

PrePublication Courtesy Copy

Advanced Technology Subsonic Transport Study

N+3 Technologies and Design Concepts



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ABSTRACT

Conceptual Research Corporation, *the Science of the Possible*, has completed a two-year study of concepts and technologies for future airliners in the 180-passenger class. This NASA-funded contract was primarily focused on the ambitious goal of a 70% reduction in fuel consumption versus the market-dominating Boeing 737-800. The study is related to the “N+3” contracts awarded in 2008 by NASA's Aeronautics Research Mission Directorate to teams led by Boeing, GE Aviation, MIT, and Northrop Grumman, but with more modest goals and funding.

CRC's contract featured a predominant emphasis on propulsion and fuel consumption, but since fuel consumption depends upon air vehicle design as much as on propulsion technology, the study included notional vehicle design, analysis, and parametric studies. Other NASA goals including NOx and noise reduction are of long-standing interest but were not highlighted in this study, other than their inclusion in the propulsion system provided to CRC by NASA.

The B-737-800 was used as a benchmark, parametric tool, and design point of departure. It was modeled in the RDS-Professional aircraft design software then subjected to extensive parametric variations of parasitic drag, drag-due-to-lift, specific fuel consumption, and unsized empty weight. These studies indicated that the goal of a 70% reduction in fuel consumption could be attained with roughly a 30% improvement in all four parameters. The results were then fit to a Response Surface and coded for ease of use in subsequent trade studies.

Potential technologies to obtain such savings were identified and discussed. More than 16 advanced concept designs were then prepared, attempting to investigate almost every possible emerging concept for application to this class airliner. A preliminary assessment of these concepts was done based on their total wetted area after design normalization of trimmed maximum lift.

This assessment points towards a Tailless Airliner concept which was designed and analyzed in some detail. To make it work, a retracting canard and an all-moving chin rudder were employed, along with the use of the Active Aeroelastic Wing technology. Results indicate that a 60% savings in fuel burn may be credibly attained, but this depends upon a lot of technology maturation, concept development, and risk reduction. This should be expected - such a dramatic reduction in fuel consumption is a “game changer” in the world of commercial aviation. It won't be easy.

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NOMENCLATURE

<i>A</i>	= Aspect Ratio (span ² /reference area, applied to wings and tails)
<i>AAW</i>	= Active Aeroelastic Wing
<i>BWB</i>	= Blended Wing Body
<i>C_L</i>	= Wing Lift Coefficient
<i>CAD</i>	= Computer-Aided Design
<i>CFD</i>	= Computational Fluid Dynamics
<i>CRC</i>	= Conceptual Research Corporation
<i>cg</i>	= Center of Gravity (mass)
<i>DATCOM</i>	= Data Compendium (USAF aerodynamics methodology report)
<i>FAR</i>	= Federal Aviation Regulations
<i>L/D</i>	= Lift-to-Drag Ratio
<i>M</i>	= Mach Number
<i>N+3</i>	= Three generations beyond the current commercial transport fleet
<i>RDS</i>	= Aerospace vehicle design software (Conceptual Research Corp.)
<i>SAWE</i>	= Society of Allied Weight Engineers
<i>SFC</i>	= Specific fuel consumption
<i>S_{wet}</i>	= Aircraft total external wetted surface area
<i>TRL</i>	= Technology Readiness Level
<i>T/W</i>	= Thrust-to-weight ratio
<i>W/S</i>	= Wing loading (weight/area)
<i>W₀</i>	= Takeoff Gross Weight
<i>W_e</i>	= Empty Weight
<i>6-DOF</i>	= Six Degree of Freedom dynamic simulation

1. INTRODUCTION

Concepts and technologies to obtain massive reductions in fuel usage in future 180-passenger commercial airliners are considered. Funded by a NASA contract related to the ongoing “N+3” efforts of NASA and its contractors, Conceptual Research Corporation’s study focused on design concepts and technologies needed to obtain a 70% reduction in fuel consumption versus current aircraft as typified by the Boeing 737.

Results point to the Open Rotor propulsion system and the Active Aeroelastic Wing as key enabling technologies, along with the application of advanced composite, subsystem, flight control, and aerodynamic technologies. As far as innovative design concepts, the commonly-considered concepts such as Canard, Forward Swept Wing, Blended Wing Body, and Joined Wing do not seem to offer a substantial net benefit when the problems of excess wetted area and inadequate trimmed maximum lift are included in the assessment. Since a nontrivial reduction in parasitic drag is essential for “N+3” goals, it seems that only concepts which actually reduce the total wetted surface area will be winners, leading to the tailless approach*.

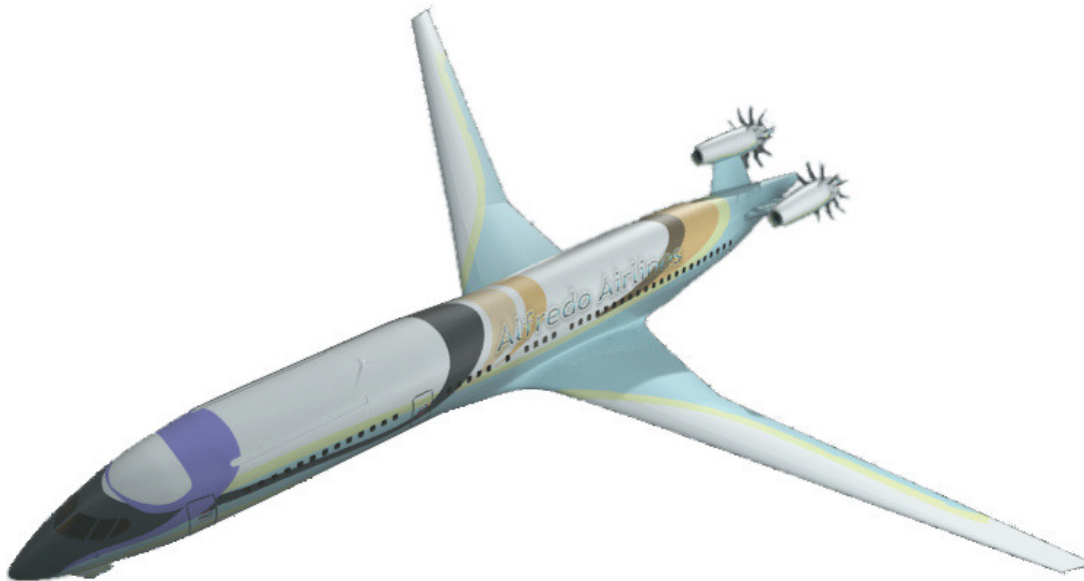


figure 1. Preferred Concept Artist’s Rendering: Up-and-Away

* This report was not written under contract funding. To permit publication as a NASA CR, it is declared by the author to be in the Public Domain. The realistic CAD renderings throughout the report were produced by Mr. Alfredo Ramirez P. who graciously authorizes their inclusion herein. The CFD studies summarized below were performed by Ms. Mengmeng Zhang and Dr. Arthur Rizzi of Sweden’s Royal Institute of Technology (KTH) as part of a cooperative effort with Conceptual Research Corporation, and are declared to be in the Public Domain.

2. BACKGROUND

NASA, since its foundation as NACA in the early days of aviation, has focused research and technology development funding on the improvement of efficiency and viability of commercial aircraft. In later years it has also spearheaded efforts to reduce aircraft noise and atmospheric pollution, and as such can be considered a leading “green” federal agency. The importance of this ongoing research cannot be overestimated. Commercial aviation is the largest single positive category in our national balance of trade, provides hundreds of thousands of jobs, projects a positive image of a “can-do” America to the world at large, and indirectly contributes to our national defense.

In 2008, NASA awarded \$8m worth of research contracts¹ to four industry teams to study technologies and concepts for subsonic commercial aircraft in the 2035 time frame. This is sometimes referred to as "N+3," denoting three generations beyond the current transport fleet.

In the contract press release Juan Alonso, director of NASA's Fundamental Aeronautics Program, is quoted as saying, "The future of air transportation is all about protecting the environment and responding to increasing energy costs in a balanced way. We will need airplanes that are quieter and more fuel efficient, and cleaner-burning fuels to power them. We are challenging industry to introduce these new technologies without impairing the convenience, safety and security of commercial air transportation."

Funding was also provided to several NASA Centers. Conceptual Research Corporation was contracted by NASA-GRC to consult in matters relating to air vehicle/propulsion design integration and to perform independent studies related to the application of N+3 to the 180-passenger class commercial transport. This effort is reported herein.



figure 2. Preferred Concept Artist's Rendering: Takeoff

3. APPROACH

The contract technical phase began with modeling and calibration of the Boeing 737-800 as a point-of-departure baseline. Using the RDS-Professional aircraft design software, CRC modeled the B-737-800 in sufficient detail to support analysis and alternative design studies. Analysis was done in RDS using classical preliminary aircraft analysis methods, mostly those described in this author's textbook *Aircraft Design: A Conceptual Approach*². These methods have been extensively calibrated in past studies versus actual aircraft including the Lockheed L-1011. For aerodynamics, the methods are primarily based on the USAF DATCOM³ plus the Leading Edge Suction induced drag methodology. Weights equations are mainly from SAWE* papers and statistical equations from Vought Aircraft⁴. For this study, propulsion was based upon data obtained from NASA.

Once results were obtained and verified with published B-737 numbers, CRC performed parametric variations of parasitic drag, drag-due-to-lift, specific fuel consumption, and unsized[†] empty weight. Potential technologies to obtain such savings were identified, then a wide variety of advanced concept designs were prepared and assessed. A preferred design approach was selected and then refined and analyzed.

This work was described in two contract-deliverable viewgraph final reports^{5,6} which contain more details of the analysis and design efforts. This written report is an attempt to expand and present these results to a wider audience in an archival manner, and hopefully influence future concept development.

Be advised that this was a “first-look” study with total funding of only 460 hours, some of which was expended in other consulting and engineering support. The budget did not permit extensive analysis such as computational fluid dynamics (CFD), structural finite element analysis (FEM), or noise propagation estimation. Nor were concepts evaluated in enough detail or by a broad enough cadre of experts to verify their feasibility. A follow-on, detailed study is recommended to increase confidence in this study's conclusions and in the viability of the preferred design and technology suite. But, this author is confident that the results below are not totally “off base.”

* Society of Allied Weight Engineers

† For those not familiar with advanced design methodologies, “sizing” refers to the calculations that determine the aircraft takeoff gross weight and fuel weight needed to obtain a specified mission range carrying a certain payload weight. This calculation uses numerous design-specific parameters such as the aircraft drag and empty weight, leading to a classic “chicken-and-the-egg” problem, namely, you can't estimate these parameters without a design layout, and you can't do a design layout without the sizing results. To get around this it is common to first do an initial design layout based upon a rough guess of the aircraft weight. This is called the “unsized” design, and is used to estimate the required parameters for sizing, which is then carried out. From those results, the “unsized” layout is scaled and redesigned to a “sized” design which, if all is well, will obtain the desired range carrying the desired payload. For details see *Raymer* (ref 2).

4. CALIBRATION BASEPOINT: BOEING 737-800

To impose reality upon such a far-term study it was decided to benchmark all analysis with a real-world, well-known existing commercial aircraft. The Boeing 737⁷ was chosen as representative of the commercial aircraft fleet. It is the most widely used airliner in the world and over 6,000 have been produced. First flown in 1967, it has been updated regularly and incorporates newer engines (CFM-56) and in some versions, state-of-the-art winglets for drag reduction.

A CAD model of the 737 was developed and analyzed to ensure that key range and performance values were reasonably matched with pilot handbook data. Aerodynamics analysis was performed, with results given in figures 1 through 3 for a no-winglet configuration. Data for the CFM-56 turbofan engine was approximated from NASA estimates, public sources⁸, and parametric cycle results. Weights were estimated using proven empirical weight methods, and adjusted via an input Miscellaneous Empty Weight to match the known B-737 empty weight (below). This 8,562 lbs adjustment is a reasonable value for unspecified empty weight items for this class of aircraft.

A complete FAR commercial transport mission model was developed. Range analysis included recalculation of the best cruise altitude and Mach number including thrust and stall limits, as well as recalculation of optimal climb schedules, both for this “stock” B-737 calculation and for all parametric trade studies and notional concepts described below.

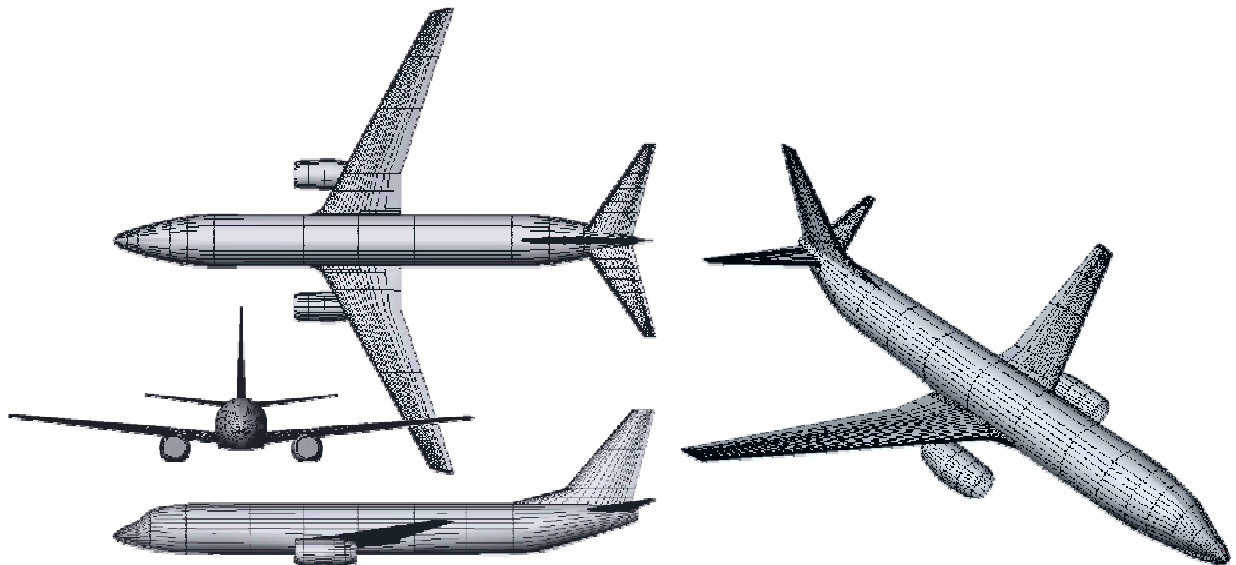


figure 3. Boeing 737 CAD model

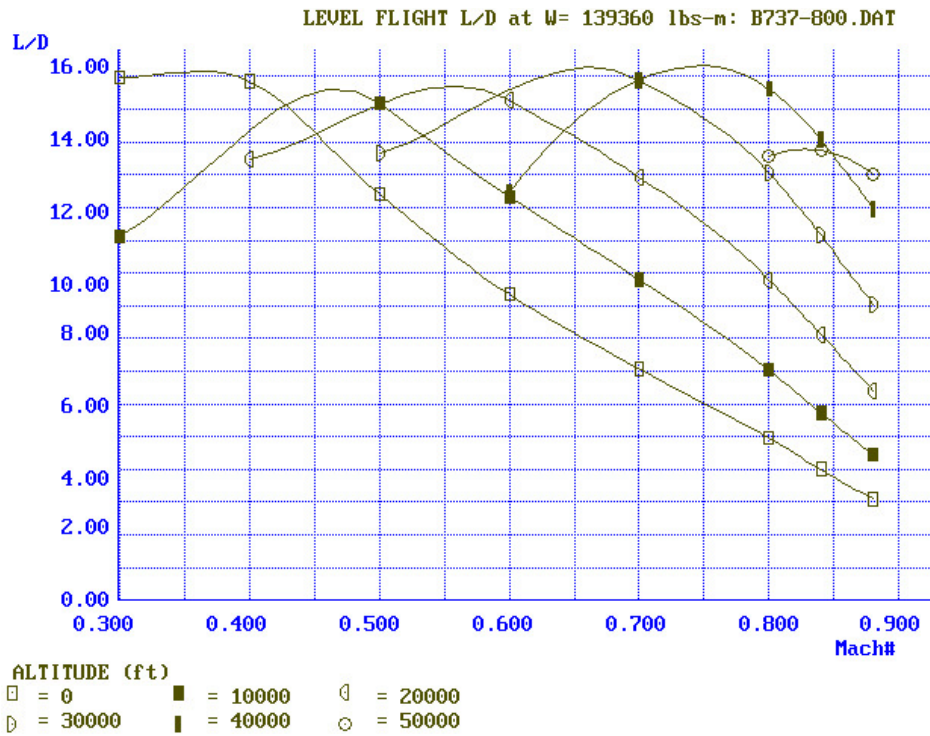
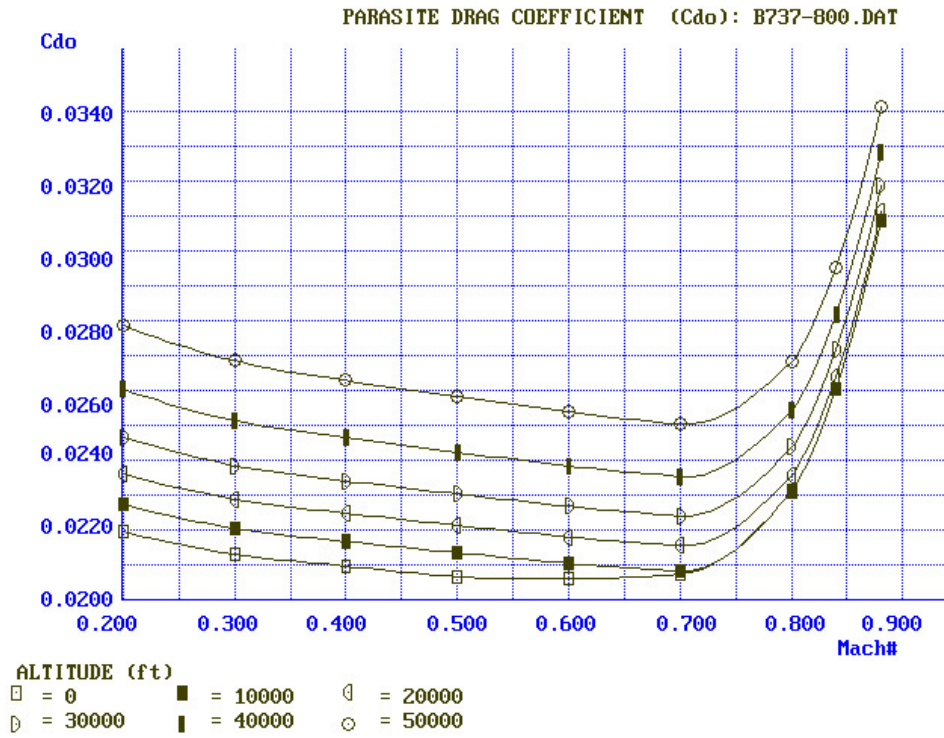


figure 4. Boeing 737 Aerodynamic Analysis Results

STRUCTURES GROUP	44896.7
Wing	16506.7
Horiz. Tail	2010.8
Vert. Tail	700.5
Fuselage	17940.3
Main Lndg Gear	3908.5
Nose Lndg Gear	908.7
Nacelle Group	2921.1
PROPULSION GROUP	11271.9
Engine(s)	10432.0
Engine Controls	42.0
Starter	174.9
Fuel System	623.0
EQUIPMENT GROUP	22879.4
Flight Controls	3758.5
Instruments	202.1
Hydraulics	1347.5
Electrical	2834.8
Avionics	1840.3
Furnishings	8147.2
Air Conditioning	2074.7
Anti Ice	1742.0
Handling Gear	52.3
APU installed	880.0
Misc Empty Weight	8562.0
We-Allowance 5.0%	4380.5
TOTAL WEIGHT EMPTY	91990.5
USEFUL LOAD GROUP	82209.5
Crew	400.0
Fuel	38629.2
Oil	110.2
Payload (max)	13910.0
Passengers	29160.0
TAKEOFF GROSS WEIGHT	174200.0

figure 5. Boeing 737 RDS Weight Estimate

These analytical results were used to calculate range which was used for comparison with the published B-737 actual range values. At a maximum takeoff weight of 174,200 lbs and an empty weight of 91,990 lbs, takeoff at maximum fuel weight of 46,750 lbs (6,875 gallons) leaves 35,460 lbs for the weight of the crew, cargo, passengers, and miscellaneous useful load. This yields a calculated range of 2,774 nm versus the B-737 Ops Manual value of 2,820 nm. For the maximum zero fuel weight takeoff (ie., additional cargo and passengers leaving only 35,900 lbs for fuel), the calculated range is 2,073 nm versus the Ops Manual value of 2,068 nm. These close results validate the methods and the model used for subsequent study and analysis.

5. PARAMETRIC TRADES & RESPONSE SURFACE

A main goal of this study was to identify a path for future airliners to obtain a 70% fuel savings versus the B-737-800. This is not an easy goal, and may prove impossible in that time frame. To better understand what it would take to reach it, CRC performed parametric studies on the B-737 baseline described above. This sought to determine what contributions must be obtained from savings in vehicle weight, aerodynamic drag, and engine specific fuel consumption to add up to such an improvement. In such parametric studies, the chosen parameter is "magically" changed to a better value. The aircraft is resized to the same airliner mission, resulting in a new sized takeoff gross weight and fuel weight to perform the mission carrying the same payload.

Using this B-737 analytical model, the parasitic drag, induced drag, empty weight, and fuel consumption were arbitrarily reduced by 20% and 40% and applied in various combinations, sizing the aircraft to the benchmark commercial aircraft mission model described above. The maximum fuel mission was used as representative of a long-range application. Wing loading (W/S) and thrust-to-weight ratio (T/W) were kept constant so that the resized aircraft would attain the required performance values for takeoff, climb, and landing. Note that this assumption for T/W may be slightly conservative for some cases since the cases that include a drag reduction may be able to attain the required performance with somewhat less thrust.

During this analysis the issue of the proper scaling of aircraft data was addressed. Normally scaling effects are negligible since the sized aircraft is usually within 10-20% of the size of the unsized airplane (here the actual B-737). This allows you to assume that the airplane, as it scales up and down in size, is essentially "photo-scaled" with all components scaling by the square root of the change in weight (so wing loading remains constant). When done this way, the calculated aerodynamic coefficients will be unchanged since they are referenced to the wing area. Similarly, it is normally assumed that for small changes, the aircraft empty weight will follow historical trend lines as expressed by a straight line on log-log graph paper. When fit to an exponential equation, an exponent of -0.06 is typical.

Initial runs were made with these normal assumptions, but the results gave airplanes sized far outside the 10-20% variation of normal sizing. Some combinations of reduced drag, weight, and fuel consumption gave a sized takeoff gross weight of 50% of the actual B-737. Clearly the usual assumptions needed reconsideration.

If the aircraft is scaled down by 50% in weight, the photo-scale assumption would have all dimensions scale by a factor of 0.707. Obviously the passenger compartment cannot scale by such an amount. In fact, the whole fuselage is already about as small as it can be for holding passengers, cargo, and the flight crew. Therefore as the aircraft scales down, the total drag coefficient will actually increase, since the unchanged fuselage drag value is referenced to the now-smaller wing.

The same is true for weight - while the weight of wings, tails, tires, and engines may follow historical trend lines, the weight of the fuselage will change little as the aircraft gross weight sizes smaller.

To address the photoscale problem, the drag calculation procedure was modified to allow holding the fuselage wetted area constant as the vehicle scales down. This was done as a percent of total wetted area, and reasonably simulates the "non-photoscale" sizing effects.

To develop a credible non-photoscale estimate of empty weight, the B-737 layout was scaled to an arbitrary 50% reduction in TOGW. The wing, tails, engines, and nacelles were scaled down holding T/W, W/S, and tail volume coefficients constant, while the fuselage was left essentially unchanged. Weights analysis inputs were revised as appropriate and the resulting empty weight was calculated, and then used to define a non-photoscale empty weight log-log trend line equation. This was found to have an exponent of -0.31, meaning that when the aircraft's sized takeoff gross weight is reduced, the empty weight does not reduce nearly as much as it would for the photo-scale assumption, and the expected fuel improvement is significantly reduced. However, this is more realistic for study purposes, and so it was used in all subsequent calculations.

Using the analysis above and the non-photoscale methods just described, single-variable trade studies were conducted and plotted as shown below.

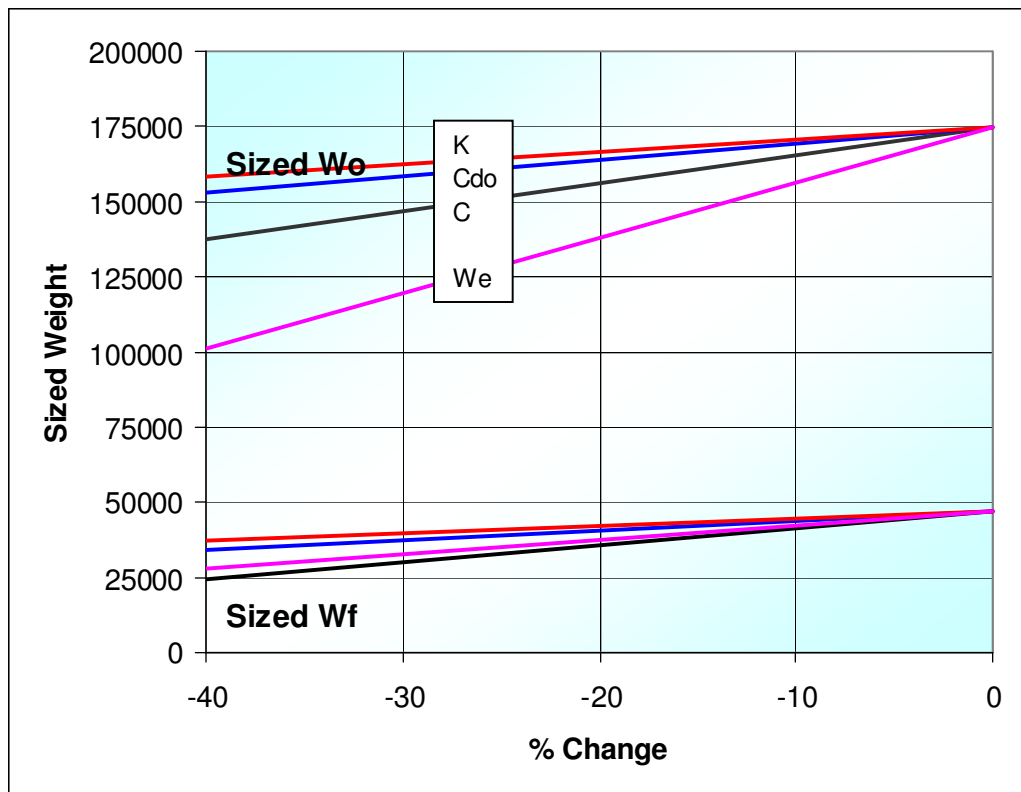


figure 6. Boeing 737 Single Variable Parametric Trades

Results indicate that a 40% improvement in a single parameter reduces the sized aircraft's fuel burn by 49% for SFC, by 28% for Cdo, by 41% for empty weight, and by 21% for induced drag factor (K). A 25% improvement in all four together reduces fuel burn by about 63%. It would take a 30% improvement in all four together to reduce fuel burn by our target of 70%.

The conclusion to be drawn from this parametric study is that a 70% fuel reduction requires massive improvements in aircraft characteristics and is unlikely to be accomplished by any one "silver bullet." Significant improvements must be found in all four parameters - parasitic drag,

induced drag, empty weight, and specific fuel consumption. Of these, the empty weight and engine fuel consumption show higher payoff on a percentage basis than aerodynamic improvements but this comparison may be meaningless. What is important is where areas for improvements can be found.

Another conclusion is that the sizing effect leverages the individual improvements but only when they are applied to an all-new aircraft design. In other words, savings of this magnitude cannot possibly be obtained if improvements are retrofitted to an existing or derivative design.

To make it easier to estimate the effects of various combinations of parametric improvements to the baseline B-737, a Response Surface model was prepared⁹. First a four-parameter Box-Behnken Scheme was devised by NASA’s Jack Wilson, defining specific combinations of variables in increments of 25% and 50%. These sample cases were analyzed by CRC using the model and methods described above, along with single variable trade cases to ensure proper tracking of the obvious variations (see Appendices for data). These results were fit to a second degree polynomial Response Surface* by Wilson using commercial software package SigmaStat, and the resulting equations are provided below.

$$\begin{aligned}
 W_0 = & 0.551*D + 0.234*K + 0.515*C + 0.0653*D^2 + 0.104*C^2 + \\
 & 0.546*We^2 - 0.341*D*K - 0.946*D*C - 0.520*D*We - \\
 & 0.429*K*C - 0.463 *C*We + 0.230*K*C*We + 0.917*D*C*We + \\
 & 0.536*D*K*C
 \end{aligned}$$

$$\begin{aligned}
 W_{fuel} = & 0.0718 - 0.154*D + 0.0861*K - 0.0722*C - 0.197* W_0 - \\
 & 0.0652*K^2 - 0.0522*C^2 + 0.175*D*C + 0.276*D* W_0 + \\
 & 0.579*C* W_0 + 0.0504*D*K*C + 0.0801*D*K* W_0 + \\
 & 0.221*K*C* W_0
 \end{aligned}$$

figure 7. Response Surface Equations

These equations were programmed by Raymer as routine B737RESP.EXE which quickly determines the change in W_0 and W_f for input changes in C_{do} , K , SFC , and empty weight. All changes are input as ratios to the baseline B-737-800 values. Several test cases were conducted to confirm the accuracy of the surface fit. Note that these results are specific to the B-737-800 as modeled, using the mission defined above. While non-photoscale effects have been incorporated, accuracy will be reduced for solutions far from the baseline B-737 size.

* Some third-degree terms are also included. Note that the fuel equation uses the takeoff gross weight response surface result as an “input” as well as the parametric variables.

6. PARAMETRIC RESULTS DISCUSSION

Sample results from the response surface were plotted⁹ as shown below. Note the curve labeled “All 4 Simultaneously.” Its intersection with the vertical axis point at 0.3 fraction of fuel burn crosses the curve at the 0.7 point on the horizontal axis, namely a 30% reduction in each of the parametric variables (parasitic drag, induced drag, empty weight, and fuel consumption). In other words, we can reach our target of a 70% reduction in fuel consumption if we can improve each of these design parameters by 30% over the baseline B-737 values.

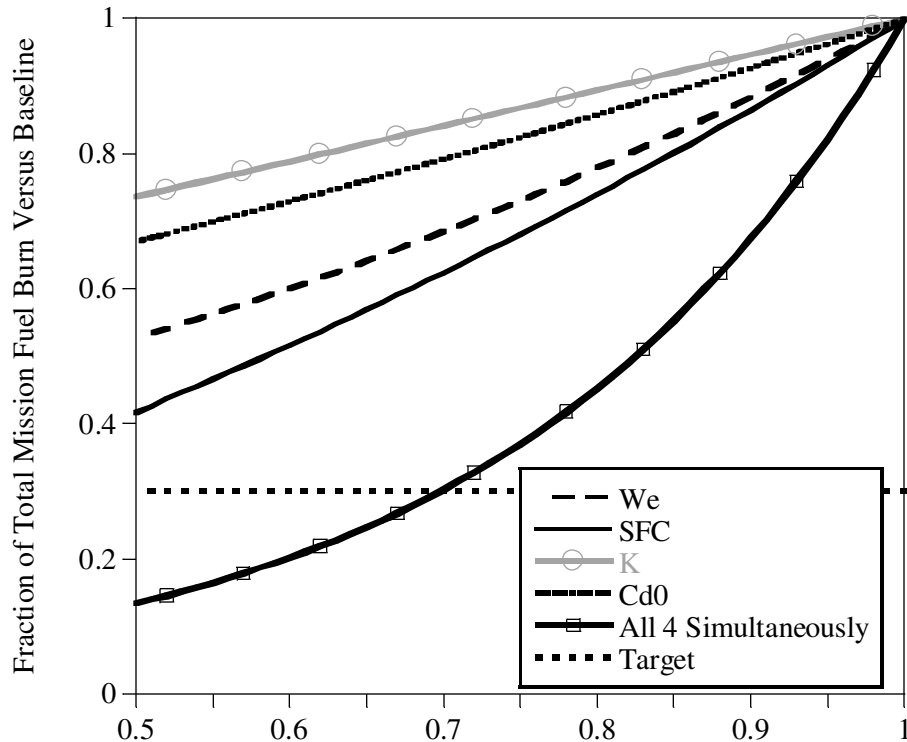


figure 8. Fraction of Aircraft Design Parameter vs. Baseline

Finding a way to obtain such savings became the goal of the rest of the study. In the area of Parasitic Drag, the obvious places for improvement are reduced wetted area, reduced viscous separation, and increased laminar flow. The wetted area can only be reduced by innovative conceptual design. The Blended Wing Body approach is often cited for reducing wetted area, but as discussed below, isn't practical for smaller airliners. To really obtain reduced wetted area in this class of aircraft, components need to be eliminated.

Reduced viscous separation can be attempted by clever shaping, active suction, and the obvious approach of thinner wings, tails, and fuselages. All have penalties.

The baseline B-737 drag buildup using RDS-Professional assumes a typical 10% laminar flow. If an average of 50% laminar flow could magically be attained, the parasitic drag reduces by our goal of 30%. Increased laminar flow is addressed with smoother fabrication methods, active

suction, and again, clever shaping. However, attaining 50% laminar flow for a real commercial airliner is unlikely even in the 2035 time frame.

The Induced Drag (drag-due-to-lift) depends on the effective span loading, often expressed using wing aspect ratio. Quite simply, we need more wing span. However, structural penalties have always prevented the use of unusually-large wing spans, along with practical matters such as airport gate and taxiway clearances. To address the latter concerns, the Boeing 777 was offered with a folding wingtip (at great expense to Boeing, but due to the weight penalty, not one airline ordered their planes that way including the airline that asked for it!).

If a 20% span increase can be obtained, the airplane sees a 30% reduction in induced drag since drag goes by span-squared. With current technologies, the wing weight penalty of the greater span would be approximately 20%, for a total empty weight increase of 4%, which must come out of fuel. This precludes the simple “more span” approach unless some enabling technology can be found which minimizes the weight penalty.

Winglets* and other aerodynamic “tricks” such as spanwise blowing or just a more-optimal spanwise lift distribution can possibly help a bit but the main need is simply for span.

The engine specific fuel consumption also needs a 30% improvement to attain our total fuel savings goal. SFC depends upon effective disk area, thermodynamic and mechanical efficiency, installation losses, propulsion drag, and other factors. Unfortunately, the design cannot tolerate any substantial increase in propulsive system weight which rules out certain approaches.

Of the available approaches to improving propulsive efficiency, the Open Rotor (OR) is probably the most promising. Somewhat like an advanced turboprop or turbofan, it increases effective disk area by using blades external to the nacelle. Earlier versions called PropFans or Unducted Fans were extensively tested and, other than noise issues, proved to be viable and highly efficient.

Exotic approaches to increase the effective disk area could include remote fans, perhaps electric, electrostatic flow acceleration, microactuator blades, or others. Again, potential weight penalties must always be considered and will often obliterate any propulsive improvement.

Along with the Open Rotor, ongoing advances in a variety of propulsion technologies contribute to the engine efficiency improvements used below. These include an advanced core with an Overall Pressure Ratio (OPR) of 70, advanced materials, improved cooling schemes, and greater component efficiencies. Should the Open Rotor, for some reason, be unsuitable or less desirable than expected, these technologies are fully applicable to an advanced high-bypass turbofan and would yield much of the expected benefit.

The final parameter needing improvement is the vehicle Empty Weight. Unfortunately, many of the “good ideas” in the other categories tend to increase empty weight. These must be viewed

* Note that winglets are of marginal benefit for a new aircraft design unless for some reason there is a limit to the aircraft’s wingspan. If span is unconstrained, numerous studies have shown that a slightly greater span without winglets gives a better aircraft, as proven again during the design studies leading to the B-787. The benefit of winglets comes later when an existing aircraft is redesigned to fly at a higher gross weight, and the wing spanloading becomes therefore excessive.

with extreme suspicion, since increases in empty weight have killed more ideas than all other factors combined.

To actually reduce Empty Weight will take an across-the-board approach. There is no single “long pole” item sitting there, waiting to be fixed. The structure of the airplane amounts to only about half the total empty weight. Certainly it must be reduced, but such reductions cannot by themselves reach our goal. Propulsion, subsystems, and even items such as furnishings must also be reduced. This reduces the attractiveness of some of the exotic vehicle designs offering structural weight savings such as the joined wing - there simply isn't enough weight in the wing structure to “save the day” especially when the penalties of those exotic concepts are considered.

7. ADVANCED CONCEPTS DESIGN

Next, the study looked at various exotic vehicle design concepts to assess what improvements if any they offer. Using the RDS-Professional aircraft design software, sixteen advanced transport design concepts (figs. 6 and 7) were developed based on the B-737 passenger compartment and payload. These were chosen to explore virtually all of the advanced aircraft concept ideas currently under consideration, such as forward-swept wings, open rotor, three-surface, blended wing body, joined wing, and more.

The first concept is a conventional Open Rotor design, similar to Unducted Fan designs done about 20 years ago. The Open Rotor is perhaps the most logical way to increase propulsive efficiency since it increases the total airflow used by the propulsion system with potentially smaller weight and drag penalties versus an oversized fan nacelle. Since Open Rotors and similar designs usually cause an increase in noise, this first configuration places the exposed rotors all the way at the back of the airplane, away from the passenger compartment. This in turn almost forces a T-tail, leading to the unintentional “DC-9” appearance.

The second design places the nacelles on the wings like in a 737. The rotors are in a pusher configuration, which might help reduce noise transmission into the passenger compartment. However, this location behind the wing can increase the noise generation since the rotor blades have to “cut” through the wake of the wing. The alternative tractor location for the propellers is problematic as to exhaust location. A much larger portion of total thrust comes from the “jet” portion of the cycle, compared to a classic turboprop, so the exhaust flow itself must be efficiently aimed to the rear and kept away from other aircraft components like the wing.

The third design has the Open Rotors at the tail and positioned over an H-tail arrangement to block noise transmission to the ground. This is probably even more important than the noise that gets into the passenger compartment, if Open Rotors are to find widespread acceptance.

The Tandem Open Rotor is an original idea for reducing wetted area by placing both engines in a single nacelle with counter-rotating rotors. However, this is mechanically complicated, the internal ducting would be difficult, and it reduces effective disk area so that some of the propulsion advantage may be lost. Still, anything that reduces wetted area is worth looking at.

Next is a forward swept wing design. FSW was extensively studied in the early 1980’s leading to the X-29 flight test program. Advantages include superior wing flow quality, a higher no-flaps maximum lift, and better aileron control especially near the stall. Disadvantages include structural divergence, in other words, the wing twisting off at a high enough speed. However, this is solvable with tailored composite materials as proven in the X-29 program. Unfortunately, FSW gives less flap effectiveness since the flaps are highly swept. This forces the wing to be larger than otherwise required.

This particular design concept adds over-the-wing nacelles located far forward of the wing so that the exhaust exit planes are over this wing. This should reduce noise transmitted to the ground. Strut bracing is used to reduce the weight penalties of both FSW and the nacelle locations.

The next two concepts are variants of the Joined Wing¹⁰ approach. NASA/Stanford studies in the 1980’s indicated a possible 25% savings on wing weight due to the bracing effect.

Disadvantages include aerodynamic interference and the inability to put big flaps on all lifting surfaces.

The first version shows the “classic” joined wing as envisioned by Julian Wolkovitch. This extends the rear bracing wing all the way to the top of the vertical tail, providing maximum triangulation for weight savings. However, a separate horizontal tail may be required to provide effective control, so the second joined wing concept has such tails. Its rear bracing wings are attached to the nacelles for better triangularization and reduced length, hence wetted area.

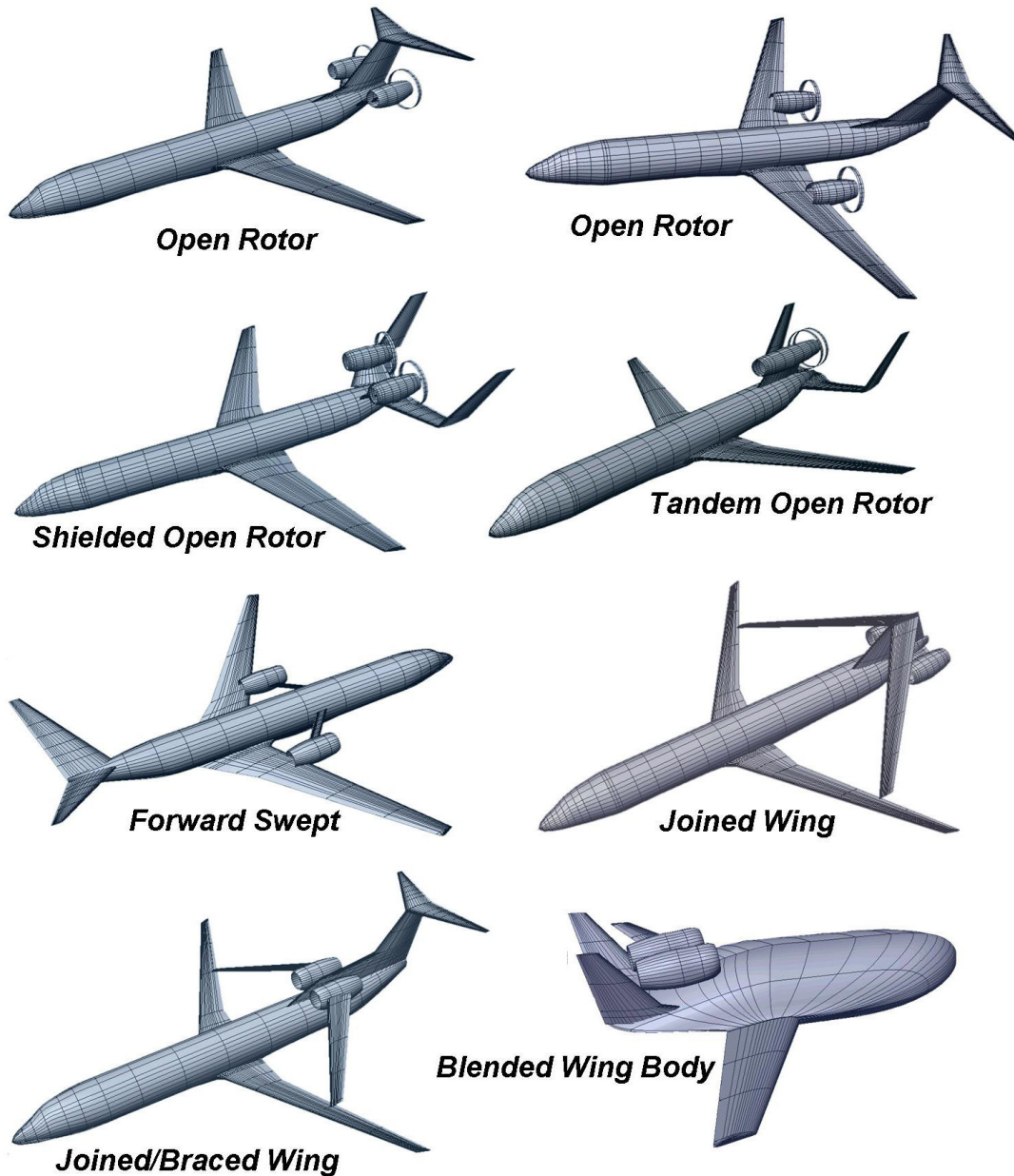


figure 9. Advanced Design Concepts (1)

Blended Wing-Bodies have been studied by Boeing for many years. The idea is to save wetted area, increase lifting efficiency, and reduce weight. The subscale X-48B UAV BWB demonstrator has completed initial flight test¹¹ and seems to be validating predicted savings. While the BWB offers savings for very large airplanes, for a smaller airplane it is difficult to package the passenger compartment without a lot of wasted space. This adds weight and wetted area.

This design layout assumes 12 abreast in two connected cylindrical compartments, each half the length of that in the B-737. These compartments are just as tall as those on a 737 so this BWB does not look much like the X-48, and it sees no reduction in wetted area nor improvement in lifting efficiency

The Oblique wing was invented for supersonic airplanes but offers several benefits for a subsonic airliner. It is mechanically simple, has a high critical Mach number, it gives great lift for takeoff and landing, and it tends to be light in weight since the wing box is effectively unswept. Of course, there is a weight penalty for the pivoting mechanism and the landing gear installation is problematic.

This design concept places the wing on a short pedestal to minimize interference effects and to avoid the possibility of the wing wake entering the inlet duct.

The Tandem Wing promises a theoretical 50% savings in induced drag, but only if the span is kept the same as the equivalent single wing being replaced. This is often misunderstood. Drawbacks include drag caused by interference between the wings, an increase in total wing weight, problems packaging the landing gear, and most important, an inability to put big flaps on the back wing requiring the total wing area to be increased substantially.

The Box Wing was studied in the 60's but never found an application. It is basically a tandem wing with vertical endplates attaching the tips. It promises less induced drag for the same span and supposedly has a good transonic area distribution which increases the critical Mach number. Unfortunately, there is probably no net structural savings since the geometry doesn't provide any triangularization. Drawbacks include the weight of the wings, the wetted area and weight of the endplates, problems packaging the landing gear, and an inability to put big flaps on the back wing. Lockheed studies in the 1960's also found weird flutter modes whose prevention would probably add even more weight.

The Twin Fuselage concept might offer a slight advantage in wing weight since the total body weight is spread out rather than concentrated at the center. However, any benefit would be obliterated by the penalties of the extra wetted surface area compared to a single, larger fuselage. In this design the fuselages are staggered to mitigate transonic effects, and the tails are mounted only on the more-rearward fuselage to maximize moment arm.

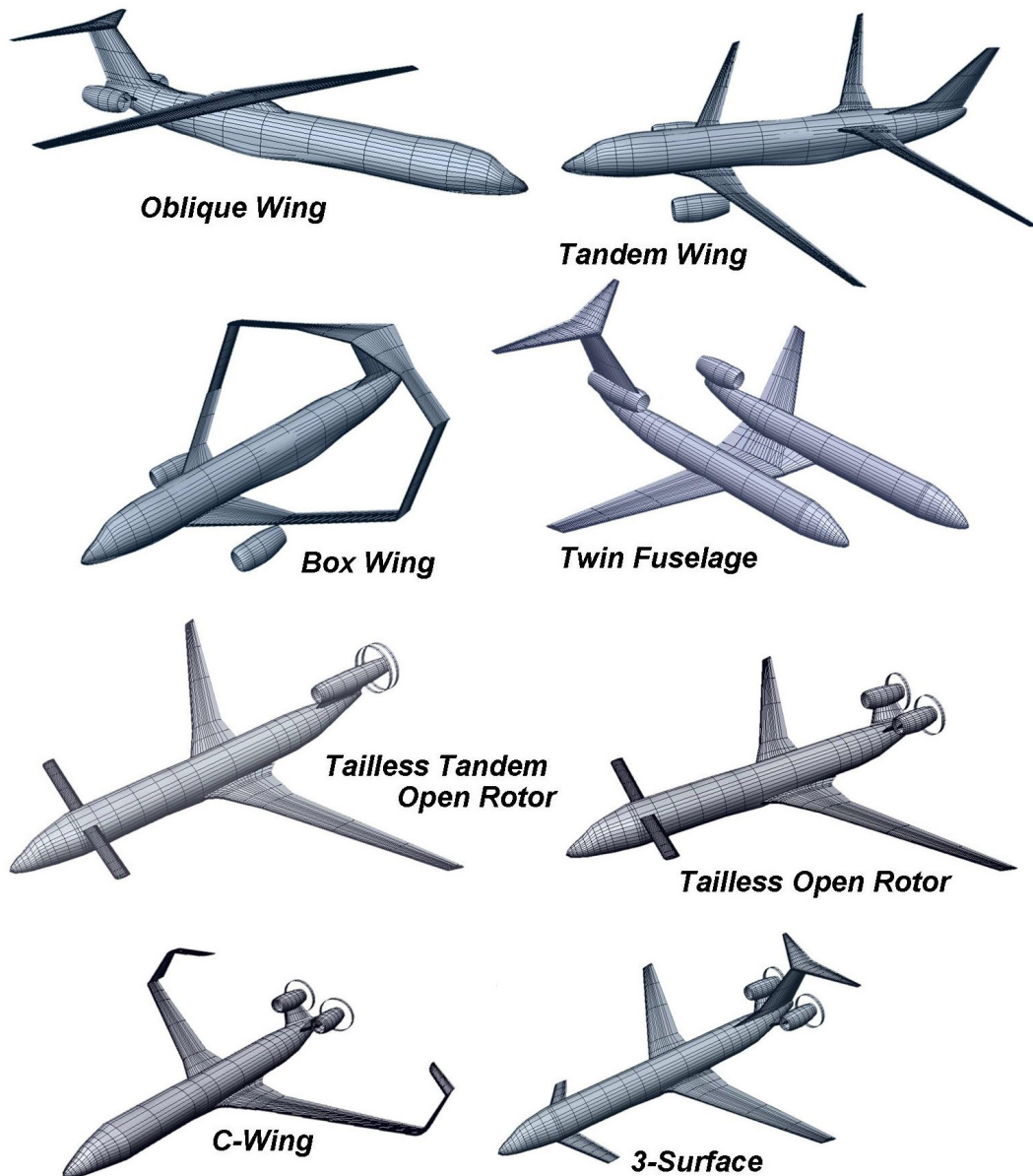


figure 10. Advanced Design Concepts (2)

The best way to get a dramatic reduction in drag is to substantially reduce the wetted area. One way to do that would be to get rid of the tails, as shown in the next two concepts. In this Tailless design, little pop-out canards are provided to trim the pitching moment from the wing flaps, otherwise the airplane would be controlled using wing surfaces, wingtip drag rudders, and possibly rudder-like surfaces on the engine pylons. Perhaps forebody vortex control could also be used, or at the edge of credulity, cyclic control on the open rotor blades. This concept, which became the preferred approach, is described below in greater detail.

The C-wing is an extension of the winglet, literally a winglet on a winglet. This provides the same drag reduction for the winglet that the winglet provides to the wing. As can be seen in the design illustration, this last extra surface can also be used as a horizontal tail for pitch control

and trim. The obvious problem, though, is the structure. These tip-mounted surfaces would cause substantial twisting in the wing, especially if used as control surfaces. There will be a severe weight penalty and a great potential for flutter. Again, it is worth a look.

The final option is similar to the Piaggio Avanti, an executive turboprop in production in Italy. This uses three surfaces, a wing, an aft tail, and a canard. This provides good pitch control and ease of trimming, and also offers a theoretical reduction in trimmed drag. Basically, the downwash from the canard cancels out the upwash from the tail resulting in a farfield downwash distribution which can be tailored to the optimal elliptical shape. There is also a possible reduction in the wing area since the canard is making lift too. It is unclear whether the total aircraft wetted area is reduced by this concept – in this study it was not.

Also, the projected benefits of the three surface design typically apply only in comparison to a conventional aircraft design where the tail must create a download for stability and trim. Modern aircraft use computerized flight control systems to virtually eliminate this problem.

(Note: These concepts were previously presented to a non-technical audience in the mass-market book *Living in the Future*¹²)

8. *ADVANCED CONCEPTS ASSESSMENT*

While funding did not permit an exhaustive analysis and comparison of each of these designs, a preliminary study was conducted of two key issues which often dominate any discussion of potential improvements: trimmed maximum lift coefficient, and design wetted surface area. These were used for an initial ranking.

First, these designs were all adjusted to approximately the same lifting capability by scaling wing areas up or down depending upon estimated trimmed lift capability. Relative lifting abilities were estimated based on the total areas of the lifting surfaces, with adjustments based on the likely use of high lift devices. A wing surface far to the rear of an aircraft cannot use large flaps – the design can't be trimmed. Such a design would need a greater total lifting area.

In the absence of a detailed computational aerodynamics study, preliminary estimates of flap effectiveness were made based upon historical lift data and approximate balance estimates. It was assumed that all lifting surfaces would have the same lift per exposed area without flaps. Then the flap effectiveness for each was estimated including trim and nacelle effects. This took into account trim issues, with a wing near the center of gravity assumed to have flaps as effective as on a normal airliner, while a wing far to the rear would be credited with only 20% of the extra lift from flaps*. The B-737 has nacelles on the wing which reduce the trailing edge span available for flaps so concepts with tail-mounted engines gain about 10% in flap effectiveness. This is shown in the table below (file names are the RDS design layout files).

* These qualitative assessments are debatable, and a detailed analysis should be made. However, the trim effects cannot be ignored. There are canard aircraft that require the wing trailing edge surfaces to be deflected *upwards* for landing, since the wing is so far to the rear. There is definitely a penalty - the question is how much.

Description	FileName	Sref	Main Wing Flap % effect.	2nd Wing Flap % effect.	Relative Lifting Ability
Baseline 737	B737-800	1255	1.00	0	1.00
OpenRotor Aft Engine	NASAWLD1.DSN	1255	1.10	0	1.10
OpenRotor U-tail	NASAWL1A.DSN	1255	1.10	0	1.10
Tandem OR U-tail	NASAWL1C.DSN	1255	1.10	0	1.10
OR pusher on wing	NASAWL1D.DSN	1255	0.95	0	0.95
FSW turbofan	NASAWLD2.DSN	1255	0.90	0	1.07
Joined/braced Wing	NASAWL3A.DSN	766	1.05	0.3	0.97
Joined Wing	NASAWLD3.DSN	766	1.05	0.6	0.88
BWB	NASWLD4B.DSN	1255	1.10	0	0.72
Oblique Wing	NASAWLD5.DSN	1050	1.20	0	1.00
Tandem Wing	NASAWLD6.DSN	630	1.00	0.2	0.88
Box Wing	NASAWLD7.DSN	630	1.00	0.2	1.13
Twin Fuselage	NASAWLD8.DSN	1255	0.95	0	0.95
Tailless Tandem OR	NASAWLD9.DSN	1255	1.10	0	1.10
Tailless OR	NASWLD10.DSN	1255	1.10	0	1.10
C-Wing	NASWLD11.DSN	1255	1.05	0	1.05
3-Surface	NASWLD12.DSN	1255	1.10	0.8	1.21

figure 11. Advanced Design Concepts Lift Assessment

Based on these assessments of relative trimmed maximum lift, each design's lifting surfaces were scaled to give that design the same total lift as the B-737. Tail areas were adjusted in proportion to wing area adjustments. Concepts with tail-mounted engines suffered due to the extra wetted area of the nacelle pylons, vs. the B-737 wing-mounted nacelles which use miniscule stub pylons.

Total wetted areas were recalculated for each design, and then the concepts were sorted by total wetted surface area relative to the B-737 baseline (table below). Some concepts which appeared beneficial based on their initial layout lost their appeal when lift and wetted surface area were taken into account.

Description	FileName	Sref	scale factor to normalize lift	S-wet after lift normalized	S-wet relative to baseline
Tailless Tandem OR	NASAWLD9.DSN	1255	0.909	7422	85.3%
Tailless OR	NASWLD10.DSN	1255	0.909	7843	90.2%
Tandem OR U-tail	NASAWL1C.DSN	1255	0.909	8548	98.3%
Joined/braced Wing	NASAWL3A.DSN	766	1.029	8565	98.5%
C-Wing	NASWLD11.DSN	1255	0.952	8585	98.7%
Baseline 737	B737-800	1255	1.000	8696	100.0%
FSW turbofan	NASAWLD2.DSN	1255	0.931	8700	100.0%
OpenRotor U-tail	NASAWL1A.DSN	1255	0.909	8780	101.0%
3-Surface	NASWLD12.DSN	1255	0.826	8797	101.2%
Tandem Wing	NASAWLD6.DSN	630	1.141	8814	101.4%
OR pusher on wing	NASAWL1D.DSN	1255	1.053	8897	102.3%
Oblique Wing	NASAWLD5.DSN	1050	0.996	8910	102.5%
OpenRotor Aft Engine	NASAWLD1.DSN	1255	0.909	8920	102.6%
Joined Wing	NASAWLD3.DSN	766	1.140	9188	105.6%
BWB	NASWLD4B.DSN	1255	1.385	9424	108.4%
Box Wing	NASAWLD7.DSN	630	0.883	9734	111.9%
Twin Fuselage	NASAWLD8.DSN	1255	1.052	9796	112.6%

figure 12. Advanced Design Concepts Sorting

The only concepts that significantly reduced the lift-normalized wetted area were those that completely eliminated the tails. Most other concepts wound up about the same as the baseline B-737. Note that plus or minus 5% is probably within the “noise level” for this approximate analysis.

The best concept was the Tailless design with a single nacelle containing twin tandem open rotor engines. This seems to be difficult or impossible to integrate, so it was dropped from consideration in the end. The Tailless design with two separate nacelles was next best, showing a potential 10% reduction in wetted area and hence parasitic drag. It became the baseline for further study as described below.

The worst concepts are those that add a lot of wetted area such as box wing and twin fuselage. The Blended Wing Body, developed to reduce wetted area in large aircraft, actually increases it for a smaller transport. This occurs because of packaging - it isn't possible to fit people and cargo into the BWB shape without a lot of wasted volume, and that leads to extra wetted area. All the “good” concepts have a conventional airliner “cigar” fuselage.

Another key result is that, unfortunately, none of these advanced concepts appears to be vastly better than the baseline Boeing 737, so it appears that an exotic configuration, by itself, is unlikely to “save the day.” In fact, it may prove in the end that a traditional Boeing design, looking like the 737, 757, and 767, is about as good as you can get. That means that tomorrow's 737 replacement, like the B-787, may look fairly normal from afar while incorporating the latest advanced technologies “under the skin.”

These comparisons do not yet include the weight effects. Qualitatively, weight tends to be related to total wetted surface area so the four concepts with the greatest wetted areas are likely to be heavier as well as “draggier.” This is another benefit of getting rid of the tails – missing tails weigh nothing. Of course, the unknown mechanisms that must be used to provide control and trim will weigh something. Only a detailed study can sort things out.

Designs with high aspect ratio wings are heavier. This is especially a problem for the tandem wing where chord length was halved to maintain span with a similar total wing area. A more detailed study may find a more-optimal approach than this theoretical assumption, but it is doubtful that the tandem wing will ever look good simply because the back wing cannot use large flaps.

The Oblique Wing should show a substantial weight savings in the wing itself, since it has zero effective structural sweep. The pivot mechanism and landing gear installation will add back some weight.

9. PREFERRED CONCEPT – TAILLESS AIRLINER

Concept Selection and Sizing

With everything considered, the advanced design concept with the best potential for obtaining meaningful improvements seems to be the Tailless approach. It alone provides a substantial reduction in wetted surface area once the wing size is adjusted to provide equivalent lift. Reduced wetted surface area leads directly to reductions in both parasitic drag and weight - if this obviously-risky design approach can be made to work. The Open Rotor propulsion system, while not essential to the Tailless design approach, seems to offer the greatest payoff in terms of engine specific fuel consumption and is included in this baseline.



figure 13. Preferred Concept Tailless Airliner

Of the two Tailless designs shown in figure 10, the better in terms of wetted area is the one with both of its Open Rotor propulsion systems integrated into a common nacelle. Such an approach is not unheard of - several large propeller-powered aircraft like the new Dornier Seastar CD2 have used twin engines in a single nacelle, back-to-back with a tractor propeller at one end and a pusher propeller at the other. Alternatively, the never-produced LearFan flew well with twin, side-by-side turboshaft engines driving a single pusher propeller.

It is possible that one of these approaches could result in a workable tandem nacelle Open Rotor approach. However, the greater core massflow of the Open Rotor system would make it difficult to have the exhaust from the front engine get safely past the second engine and rear-mounted rotor, so both engines were assumed to be at the rear. This still leaves a substantial packaging problem, with twin tandem core turbojets, shafting to get mechanical power from

each core to its respective Open Rotor, perhaps gearboxes, and the ducting associated with intake air and core exhaust flow. In the concept layout shown above this was roughly “eyeballed” but subsequent review by CRC and NASA indicates that such packaging is closer to “impossible” than merely “difficult.”

Thus, the twin-nacelle Tailless Open Rotor design was selected as the most-promising approach with a reasonable chance of success. A detailed configuration design layout of this preferred concept was made using RDS-Professional. First an “unsized” layout was done (NAS1, not shown), assuming the same takeoff gross weight as the B-737-800. The fuselage geometry was a virtual copy in terms of length and diameter, with slight reshaping to accommodate the retracting canard. The engines were analytically scaled to provide equivalent thrust. Wing area of the unsized design matches that of the B-737, as do tire sizes.

The wing aspect ratio is substantially higher than the B-737. This offers a major improvement to the drag-due-to-lift (induced drag) but is normally not permitted due to the weight penalty. As discussed below, the Active Aeroelastic Wing (AAW) technology permits a higher aspect ratio with minimal weight penalty, and is potentially a key enabler for N+3 aircraft. Note that the total wing span of 115 feet, despite the higher aspect ratio, is only 2.6 feet (2%) greater than the B-737 once sizing effects are taken into account (below).

This unsized layout was then analyzed as to aerodynamics and weights. Along with NASA-provided propulsion data, these results were used to resize the airplane, yielding a takeoff gross weight (W_o) of 122,592 lbs and a fuel weight (W_f) of 17,203 lbs. This sizing should allow the airplane to carry the same payload over the same FAR mission range as the B-737-800. The baseline design (NAS2) was redrawn accordingly, as shown in figure 14 and figure 15. The fuselage stayed about the same, but the wings, landing gear, engines, and canards were reduced in size since the aircraft weight was reduced. A description of the features of this baseline design follows.

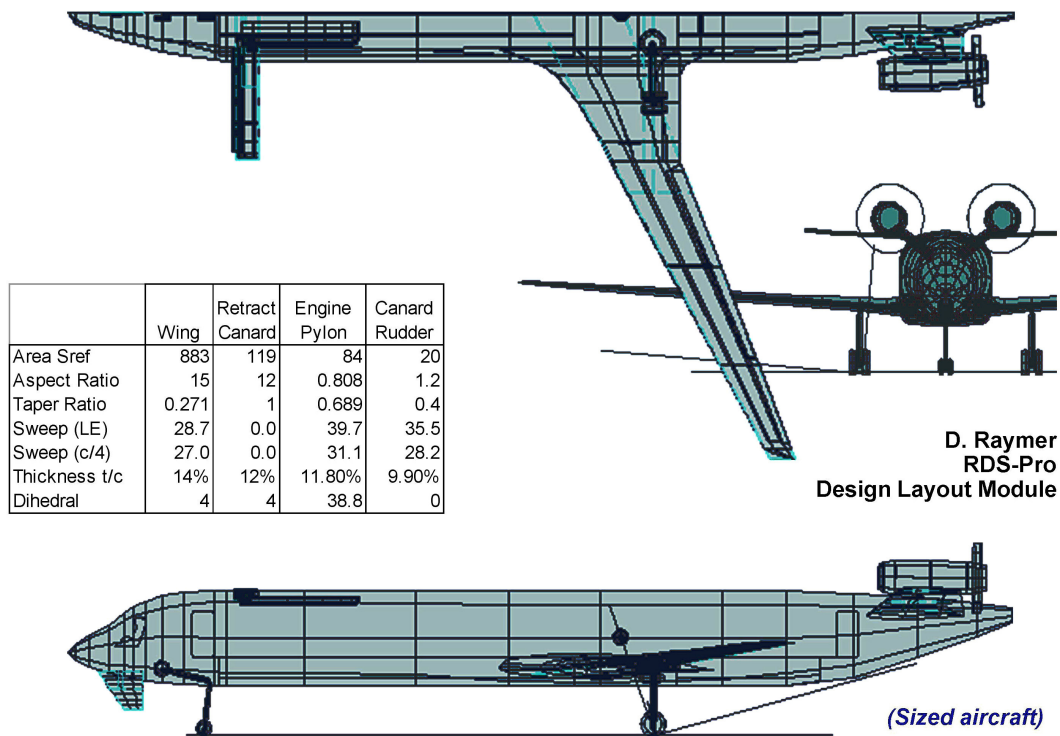


figure 14. NAS2 Vehicle Internal Arrangement Three-View

The NAS2 preferred concept is a normal airliner in most regards, with a conventional airliner fuselage, passenger compartment, cargo bay, cockpit, landing gear, and aft-fuselage-mounted engines. In some ways it looks like the old DC-9. The big difference, of course, is the absence of both vertical and horizontal tails.

Its fuselage would be fabricated from next-generation advanced composites. The passenger and cargo arrangements are similar to the B-737, including doors, galleys, toilets, and all the mundane details of airliner design. Landing gear is conventional, but presumably lighter in weight using composites or advanced metallics.

The two-man crew station is conventional in arrangement but would incorporate the latest in display and control technology. By that time frame a one-man crew might be used, with sufficient automation to land the plane should the pilot become incapacitated. Even an unpiloted airliner may occur by this time frame but in all the vehicle analysis below, a two-man crew was assumed.

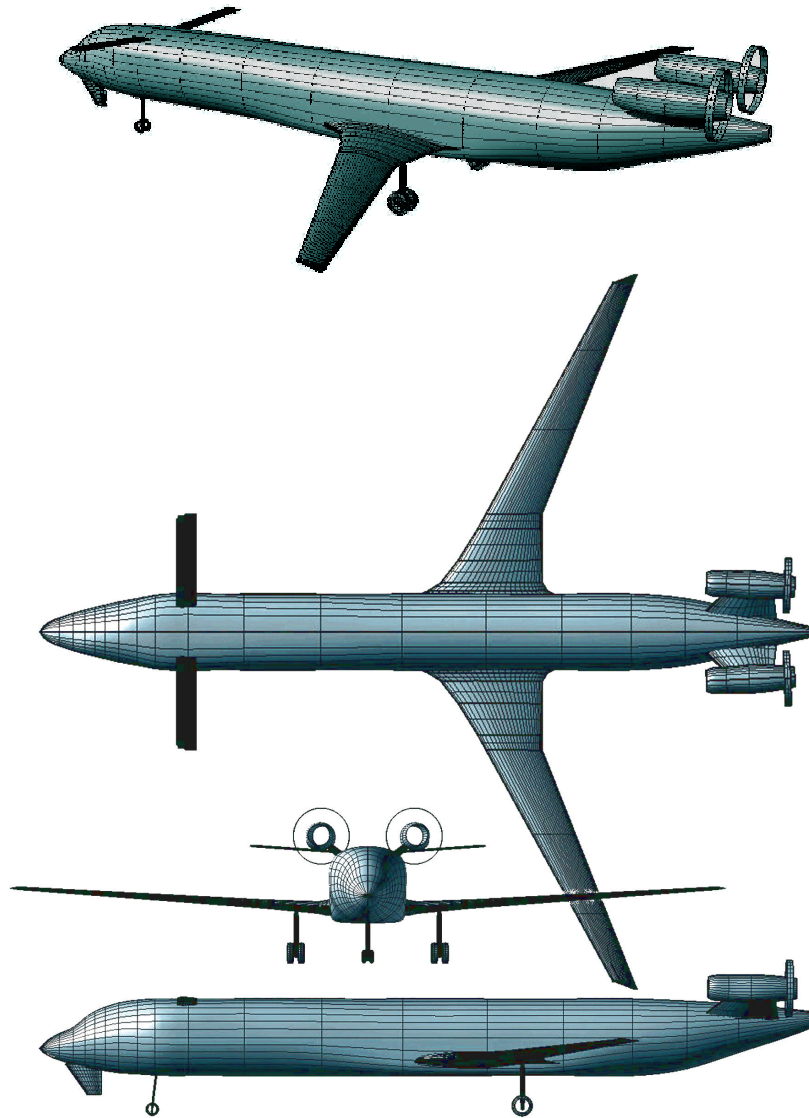


figure 15. NAS2 External Arrangement (Sized)

Enabling Technology: Retracting Canard and Chin Rudder

The obvious difference in this design compared to current airliners is the aft tails. There aren't any. This saves a lot of weight and drag (wetted surface area) but so far, all airplanes of this configuration have needed tails.

Eliminating tails provides much of the benefit of the flying wing. The Blended Wing Body discussed above is a direct result of attempts to provide these flying wing benefits in a design with sufficient room for passengers. Unfortunately, packaging considerations make the BWB a poor choice for smaller airliners. There is just too much wasted space. This tailless design can be seen as an attempt to get the same benefit - a reduction in wetted area and weight - in an airliner with tighter internal packaging.

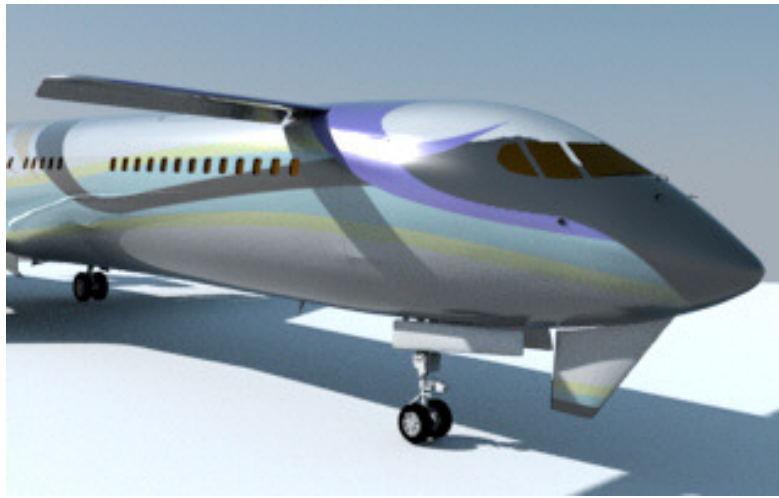


figure 16. NAS2 Showing Chin Rudder and Retracting Canard

Tails are needed for three things - stability, control, and trim. With a modern flight control system, stability is unneeded as long as sufficient control is attained. This design philosophy has been in use since the F-16 for military aircraft. The N+3 timeframe will be 50 years after the F-16 entered production. It is time for that technology, like so many military technologies before it, to be accepted for airliners. So forget stability - we just need control.

However, we must also make sure that trimming the aircraft under widely-variable loading conditions does not cause excessive trim drag. Airliners see wider ranges of payload cg location than do fighters and bombers. To provide trim, the nacelle pylons have movable “ruddervators” at the trailing edge. These are also used for additional pitch and yaw control when needed.

In addition, the wing itself will provide pitch and yaw control as well as the traditional roll control. This is done using the Active Aeroelastic Wing (AAW) technology, described in a separate section below.

A retracting canard horizontal tail surface is provided, mostly to counter the huge nose-down pitching moments created by the large wing flaps. On a normal, aft-tail configuration, the horizontal tail deflects to an extreme angle when flaps are extended, creating a download just when additional lift is desired. This retracting canard was sized by these flaps-down moments, with a 15% lift excess for control purposes. Extending the retractable canard also adds lifting surface for takeoff and landing, allowing the actual wing to be smaller for reduced drag during cruise.

This canard mechanism, when extended, is similar to that of the Boeing Sonic Cruiser where a lot of technology development work was put into exactly such a system. This design is similar, but adds retraction to the problem. This would be similar to the wing pivot on the B-1 or F-14. Luckily, “N+3” means that there is a lot of time to develop practical mechanisms.

The canard also provides pitch control and trim during takeoff and landing. When the canard is retracted, these are provided by a combination of wing moments (like the B-2) and nacelle pylon ruddervators.

Note that this design is *not* simply a new form of the rarely-used lifting canard configuration. In our design the canard retracts completely for efficient cruising flight. In the Sonic Cruiser and recent studies by a major contractor, the design is a LIFTING canard. This acts much like a tandem wing and, like a tandem wing, is less efficient for lifting than a wing by itself. For stability reasons the canard of such a design is usually carrying more than its proportional share of the weight, leading to inefficiencies. This problem with lifting canards has been known since the 1930's by airplane designers, and is why that type is rarely seen. The NAS2 design reported herein is a tailless design during cruising flight, with its pop-out canard only used when wing flaps are deployed.

A computational aerodynamic study with detailed 6-DOF dynamic simulation is required to properly assess canard sizing and elevator actuation requirements. Hand calculations were used to initially size the required surfaces.

For yaw control, the preliminary layout assumed a to-be-determined solution. After considering wingtip drag devices, vectored thrust, and forebody vortex control, an all-moving chin rudder was designed for the actual NAS2 layout. Since it is farther from the aircraft center of gravity than an aft vertical tail, it can provide the same yawing control with a smaller area. Being all-moving, it provides more control authority and can be made even smaller.

While the chin rudder could also be retracting, it is probably not worth the trouble and was left fixed in this design. It was sized to provide adequate yaw authority for an engine-out case, with a 10% force margin.

Nacelle pylon ruddervators, along with wingtip drag control (see below), provide an additional margin for extreme yaw upsets. This too needs a full analysis and dynamic simulation.

Both the horizontal canard and the vertical chin rudder make the aircraft unstable, requiring high-speed actuation and a sophisticated computer system. While ambitious for a commercial airliner, such technology has been flight tested in the pitch axis numerous times, most notably on the X-31. Applying the same technology to the yaw axis should pose no insurmountable problem in the N+3 timeframe.

The X-31 program also demonstrated the technologies for flight without a vertical tail, but in a manner not quite identical to that proposed here. In the “Quasi-Tailless Flight Demonstration” program¹³, the X-31’s computerized flight control system was modified to have the rudder and ailerons deliberately negate the stabilizing effects of the vertical tail. Then the nozzle vectoring system was used to stabilize the aircraft in yaw. With the tail fully removed, aerodynamic lateral stability would go from +.0040 to -.0018 at Mach 1.2 which is beyond the yaw authority of the nozzle vectoring so a “partial tail removal” scheme was implemented. Flight test reached 70% effective tail removal, a good demonstration but not quite full tailless flight. However, the X-31 wasn’t originally designed for tailless flight and has no suitable controls other than the nozzle, which was not designed with tailless flight in mind.

More recently the McDonnell Douglas/Boeing X-36, having no vertical tail, did fully demonstrate tailless flight¹⁴. X-36 was naturally unstable in the yaw axis and used an advanced thrust vectoring nozzle for directional control. In 1997 this unmanned technology demonstrator made 31 flights and is said to have flown quite well.

The relevant lesson-learned from these flight test programs is that such tailless flight using artificial stability is indeed possible, but it is necessary to have sufficient control authority. In the NAS2 design this is provided by the chin rudder with augmentation as needed from the

pylon ruddervators and the application of wingtip drag via the Active Aeroelastic Wing. An important objective of future studies will be to perform CFD and 6-DOF studies in enough detail to confidently size the chin rudder to meet all contingencies in a manner consistent with flight safety and relevant FAR's. This is further discussed in the CFD section below.

Enabling Technology: Active Aeroelastic Wing

One of the most exciting technologies that could be applied to N+3 airliners is the Active Aeroelastic Wing (AAW)¹⁵. Developed by Rockwell International (now Boeing) during the Advanced Tactical Fighter (F-22) program and flight tested on the X-53, AAW can provide 3-axis flight control, modulate drag, alleviate gust loadings, reduce wing weight, and permit higher aspect ratio wings.

Originally developed to solve problems with excessive flexibility in Rockwell's Advanced Tactical Fighter design, the AAW was first conceived as simply a computerized implementation of a part of every B-47 pilot's training. As described in *Living in the Future*¹²;

“The B-47 was the first high-speed jet with long, thin, skinny swept wings. It had such bad roll reversal that Boeing had to add wing spoilers. Above 450 kts the plane is rolled using spoilers to kill some lift on one side. But sometimes the spoilers broke. So the pilots trained to fly the plane backwards. They'd take it up to about 500 kts, pull the spoiler circuit breaker, and practice moving the stick to the right to roll the big bomber to the left.”

In the AAW, the wing is deliberately made “wimpy” with less-than-usual torsional stiffness. Normally, torsional stiffness requirements substantially increase the weight of an airliner's wings and are frequently the most-critical loads on the outer third or more of the wing. So weight is saved, right at the start.

Next, high-speed actuators are used on both leading edge and trailing edge control surfaces. Rather than traditional airliner slats, the leading edge movable surfaces are designed like those for fighter wings, pivoting flaps that can be deflected at low and high speeds. They can deflect up as well as down.

Finally, a computerized control system is implemented to deflect those surfaces properly. For roll control, the trailing edge surfaces deflect like normal ailerons at low speeds. At higher speeds they deflect in the opposite direction. If the trailing edge control surface is deflected downwards it sees increased lift, which lifts the back of the wing box and twists the wing leading edge down. This twisting reduces the lift. At higher speeds, enough twist is obtained to overpower normal aileron effect and the net force is downward. Like the B-47, the airplane rolls in the opposite direction.

Similarly, downward deflection of the leading edge flaps produces a download at the front of the wing box, twisting the wing leading edge down.

This wing twisting ability can also be used to twist both wings leading edge down, reducing lift out at the tips. This can be used for gust alleviation, for optimizing spanwise lift distribution for

drag and structural relief, and for pitch control much like the elevons of a flying wing. The high-speed gust alleviation will reduce wing structural loads, reducing weight even more and allowing a higher aspect ratio wing.

AAW even allows the creation of additional wingtip drag for yaw control and to act as speed brakes. This is done by deflecting the leading and trailing edge surfaces so that they “fight” each other, each trying to twist the wing in the opposite direction.

The Active Aeroelastic Wing is at TRL 6 or 7 for application to commercial airliners. It was flight tested on a modified F/A-18 Hornet as a joint project of the Air Force Research Laboratory, Boeing Phantom Works and NASA Dryden. The F-18, renamed X-53, was modified to make its wings more flexible. It flew in 2002 and made over 50 flights, half of which were supersonic¹⁶.

Given that most commercial airliners must lock out the outboard ailerons in high-speed flight to prevent roll reversal, the fruitful application of AAW seems assured.

10. TAILLESS AIRLINER ANALYSIS & ISSUES

Aerodynamics

While not visible on the drawing, a number of advanced technology aerodynamic improvements were assumed for the NAS2 design. An increase in laminar flow from a current 10% to an overall 25% assumes the use of CFD for design shaping, smoother skins from composite material, better fabrication quality, and possibly active suction in key areas. The flat-glass windshield drag penalty of the B-737 was eliminated, as is the case for the B-787.

In classical airliner aero analysis there is a substantial penalty from the bottom rear of the fuselage, where the contour suddenly angles up towards the tail. This “upsweep angle” as used in a common drag equation was reduced from the actual 8 degrees, to 6 degrees representing improvements in bottom flow separation via CFD, optimal design, and possibly local suction.

The induced drag receives an obvious credit for the high aspect ratio wing, permitted by the use of AAW technology.

Of course, the greatest improvement in aerodynamics comes from the reduced wetted surface area brought about by the tailless design approach.

Aerodynamic analysis for the NAS2 design was done using the classical methods in the RDS-Professional program¹⁷. As described above, this analysis was calibrated to the B-737-800 and gave good results. Subsonic parasite drag was estimated by the component buildup method. Key aerodynamic assumptions and sample parasitic drag results are listed below.

- Smooth Paint Equivalent Roughness
- 25% Laminar Flow (averaged over whole surface)
- 4% Leakage & Protuberance Drag applied to total wetted area drag

		Altitude = 30000. ft		Mach = 0.80		Velocity = 471.5 (kts)			
	#	R# 10 ⁶	Cf	FF	Q	Adj	S-wet	Cdo	
WING	1	19.433	19.921	1.553	1.000	1.000	1954.2	71.2	
FUSELAGE	1	285.230	13.265	1.092	1.000	1.000	4350.9	95.5	
					Includes Upsweep drag= 20.4				
NACELLE	2	32.419	18.322	1.076	1.000	1.000	190.0	8.8	
PYLONS	1	23.590	19.292	1.479	1.000	1.000	171.3	5.8	
								Drag rise or Wave Drag coeff Cdw	13.7
								TOTAL PARASITE DRAG COEFFICIENT Cdo	195.0

-Drag is referenced to the theoretical reference wing area: Sref=883 sqft
 -Drag is expressed in "counts" - multiply by .0001 to get coefficient

figure 17. NAS2 Aerodynamic Analysis

The drag results below are from the unsized NAS2 design, with the same wing as on the B-737. This illustrates the total 33% drag savings obtained from these combined improvements. The individual contributions are detailed in the next figure.

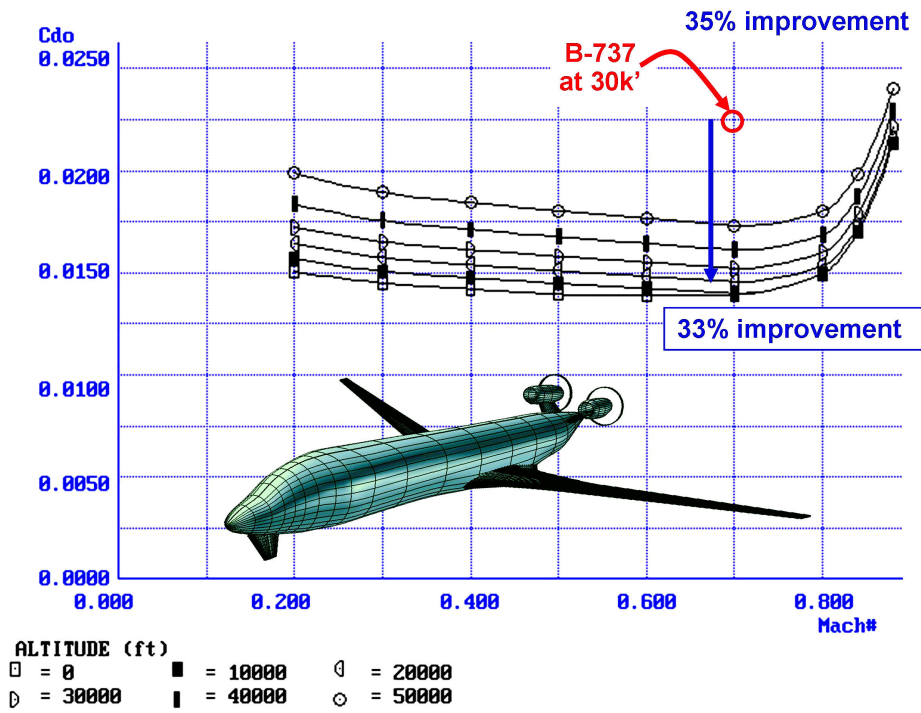


figure 18. NAS2 Parasitic Drag Comparison (unsized NAS2, ref. to B-737 wing area)

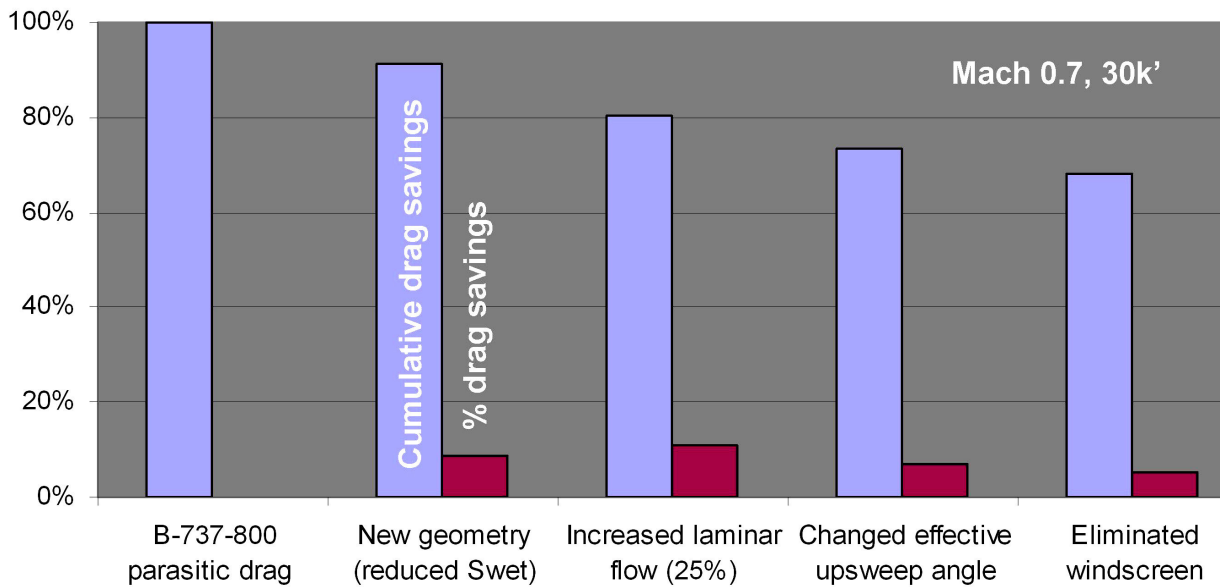


figure 19. NAS2 Drag Savings vs. B-737

The drag-due-to-lift was calculated by the leading-edge suction method using a calculated lift curve slope based upon DATCOM methods. A leading-edge suction schedule typical for commercial transports was employed, based on the design lift coefficient.

The ultimate drag measure of merit is the aircraft's total lift-to-drag ratio (L/D), which includes parasitic drag and the drag-due-to-lift. This term alone enters into the classic Breguet Range Equation, and the resulting range of an aircraft is directly proportional to L/D. The L/D of the unsized NAS2 is shown below, showing a 52% improvement over the baseline B-737 with the same size wing for comparison sake.

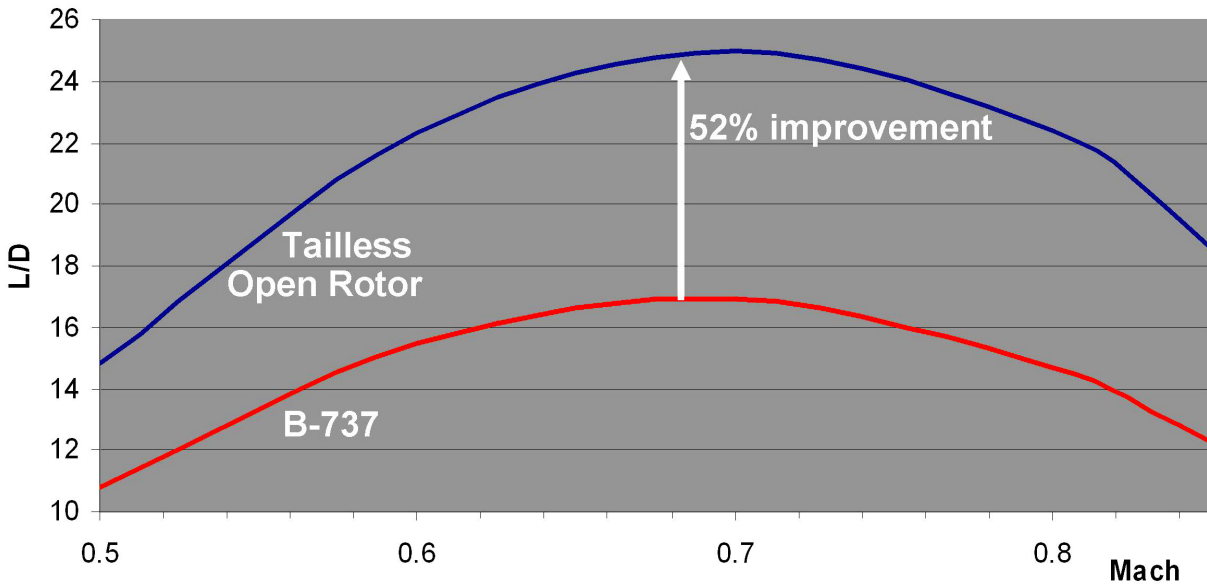


figure 20. NAS2 L/D Improvement vs. B-737

With the limited budget of this project, detailed stability calculations were not permitted. A classical pitch stability method estimated a Static Margin of -4.73 at Mach 0.6 (canard retracted), which is a reasonable goal for an advanced technology, computer-controlled aircraft.

Far more work is required in the area of stability and control. A believable answer will require CFD coefficient analysis and a 6-DOF aeroelastic analysis with active flight controls in the loop. Based on experiences during the design of Rockwell's highly-flexible Advanced Tactical Fighter concept, this author expects ultimate success in the area of control system design including the AAW system. Of course, obtaining FAA certification for such a design will be yet another challenge, but such challenges must be met if our fuel savings goals are to be attained.

Computational Fluid Dynamics (CFD)

To permit computational analysis not budgeted under contract funding, an arrangement was made with Sweden's Royal Institute of Technology (KTH) wherein the external geometry of the NAS2 was provided as a sample case for an ongoing cooperative effort. This effort is aimed at creating a rapid interface between Conceptual Research Corporation's RDS-Professional

Design Layout Module and the CFD model interface program¹⁸ being developed at KTH under the direction of Dr. Arthur Rizzi.

After loading the geometry and converting it via the interface program, KTH graduate student Mengmeng Zhang performed Euler analysis using the Swedish EDGE unstructured CFD solver. Additional analysis was done using the TORNADO vortex lattice method (VLM), especially for analyzing control effectiveness. These results should be considered preliminary since the goal of the KTH researchers was tool development¹⁹ and not final aerodynamic calculations. Nevertheless, the results are of considerable interest to this project.

One calibration point can be extracted from the data which allows comparing the results from the classical analysis in RDS to the Euler result. The difference in C_L from 0 to 1 degree at Mach 0.8 in the Euler analysis gives a $C_{L-\alpha}$ of 0.155 per degree. The RDS classical analysis, mostly based on DATCOM, gives $C_{L-\alpha} = 9.18$ per radian, or 0.160 per degree.

Pressure profiles from the Euler runs are shown below, at Mach 0.8 and one degree angle of attack. Nothing unusual is seen, although better streamlining of the cockpit area appears in order. A closer investigation showed that the RDS geometry in this area is a bit rough, having originally been based on the B-737 cockpit like all of the fuselage. In a subsequent study it should be smoothed out, like on the B-787 (which itself is based on the deHaviland Comet, in a full circle of jet aircraft history).

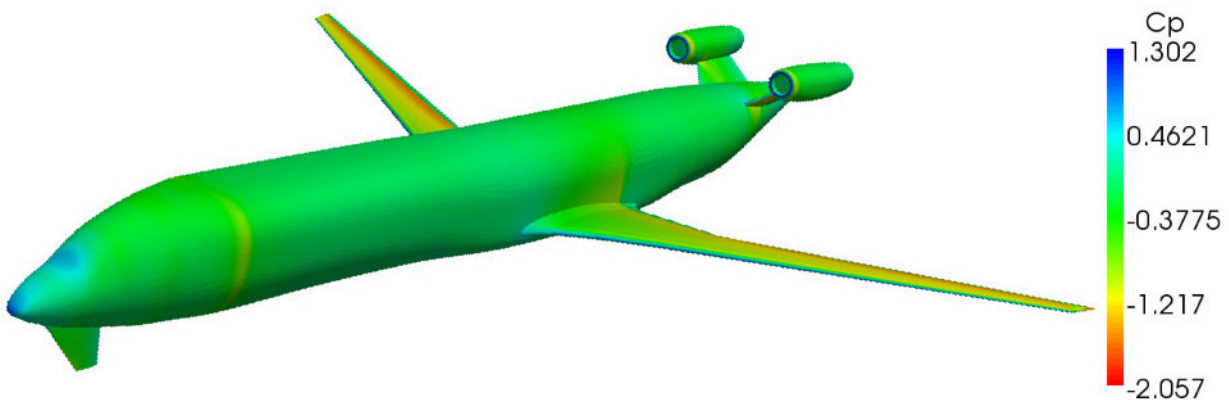


figure 21. NAS2 CFD Analysis

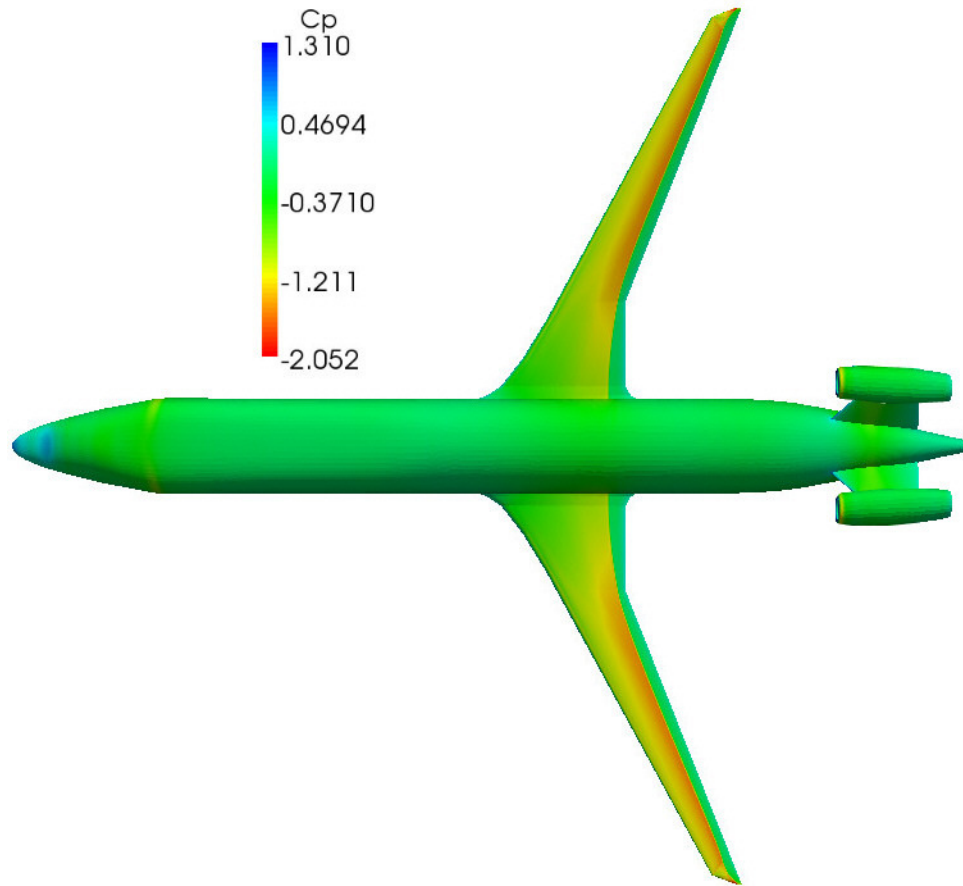


figure 22. NAS2 CFD Analysis (beta=3deg)

Given the absence of a traditional vertical tail, the most critical calculation for this exotic design is the yaw control via chin rudder. It is assumed that stability is provided artificially, but to make that happen, adequate control must be assured. To improve effectiveness, the chin rudder is all-moving and in an ideal location for control effectiveness, being both at the front of the aircraft where good flow quality is assured, and being at the end of a long moment arm relative to the center of gravity.

It must be assumed that the chin rudder actuator will be totally fail-safe and will operate at a high enough pivot rate and frequency that its time lag will be negligible. This is not a problem for modern flight control actuators, being just a matter of cost and weight. The X-31 canard is a good example, and that flew over 20 years ago. Of course, one of the X-31's crashed due to a flight control system failure, but that involved a non-redundant, unheated pitot tube which was inadvertently taken into icing conditions.

When developing the NAS2 design layout, the chin rudder was sized based on countering the yawing moments produced during an engine-out event. These include the unbalanced thrust of the remaining engine, and the drag of the inoperative engine and its open rotor. These drags were approximated in the absence of manufacturer's data, but shouldn't be too far off.

However, engine-out control is not the only concern for the design of the chin rudder. As an unstable system, the control effector must provide a sufficient restoring moment from a sideslip

condition. The control gain is also important. This is the number of degrees of deflection required to counter a single degree of system offset, in this case being a yaw or sideslip. If it takes, say, 5 degrees of rudder deflection to create a restoring moment in the event of a one degree yaw upset, the gain is probably too high. The problem is, what happens if there is a huge lateral gust or other upset that causes a 10 degree yaw offset? It would not be practical to expect a 50 degree chin rudder deflection to correct the yaw. The chin rudder probably stalls at 25 degrees deflection or less.

A conservative rule of thumb for aft control surfaces is to limit the gain to one. A 10 degree sideslip offset would require only a 10 degree deflection of a traditional rudder. Note that for a traditional aft rudder, attached to the aircraft, that 10 degrees of sideslip already provides 10 degrees of rudder deflection relative to the freestream. A gain of one is, in effect, a total gain of two. This is the conservative rule of thumb for gain, re-expressed in terms of the freestream.

For an all-moving canard surface (vertical or horizontal), the computer can easily actuate the surface to “weathervane.” In other words, if the aircraft nose deflects 10 degrees to the left, the computer automatically pivots the chin rudder 10 degrees to the right, so that it remains aligned with the freestream. If it is then pivoted an additional 10 degrees to the right for a total of 20 degrees relative to the body axis, there is a mechanical gain of two that is, in effect, a gain of only one relative to the free stream.

While of a preliminary nature, the Euler code analysis indicates that the yawing moment at Mach 0.8 and three degrees of sideslip is about 0.00297. A vortex lattice analysis of the chin rudder gives its yawing moment (C_n) per degree as about -0.0005, so about 6 degrees relative to the freestream provides the required moment. This is a gain of two relative to the freestream, identical to the “rule of thumb” discussed above.

Obviously this result is preliminary and is subject to revision as detailed analysis becomes available. Still, it is encouraging that an Euler analysis seems to support the basic notion of an unstable tailless commercial transport that uses an all-moving chin rudder to provide both yaw control and artificial yaw stability. This creative definition of gain is debatable and only a detailed analysis and simulation will ultimately answer the question, “is this feasible?”

These results conservatively assume that the chin rudder is being used alone for yaw control. As described above, it would be augmented with differential drag from the Active Aeroelastic Wing, and with the ruddervators on the back of the nacelle pylons. These will reduce the gains required for the chin rudder.

One additional effect that awaits detailed analysis - a conventional aft-rudder suffers from aeroelastic effects. The fuselage bending allows deflection of the fixed vertical tail in a direction which reduces net yaw control. With a canard rudder the opposite effect is seen. Fuselage bending will actually increase control effectiveness as the now-bent fuselage generates its own yawing moments. This effect, probably minor, was ignored for this study.

Weights

The empty weight buildup for the NAS2 was estimated in RDS-Professional using classical methods, mostly the Vought Aircraft semi-physics-based empirical transport weight equations⁴. For calibration purposes, these time-honored methods were applied to the B-737-800 as described above, and provided what seem to be reasonable answers. Unfortunately, direct comparison was not possible since the actual empty weight statement of the real airplane is considered company proprietary even after all these years.

For the NAS2, the design geometry was used along with various parameter improvements to the weight model representing advanced technologies. In the absence of a detailed FEM analysis, the reduction in wing weight due to the use of the Active Aeroelastic Wing was approximated by analogy. It was assumed that the AAW technology would minimize the need for torsional stiffness and would also be used to provide maneuver load control, gust alleviation, and flutter suppression, thus countering the weight penalty normally associated with increased aspect ratio. The B-737 wing aspect ratio was parametrically increased by 50% and its weight recalculated. An 18% weight reduction was found to negate the weight penalty, and was then applied to the NAS2 wing.

Weight reduction factors were applied to various aircraft structures to account for the use of next-generation advanced composite materials, namely 15% for the wing, 20% for the canard, 18% for the fuselage, and 20% for the pylon. These are slight improvements over the values that have been widely used for current technology composites. Systems, furnishings, and avionics weights were reduced 25% versus B-737 technology levels.

The additional weight penalty for the retracting canard was estimated by analogy to variable-sweep wings, which normally suffer a 19% penalty. The chin rudder calculated weight was increased by 20% to account for mechanisms and stress concentrations associated with an all-moving surface.

A 5% empty weight margin was then applied on top of the total estimated empty weight. The resulting Group Weight Statement for the unsized aircraft is below. Recall that this is the initial layout using the original B-737 wing area, thrust, tire size, and such, and shows the design and technology savings for direct comparison.

	Weight lbs	Loc ft	Moment ft-lbs		Weight lbs	Loc ft	Moment ft-lbs
STRUCTURES	38381		2683580	EQUIPMENT	23703		1551014
Wing	14201	74.8	1062591	Flight Controls	2819	70.0	197323
Retracting Canard	1130	30.0	33888	Instruments	159	10.0	1593
Chin Rudder	207	6.7	1387	Hydraulics	1109	80.0	88720
Fuselage	14818	60.0	889080	Electrical	2126	80.0	170088
Nacelle & Inlet	1100	112.9	124190	Avionics	1387	10.0	13870
Nacelle pylon	2656	110.0	292160	Air Conditioning	1512	60.0	90714
Main Landing Gear	3488	77.0	268568	Anti-Icing	1307	75.0	97988
Nose Landing Gear	781	15.0	11717	APU installed	660	115.0	75900
				Furnishings & Handling	7843	60.0	470586
				Other & misc	4781	72.0	344232
				5% Empty Weight Allowance	3751	75.9	284744
PROPULSION	12929		1460290	TOTAL WEIGHT EMPTY	78764	75.9	5979628
Engine	5674	112.9	640595	USEFUL LOAD	95436		
Open Rotor & Mech	5038	118.0	594484	Crew	400	9.0	3600
Accessories/Mounts	1708	110.0	187880	Fuel	51856	75.0	3889219
Engine Controls	42	110.0	4620	Oil	110	112.0	12342
			0	Passengers	29160	65.0	1895400
			0	Payload	13910	65.0	904150
			0				
Fuel System	467	70.0	32711	TAKEOFF GROSS WEIGHT	174200	72.8	12684339

figure 23. Unsized NAS2 Group Weight Statement

With all these assumptions, reductions, penalties, and margins, the unsized NAS2 design empty weight estimate of 78,764 is 14% less than the B-737. While in the right direction, this is far less than the top-level goal of a 30% reduction. Since Boeing itself claims a 20-25% weight savings on the current-technology B-787 versus the same design using conventional construction as on the B-737, it is likely that these weight results are conservative for the N+3 timeframe. However, in the absence of detailed structural calculations and subsystems engineering, such conservatism seems appropriate.

Note that the Center of Gravity (cg) travel is a bit excessive, and needs further attention in a subsequent design effort. This is within the “normal” band of early layout problems, and is nothing to be worried about.

The following weight statement is for the resized NAS2 as described below. Component weights are reduced because the wings, canard, tires, engines, and other items are smaller as a result of the “leverage” effect of the sizing process.

	Weight lbs	Loc ft	Moment ft-lbs		Weight lbs	Loc ft	Moment ft-lbs
STRUCTURES	28094		1956000	EQUIPMENT	23024		1501234
Wing	8974	74.8	671463	Flight Controls	2634	70.0	184373
Retracting Canard	659	30.0	19773	Instruments	152	10.0	1524
Chin Rudder	170	6.7	1141	Hydraulics	1021	80.0	81688
Fuselage	12431	60.0	745842	Electrical	2126	80.0	170088
Nacelle & Inlet	747	112.9	84380	Avionics	1387	10.0	13870
Nacelle pylon	2276	110.0	250381	Air Conditioning	1512	60.0	90714
Main Landing Gear	2266	77.0	174459	Anti-Icing	919	75.0	68955
Nose Landing Gear	571	15.0	8561	APU installed	660	115.0	75900
				Furnishings & Handling	7832	60.0	469890
				Other & misc	4781	72.0	344232
				5% Empty Weight Allowance	3000	74.3	222815
PROPULSION	8875		999066	TOTAL WEIGHT EMPTY	62993	74.3	4679116
Engine	3855	112.9	435250	USEFUL LOAD	59599		
Open Rotor & Mech	3423	118.0	403920	Crew	400	9.0	3600
Accessories/Mounts	1160	110.0	127654	Fuel	16029	75.0	1202153
Engine Controls	42	110.0	4620	Oil	100	112.0	11200
			0	Passengers	29160	65.0	1895400
			0	Payload	13910	65.0	904150
			0				
Fuel System	395	70.0	27622	TAKEOFF GROSS WEIGHT	122592	70.9	8695619

figure 24. NAS2 Sized Weight Statement

Propulsion

The Open Rotor propulsion system was defined by NASA-GRC personnel for this study. Its analysis assumed an N+3 collection of propulsion technologies advances in addition to the Open Rotor itself, including an advanced core with an Overall Pressure Ratio (OPR) of 70, advanced materials, improved cooling schemes, and greater component efficiencies. Note that these technologies, when applied to a more-traditional advanced high-bypass turbofan, would yield much of the expected benefit and probably at a reduced weight. Considering the potential noise problems of the Open Rotor, this would make an excellent trade study.

Data representing NASA's Open Rotor engine was provided as a collection of thrust and fuel consumption at various speeds, altitudes, and atmospheric conditions. To populate a complete engine map, those values were extrapolated to other conditions based on previous engine data and in some cases, "eyeball" fairing. The resulting data curves, shown below, were reviewed by NASA-GRC personnel and found to be reasonable for a first-pass design study. The circled points are those originally supplied by NASA.

The engine was assumed to be "rubber", ie., scalable to any desired thrust level. For this study, engine scaling was used to provide the same thrust-to-weight ratio (T/W) as the B-737. Standard engine scaling rules were applied when the NAS2 design was sized to the mission, reducing the thrust requirement.

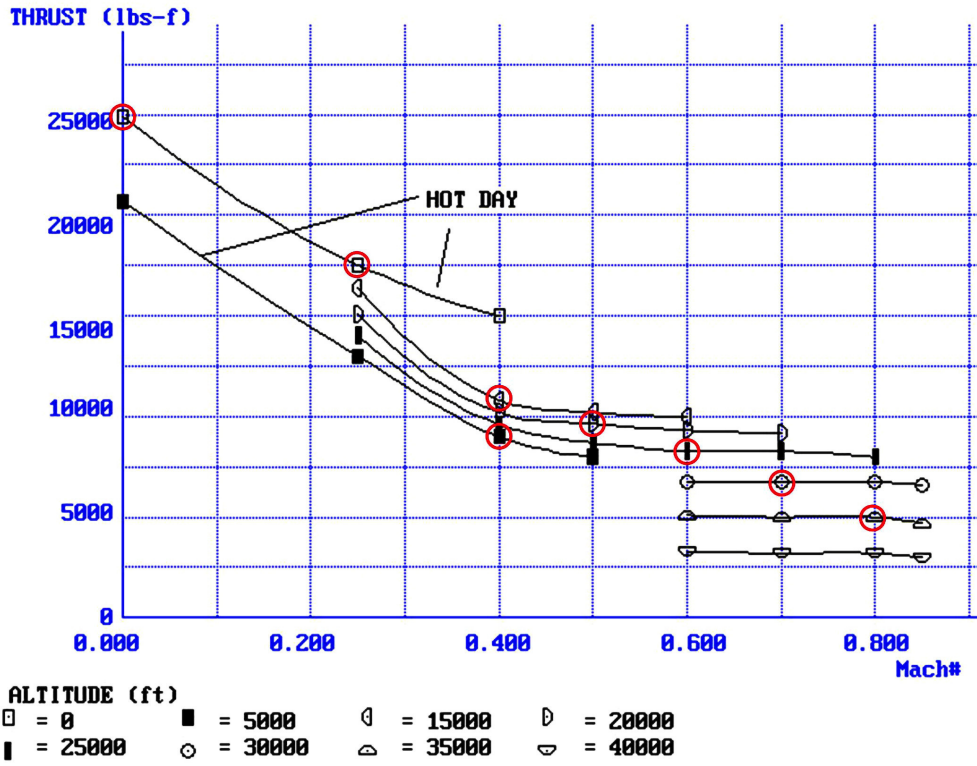


figure 25. Open Rotor Engine Thrust

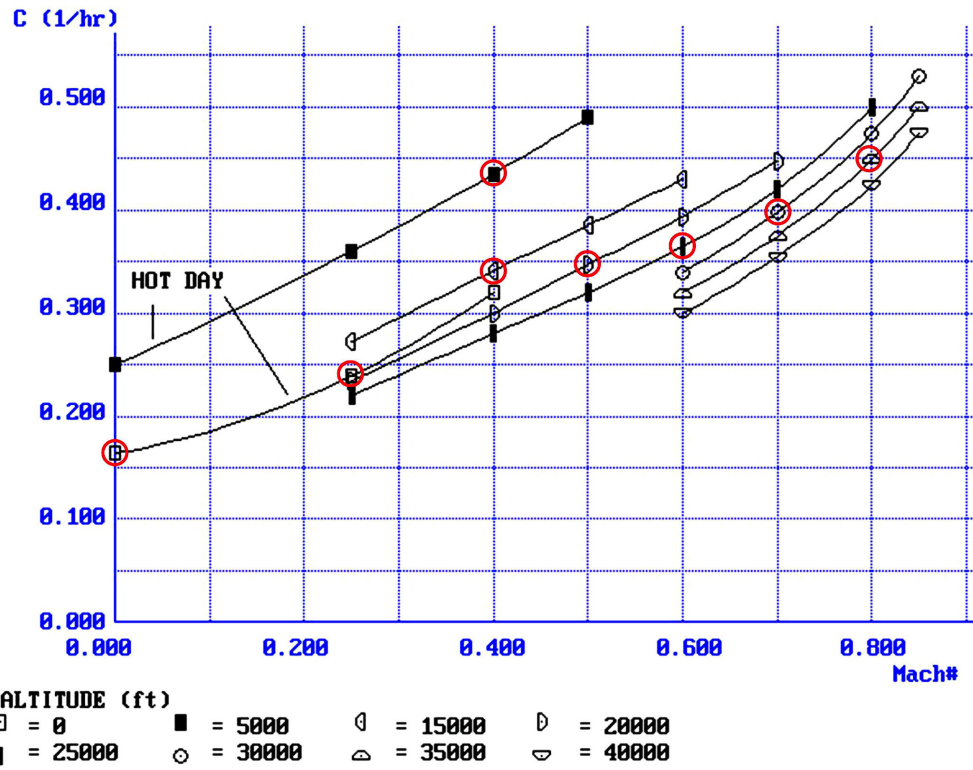


figure 26. Open Rotor Engine Fuel Consumption

Sizing

The NAS2 design was then resized, based on all the calculations above, to the same mission as the baseline B-737. Since the drag, fuel consumption, and empty weight are all much better than the B-737, a smaller and lighter airplane can carry the same passengers and payload over the same distance. Of course, the fuselage has to be about the same size to hold the people, but everything else can shrink.

Sizing results are shown below. The summed fuel consumption is in the far-right column, with the total fuel weight, empty weight, and aircraft takeoff gross weight at the bottom. For a full explanation of these terms and methods, see Raymer².

	MISSION SEGMENT	Wi/WO		FUEL BURN (lbs-m)	
		WEIGHT	FRACTION	SEGMENT	TOTAL
1	TAKEOFF SEGMENT	0.9989	0.9989	143.8	143.8
2	TAKEOFF SEGMENT	0.9987	0.9976	166.7	310.4
3	CLIMB and/or ACCEL.	0.9857	0.9833	1809.4	2119.8
4	CRUISE SEGMENT	0.9472	0.9314	6607.4	8727.3
5	CLIMB and/or ACCEL.	0.9994	0.9308	68.2	8795.5
6	CRUISE SEGMENT	0.9481	0.8825	6149.3	14944.8
7	DESCENT ANALYSIS	0.9976	0.8804	269.3	15214.1
8	CLIMB and/or ACCEL.	0.9905	0.8720	1058.6	16272.7
9	CRUISE SEGMENT	0.9951	0.8678	542.2	16815.0
10	DESCENT SEGMENT	0.9950	0.8634	551.8	17366.7
11	LANDING SEGMENT	0.9950	0.8591	549.0	17915.7
				Reserve & trap :	1074.9
				Total fuel :	18990.7
Seg. 4	CRUISE :	410.6 kts at	34000.0 ft	RANGE =	1387.0 nm
Seg. 6	CRUISE :	410.6 kts at	34000.0 ft	RANGE =	1387.0 nm
Seg. 9	CRUISE :	370.6 kts at	25000.0 ft	RANGE =	200.0 nm
	FUEL WEIGHT =	18991.2		EMPTY WEIGHT =	64607.6
	USEFUL LOAD (less Wf)=	43570.0		AIRCRAFT GROSS WEIGHT =	127168.8

figure 27. NAS2 Sizing Calculations

The results are encouraging. The sized takeoff gross weight of the NAS2, carrying the same passengers and payload over the same mission range, is 127,169 lbs, burning 18,991 lbs of fuel. This is 60% less fuel consumption than the B-737-800 which weighs 174,200 lbs and burns 46,750 lbs of fuel.

While our goal was a 70% reduction, this 60% reduction is quite an accomplishment and, if the proposed design and technologies all work as hoped, has a realistic chance of success.

The NAS2 design was redrawn to reflect the sizing results, with wings, engines, canard, and landing gear reduced in size. The design layouts shown above all reflect this resized version.

Issues & Way-Forward

The NAS2 design concept is exciting and seems to offer a real path forward to obtain a tremendous saving in fuel consumption. However, this study was done with a limited budget so certain issues were not addressed. Some of these are discussed below.

- Noise reduction is a key issue for N+3, and the selected Open Rotor propulsion concept is inherently noisier than a traditional turbofan. Several of the initial design concepts in this study used either the wing or the horizontal tail to prevent engine noise from reaching the ground. In the interest of aerodynamic efficiency, the final preferred concept Tailless Open Rotor does not have such noise blocking geometry, so the open rotor itself must be noise-suppressed. Failing that, it may be necessary to put a shroud around the rotor, turning the engine into an ultra-high-bypass turbofan.
- The Open Rotor provides no natural ballistic containment in the event of rotor or other engine failure. The nacelles are positioned behind the fuselage pressure vessel so its penetration is not a problem, but one engine failure could damage the other engine. It may prove necessary to offset the engines or provide a stub vertical tail as a “wall” between them, or reposition them downwards so that the aft fuselage separates them. Again, a shroud could be used around the rotor, making the engine a turbofan.
- The thrust axis seems rather high and may pose problems in nose-wheel liftoff and perhaps in cruise trim. The canard elevator/flap was deliberately oversized to handle the nose-wheel liftoff problem, but detailed analysis is required. If necessary there is some room to move the nacelles downwards, but this would bring the rotors close to the ground in an extreme nose-up takeoff or landing.
- If the canard should fail to deploy for landing, the no-canard, no-flaps landing speed may be excessive even for emergency operation at extra-long runways. If true, either the canard extension needs some failsafe emergency actuation, or the design may need modification to provide a safe landing in its absence.
- An aircraft which is unstable in yaw may, in a worst-case scenario, experience an extreme yaw upset in excess of available recovery control power. This must be determined to occur at such a low probability that the failure mode likelihood is in line with other catastrophes such as wing structural failure, total loss of control actuation, etc.
- The flexibility of the Active Aeroelastic Wing will result in greater bending and torsional deflections during its life, leading to greater fatigue potential. This may limit the permissible weight savings, and will require sophisticated health monitoring systems to ensure that accumulated damage is detectable.

This study was performed on a limited budget by a small company. The answers are good enough and interesting enough that further study appears warranted, but nobody should claim that these answers are final or that anything has been “proven.” Areas recommended for further study include:

- Acquisition and use of a detailed Open Rotor engine model including full thrust and fuel flow calculations, geometry, installation guidance, etc...
- Trade studies of Open Rotor versus Ultra High Bypass Turbofan
- Computational aerodynamics (CFD) for analysis and design shape optimization
- Structural finite element analysis (FEM) and advanced materials trade studies
- Aeroelastic 6-DOF dynamic simulation including the use of the Active Aeroelastic Wing technology and the controllability issues in pitch and yaw
- Weights estimates based on structural and subsystem design and analysis
- Numerous trade studies of propulsion, materials, subsystems, and design configuration
- Multidisciplinary Design Optimization (MDO) studies
- Detailed performance analysis including FAA climb specifications, takeoff, etc...
- Additional design iterations with detailed CAD work to verify installation of the retracting canard, landing gear kinematics and actuation, fuel tanks, passenger compartment, cargo bays and handling, and nacelle/pylon design.
- Development planning and cost analysis

11. SUMMARY & CONCLUSIONS



figure 28. NAS2 On the Ramp

Conceptual Research Corporation has completed its N+3-related study of advanced transport aircraft in support of NASA's ongoing Subsonic Fixed Wing project. The overall goal was to assess what it would take to obtain a 70% reduction in fuel use for a 2035 timeframe commercial airliner, and to define vehicle concepts and technologies that show promise in that direction.

Parametric studies using the Boeing 737 found that a simultaneous 30% improvement in vehicle weight, aerodynamic drag (parasitic and induced), and engine fuel consumption will together add up to the desired 70% fuel savings. To obtain such improvements, a design approach with reduced wetted surface area and increased laminar flow is essential. To reduce drag-due-to-lift, simple physics says that the aspect ratio must be substantially increased.

The Active Aeroelastic Wing technology, flight tested and proven, is suggested to permit this with minimal weight penalty. It also facilitates the tailless design approach because it allows the use of the wing for pitch, yaw, and maneuver load control as well as the obvious roll control.

A propulsion approach which increases the effective bypass ratio is needed, with the Open Rotor as the most-likely emerging concept to obtain this.

Aircraft weight reductions are required across-the-board since no one weight category has enough weight to reach the goal alone.

Notional design studies of various novel configuration arrangements showed several concepts with potential for benefit. A top-level evaluation based on trimmed maximum lift coefficient and lift-normalized wetted surface area was used to rank these concepts. From this it was concluded that the designs which eliminated the tails showed the greatest promise. Note that this result is specific to smaller airliners. For the largest airliners, it is likely that the Blended Wing Body would show higher promise, but for a smaller airliner the BWB suffers from internal packaging inefficiencies.

The CRC-developed NAS2 Tailless Open Rotor design concept, sized to the same payload and range as the B-737-800, was found to burn 60% less fuel over the same mission. While a lot of work is required to mature and validate this design concept, it offers a way-forward towards the N+3 goals and, while admittedly exotic, is based on proven or clearly-emerging technologies and design approaches. It should work.

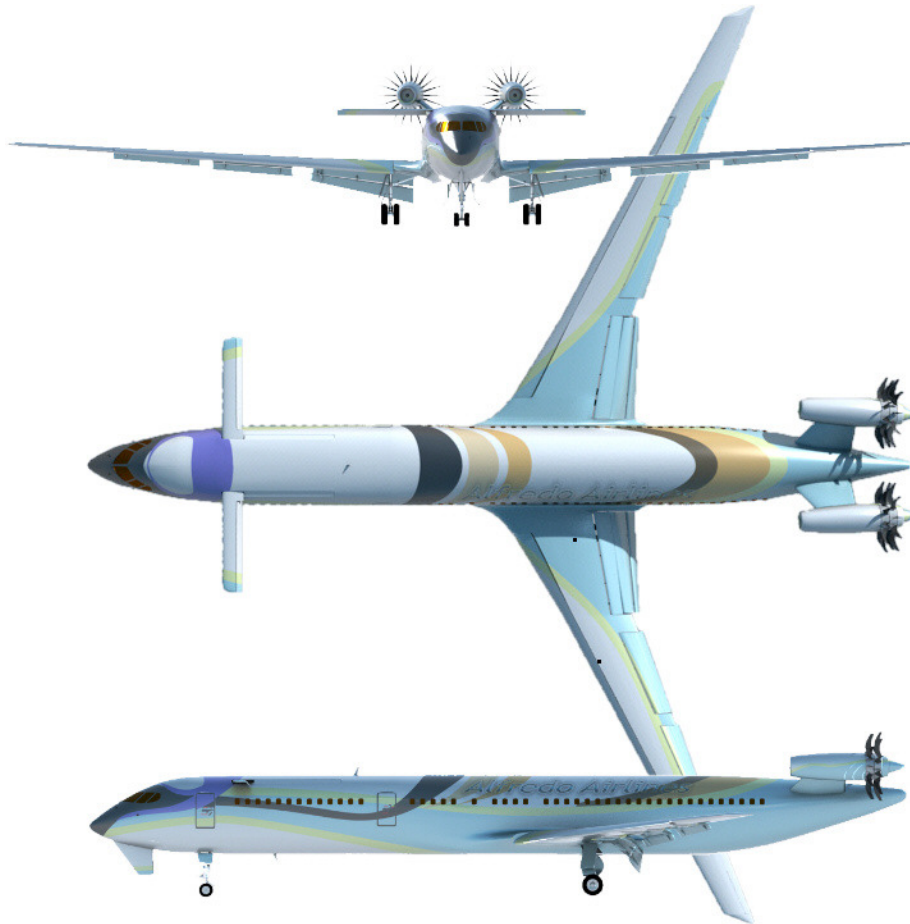


figure 29. NAS2 Three-View

12. APPENDIX: Parametric Sizing Data

Run	Cd0	K	sfc	W	F0	Results - true scaling		
						Wo (lbs)	We (lbs)	Wf (lbs)
0	D0	K0	C0	W0	F0	174361	92048	46455
1	D0	K0	C0 -25%	W0-25%	F1	108417	49820	23140
2	D0-50%	K0-50%	C0 -25%	W0-25%	F2	92594	44706	12430
3	D0	K0-50%	C0 -25%	W0-25%	F3	100313	47232	17622
4	D0-50%	K0	C0 -25%	W0-25%	F4	97993	46480	16055
5	D0	K0-25%	C0	W0-25%	F5	117809	52743	29607
6	D0-50%	K0-25%	C0	W0-25%	F6	103768	48343	19967
7	D0	K0-25%	C0-50%	W0-25%	F7	93393	44971	12964
8	D0-50%	K0-25%	C0-50%	W0-25%	F8	87853	43122	9273
9	D0	K0-25%	C0 -25%	W0	F9	144215	80799	27958
10	D0-50%	K0-25%	C0 -25%	W0	F10	130162	75307	19397
11	D0	K0-25%	C0 -25%	W0-50%	F11	77192	26304	15430
12	D0-50%	K0-25%	C0 -25%	W0-50%	F12	71127	24867	10802
13	D0-25%	K0	C0	W0-25%	F13	115468	52021	27988
14	D0-25%	K0-50%	C0	W0-25%	F14	105030	48746	20826
15	D0-25%	K0	C0 - 50%	W0-25%	F15	92413	44646	12308
16	D0-25%	K0-50%	C0 - 50%	W0-25%	F16	88337	43285	9594
17	D0-25%	K0	C0-25%	W0	F17	141860	79891	26511
18	D0-25%	K0-50%	C0-25%	W0	F18	131182	75712	20012
19	D0-25%	K0	C0-25%	W0-50%	F19	76086	26045	14583
20	D0-25%	K0-50%	C0-25%	W0-50%	F20	71697	25003	11235
21	D0-25%	K0 - 25%	C0 - 50%	W0	F21	122266	72140	14667
22	D0-25%	K0 - 25%	C0	W0	F22	153280	84253	33569
23	D0-25%	K0 - 25%	C0 - 50%	W0-50%	F23	67937	24096	8383
24	D0-25%	K0 - 25%	C0	W0-50%	F24	80675	27114	18104
25	D0-25%	K0 - 25%	C0 -25%	W0 - 25%	F25	99819	47072	17288
Base	D0	K0	C0	W0	F0	174361	92048	46455
1-Var	D0-50%	K0	C0	W0	F26	149297	82743	31096
	D0	K0-50%	C0	W0	F27	154288	84632	34196
	D0	K0	C0-50%	W0	F28	130187	75317	19412
	D0	K0	C0	W0-50%	F29	88958	28995	24505
	Cd0	K	sfc	W		Wo (lbs)	We (lbs)	Wf (lbs)

figure 30. Parametric Sizing for 4 Parameter Box-Behnken Scheme Response Surface

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