rise in the thicknesses beyond the strut with a monotonic decrease towards the minimum thickness at the tip. Beyond the strut the wing is cantilever, so this trend is expected.

Figure 3.10 shows that the thickness distribution for a SBW with wing engines.

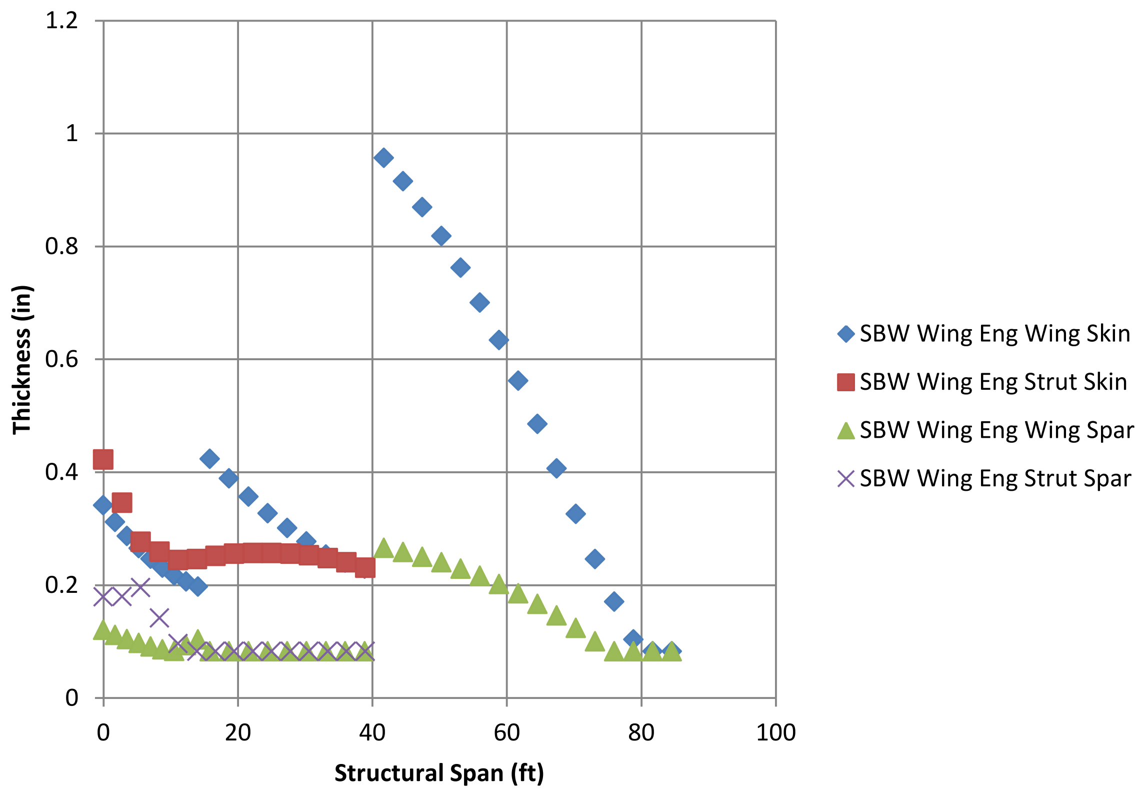


Figure 3.10: 1990's Minimum Fuel SBW with Wing Engines Structural Thickness Distributions

The plot above shows trends similar to the SBW with fuselage engines however the SBW with wing engines has a variation in the wing skin and spar thickness due to the engine weight. It also seems that the skin thickness varies the most. In fact, the spar thickness on the strut and wing exhibit only small variations from the minimum thicknesses. It is also important to notice that the wing skin thicknesses for the SBW with wing engines are much smaller than the SBW with fuselage engines at the root and strut junctions. This translates to the lower structural wing weight. Figure 3.12 shows the thickness distributions for the 1990's minimum fuel TBW.

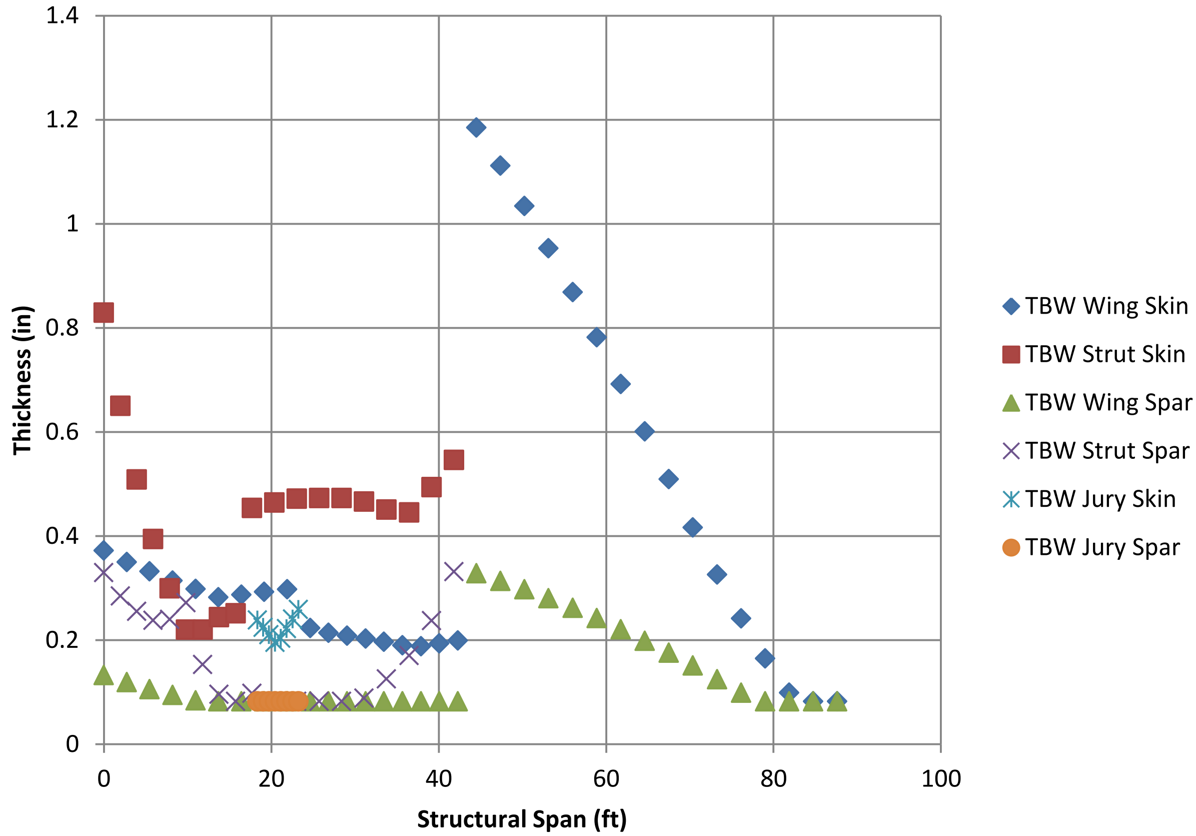


Figure 3.11: 1990's Minimum Fuel TBW with Fuselage Engines Structural Thickness Distributions

The TBW results show that the strut skin thickness is much higher than for the comparable SBW configuration. This means the strut is carrying more load than the wing. This solution could cause the jury thicknesses to be greater than necessary due to compressive loads. As a result, the wing skin and spar thicknesses are very small. The following Figure 3.12 shows the thickness distributions for the 1990's minimum fuel TBW with wing engines.

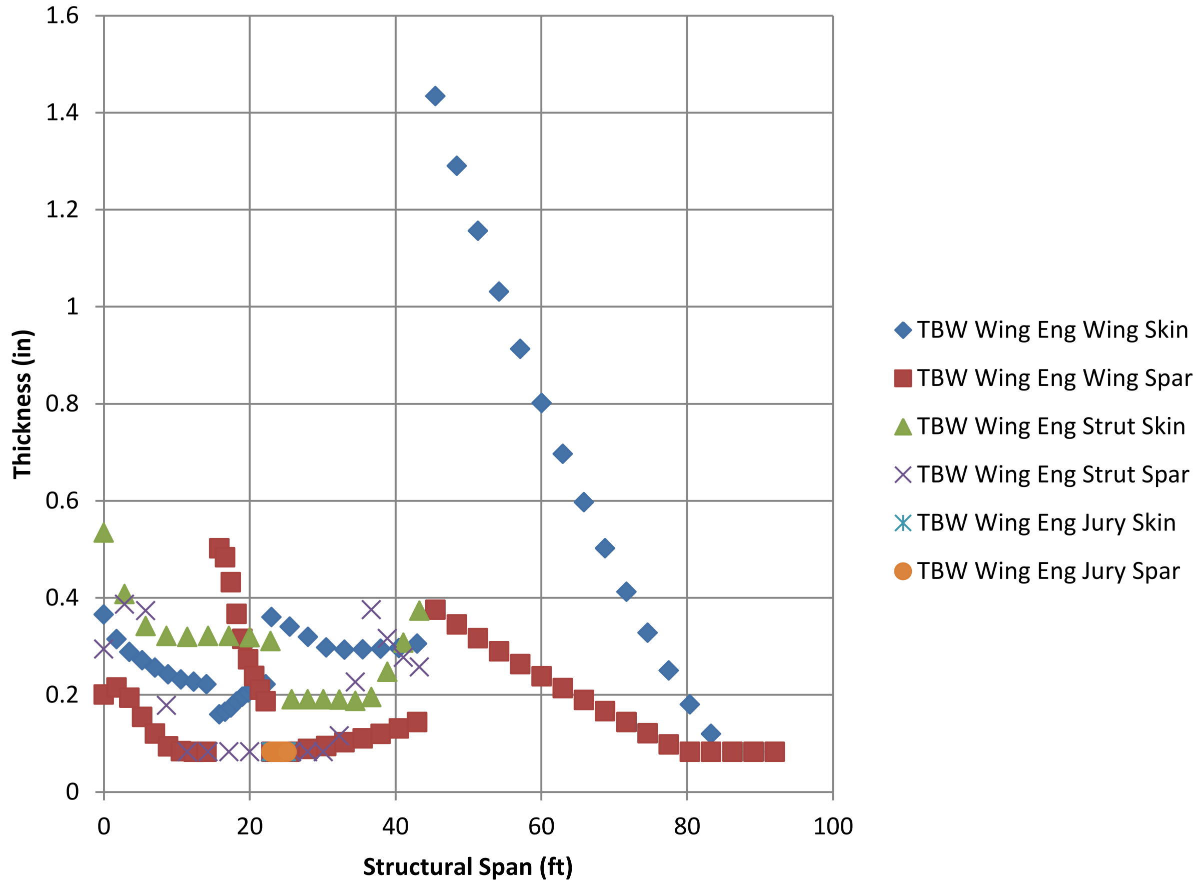


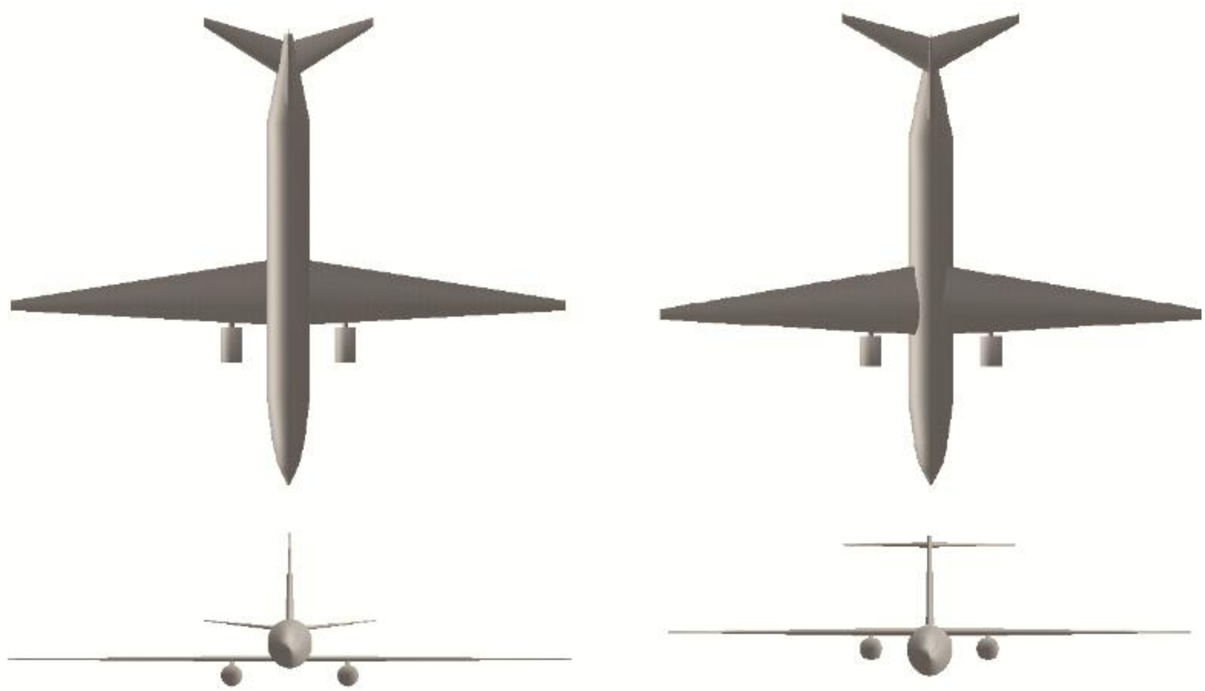
Figure 3.12: 1990's Minimum Fuel TBW with Wing Engines Structural Thickness Distributions

Figure 3.12 shows that the TBW with wing engines benefits from reduced structural thicknesses compared to the TBW with Fuselage Engines. In this case, the jury members appear to have the minimum structural thicknesses. There are jumps in the wing thicknesses at the engine, jury and strut locations. The jury and engine loads help to decrease the thicknesses of the individual wing structural members. This is the desired benefit of the TBW configurations. Note that the engine load has the same role as the jury member but does not require the additional structural weight however these high wing configurations tend to require a larger vertical tail area. This is due to the reduced rudder effectiveness due to wing turbulence.

The previous analysis helps to understand the performance advantages and disadvantages of each configuration. The results further show that the TBW with wing engines is the best configuration for minimum fuel. However, the fuel weight is only slightly smaller than the SBW with wing engines. Within the fidelity of the analysis, either configuration is a viable design.

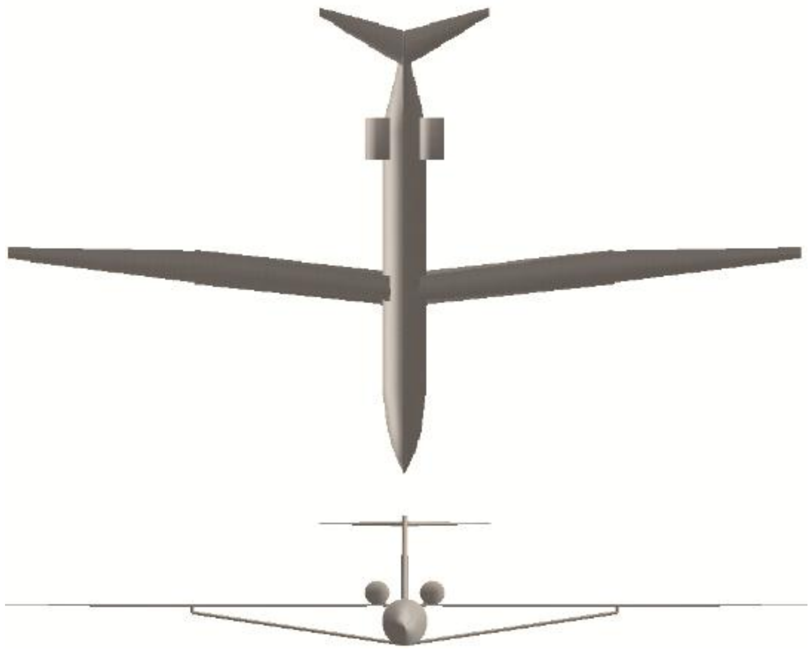
The following results are for the advanced aerodynamics technology minimum fuel configurations. Figure 3.13 and Table 3.8 show all of the optimized configurations.

a) Cantilever Configurations



Low-Wing, Conventional Tail High-Wing, T-tail

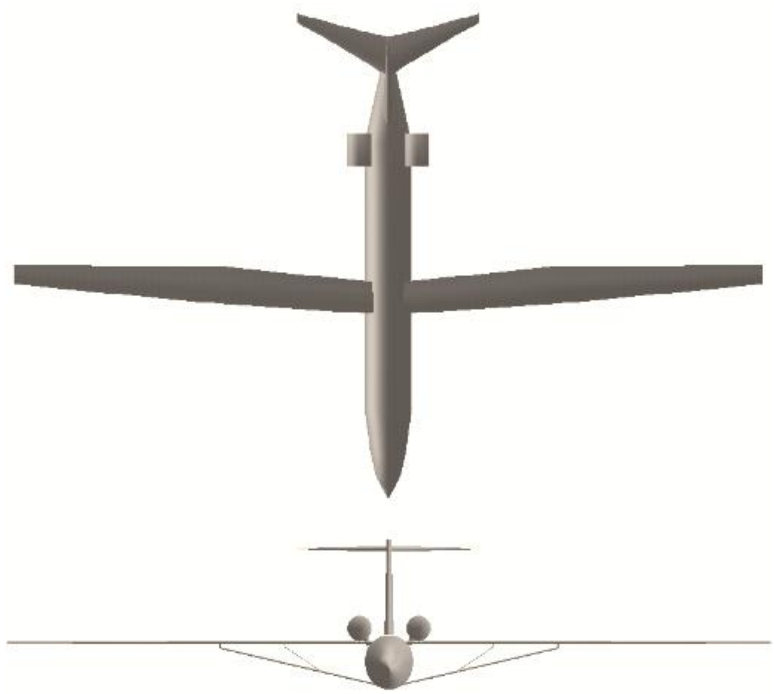
b) SBW Configurations



Fuselage Engines

Wing Engines

c) TBW Configurations



Fuselage Engines

Wing Engines

Figure 3.13(a-c): Advanced Technology Fuel TOGW Optimized Configurations

Table 3.8: Advanced Technology Minimum Fuel Optimized Configurations

Characteristics	Low Wing Cantilever	High Wing Cantilever	SBW with Fuselage Engines	SBW with Wing Engines	TBW with Fuselage Engines	TBW with Wing Engines
TOGW(lb):	156,300	153,600	161,600	151,000	170,100	159,600
Fuel Weight (lb):	**27,200**	**28,900**	**24,400**	**24,900**	**25,600**	**24,700**
Wing Weight (lb):	27,700	22,500	29,100	22,900	31,400	29,800
Structural Wing Bending Weight (lb):	17,700	11,800	19,400	13,500	18,300	19,900
Design L/D:	33.6	30.0	39.9	35.9	34.1	38.9
Cruise C_D:	0.015	0.016	0.021	0.021	0.021	0.020
Maximum Thrust Required (lb):	18,300	18,800	26,200	21,600	28,100	23,600
Wing/Strut Half-span(ft):	76.8	71.2	109.5/58.3	90.3/43.2	97.5/42.8	100.7/51.9
Wing ¼ chord sweep (deg):	0	0	6.19	1.98	4.27	1.28
Design Altitude (ft):	40,200	39,400	49,000	45,700	45,400	48,800
Wing Area (ft):	1,670	1,700	1,630	1,460	1,730	1,770
Root Chord (ft):	19.07	20.90	7.13	8.32	9.681	9.49
Jury Chord (ft):	-	-	-	-	3.11	3.12
Strut Junction Wing Chord (ft):	-	-	9.54	11.04	10.364	10.87
Strut Chord (ft):	-	-	9.99	8.60	5.88	5.97
Tip Chord (ft):	2.68	3.04	3.37	2.12	5.90	3.78
Root t/c:	0.097	0.110	0.069	0.067	0.081	0.074
Jury t/c :	-	-	-	-	0.059	0.094
Strut Junction Wing t/c:	-	-	0.097	0.087	0.095	0.074
Strut t/c:	-	-	0.106	0.110	0.079	0.089
Tip t/c :	0.089	0.100	0.081	0.069	0.071	0.066

The results above show trends similar to the 1990’s technology minimum fuel configurations. These consist of low sweep, high aspect ratio configurations. All of the configurations also have low drag and significantly higher L/D values when compared to the minimum TOGW cases or 1990’s technology minimum fuel configurations.

The cantilever results show a fuel reduction of about 39% compared to the simulated 737 mentioned previously in this section. These cases have a reduced span compared to the 1990’s technology configurations along with thicker wings due to the increased aerodynamic efficiency.

The low-wing configuration has a slightly better fuel weight then the comparable high-wing configuration consistent with previous results.

The SBW and TBW configurations have similar fuel weights. These all fall within 1,000 pounds of each other. Within the analysis uncertainty, these configurations have comparable performance. For this advanced technology minimum fuel case, the SBW and TBW configurations have fuel weights over 10% less than the comparable cantilever configurations. This is nearly a 47% reduction in fuel consumption for the best configuration, the SBW, when compared to the simulated 737.

The results above show 12 aircraft configurations optimized for minimum fuel with either 1990's or advanced technology aerodynamics. 1990's and advanced configurations show significant fuel weight reductions compared to the simulated 737. These configurations have common characteristics such as large span, high aspect ratio wings. The 1990's aerodynamics technology configurations tend to favor thinner wings than the advanced configurations due to wave drag. The advanced aerodynamics technology configurations are less sensitive to wave drag and tend to have thicker wings. These details characterize minimum fuel designs.

Chapter 4: Conclusions

The present study investigates the benefits of the SBW and TBW configurations in enhancing the performance of a medium range, transonic transport. The mission was modeled after the Boeing 737-800NG. Preliminary analyses show good correlations between the TBW framework calculations and statistical aircraft weight estimates for conventional cantilever wing aircraft. Six configurations including the low-wing cantilever, high-wing cantilever, SBW with fuselage engines, SBW with wing engines, TBW with fuselage engines, and TBW with wing engines were optimized for both minimum TOGW and minimum fuel objectives with 1990's and advanced aerodynamic technology. A study of strut fuel loads concludes that fuel stored in the strut can help to reduce the wing bending and shear material weight and thus the TOGW of SBW and TBW configurations. Another study comparing fuselage and wing engine configurations determined that the wing engine configurations also benefit from reduced bending loads and thus wing structural weight.

The minimum TOGW configurations exhibit reductions in the engine, wing and fuel weights. The minimum fuel cases results in lower fuel weights and lower drag compared to the minimum TOGW cases, but higher wing weights due to the increased spans. Minimum TOGW results shows weight reductions of about 15% compared to the simulated Boeing 737-800NG with fuel weight reductions on the order of 40%. The minimum fuel weight cases result in reductions as much as 47% for the advanced SBW configuration. In all cases, the SBW and TBW configurations are superior to the cantilever however there are no significant performance differences between the optimized SBW and TBW configurations for both minimum TOGW and minimum fuel objective cases.

Chapter 5: Future Work

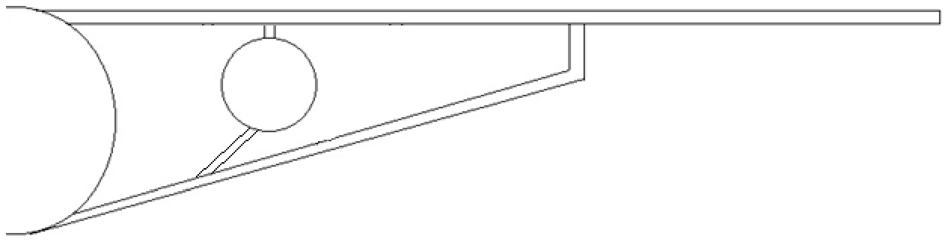
The SBW and TBW configurations show very promising performance gains compared to the cantilever. However, there are some analysis and configuration modifications that could further benefit the TBW design. These include developed optimization techniques, tapering the strut, jury engines, and split jury.

When optimizing an aircraft, the analysis is only half the story. The complicated cost functions and constraints involved require a robust optimizer to find the global optimum. Early during this study, it was determined that a standard gradient based optimizer was not capable of finding the best designs. Darwin, a Genetic Algorithm, was used for its robustness but it has long run times. Other techniques need to be explored that can better traverse the design space with reduced run times. Surrogate methods or response surfaces could be good options. Polynomial constraint approximations could ease the use of quick gradient based optimizers like DOT. Other stochastic methods like Simulated Annealing or Particle Swarm Optimization could also be studied.

Many of the configurations in this study tend to rely on the strut as a structural support as well as a lifting surface. The current models assume a constant chord and thickness strut however according to the thickness distributions, the strut could benefit from a taper. This would allow the root strut thickness to decrease with the upper wing. This could result in lower drag and lower weight configurations.

Some of the configurations of this study use wing mounted engines. The engines, similar to a jury, apply a load to the upper wing and strut helping to reduce the bending material stress and thus weight. Increased wing stiffness could result by attaching the engine to the strut with a jury member. Figure 5.1 below shows an example of the jury connected engine.

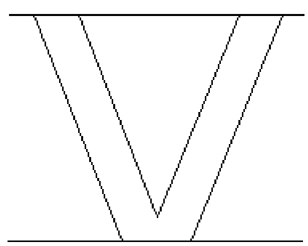
Figure 5.1: TBW with Jury Connected to Engine Nacelle



As long as the engine casing deflection does not affect engine performance, this configuration can take advantage of the engine location to stiffen the wing structure without the additional weight of an independent jury.

Split Juries could be used to control wing twist as well as passively stiffen the wing structure. Current juries are modeled like the wing and strut with a rectangular wing box and skin. It could be valuable to utilize a split jury. Figure 5.2 shows the layout of the proposed jury.

Figure 5.2: Split Jury



The picture shows the jury layout looking from the tip of the wing towards the fuselage. The branched jury would allow passive wing stiffening in bending and torsion with active control of the upper wing twist if actuators are placed in each branch. If drag penalties are small, this could enhance TBW performance.

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