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Subsonic Ultra Green Aircraft Research: Phase I Final Report

Marty K. Bradley and Christopher K. Droney
Boeing Research & Technology, Huntington Beach, California

April 2011

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Abstract

This Final Report summarizes the work accomplished by the Boeing Subsonic Ultra Green Aircraft Research (SUGAR) team in Phase 1, which includes the time period of October 2008 through March 2010.

The team consisted of Boeing Research and Technology, Boeing Commercial Airplanes, General Electric, and Georgia Tech. The team completed the development of a comprehensive future scenario for world-wide commercial aviation, selected baseline and advanced configurations for detailed study, generated technology suites for each configuration, conducted detailed performance analysis, calculated noise and emissions, assessed technology risks, and developed technology roadmaps.

Five concepts were evaluated in detail: 1) 2008 baseline, 2) N+3 reference, 3) N+3 high span strut braced wing, 4) N+3 gas turbine battery electric concept, and 5) N+3 hybrid wing body.

A wide portfolio of technologies was identified to address the NASA N+3 goals. Significant improvements in air traffic management, aerodynamics, materials and structures, aircraft systems, propulsion, and acoustics are needed.

Recommendations for Phase 2 concept and technology projects have been identified.

Acknowledgements

This project and report reflect the combined efforts of the SUGAR team. The team members are Boeing Research and Technology, Boeing Commercial Airplanes, GE Aviation, and the Georgia Institute of Technology. The combined effort of this dedicated team has produced this comprehensive final report.

The team would like to thank Erik Olson of the NASA Langley Research Center for his guidance as the NASA Contracting Officer Technical Representative (COTR).

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1.0 – Introduction and Background

Air travel had a profoundly positive impact on the world in the 20th century. Airliners provide efficient, fast, and safe transport unmatched by any other mode of long distance travel. Furthermore, air travel has rapidly expanded to connect all corners of the earth due to its flexible capacity and routing, low infrastructure cost and freedom from geographic barriers. However, several factors are now combining to threaten air transportation over the coming decades.

Increased demand for fuel and diminishing supply is resulting in increasing and volatile fuel prices. As illustrated in Figure 1.1, the inflation-corrected jet fuel price started climbing rapidly in 2000 and increased nearly four-fold compared to prices of previous decades. Growth of the world's economy is straining natural resources, increasing the cost of fuel while simultaneously growing travel demand. Global consumption of carbon-based energy for all purposes is changing the environment in worrisome and unpredictable ways[3]. While commercial aviation's share of global CO_2 production is only about 2%[4], it is a conspicuous contributor, subject to regulation or taxation that may reduce its ability to sustain growth into the future.

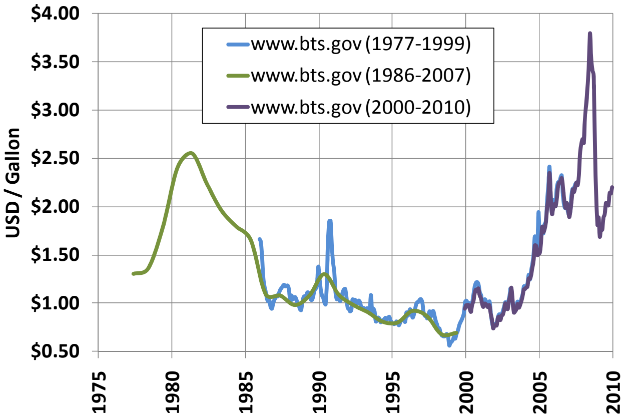


Figure 1.1 – The Rise and Volatility of Fuel Prices is Seriously Impacting Aviation[1,2]

Anticipated air travel growth may also become restricted due to airport capacities and mounting resistance to airport noise and air pollution. These factors present an important opportunity for the aerospace community to apply exciting new technologies and design tools for the benefit of the United States and the world in the 21st century.

The most challenging factors point toward the need for reduced energy consumption by airliners thus mitigating both the impact of high fuel prices and environmental effects. Exploration of alternative fuels and forms of energy along with more energy efficient aircraft will reduce the volume of fossil fuel required. These more efficient airplanes tend to be less noisy and combined with additional active and passive acoustic suppression measures can address NASA goals (Table 1.1).

The ambitious goals of the study force reconsideration of every aspect of airplane efficiency. Changes in operations can provide significant improvements in energy consumption. For example, some airlines have recently reduced cruise speeds to increase efficiency[5] and improved flight paths are increasingly applied as a means

Table 1.1 – NASA's Technology Goals for Future Subsonic Vehicles[6]

CORNERS OF THE TRADE SPACE	N+1 (2015 EIS) Generation Conventional Tube and Wing (relative to B737/CFM56)	N+2 (2020 IOC) Generation Unconventional Hybrid Wing Body (relative to B777/GE90)	N+3 (2030-2035 EIS) Advanced Aircraft Concepts (relative to user defined reference)
Noise (cum. below Stage 4)	-32 dB	-42 dB	55 LDN at average airport boundary
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%	-40%	better than -70%
Performance: Field Length	-33%	-50%	exploit metro-plex concepts

to wring the greatest possible efficiency from existing airplanes. While valuable, these changes alone cannot provide improvements that meet the goals of this study. A change to improve one factor of fuel efficiency can diminish another. However, new technologies promise to improve individual factors of airplane energy consumption with reduced adverse effects. For example, advances in material and structural technology may mitigate the increase in structural weight that usually results from using higher span to increase L/D. The broad time frame of the study encourages exploration and extrapolations of current technology trends as well as the invention of new technologies. These must be physically realistic and reasonable in the study time frame.

1.1 – Defining "N"

The definition of "N" technology is important as it serves as the reference for meeting the four NASA goals. At the beginning of the contract, communication with NASA verified that for the purpose of this study, 737NG vehicle and CFM56 engine technology are the in-service standards and thus the definition of "N". It should be noted that the 737 will not be used directly for comparison to any advanced concepts developed. The "N" Baseline configuration will be developed using the same rules, tools, and levels of fidelity as the advanced concepts but with technology levels consistent with a 737NG.

1.2 – Vehicle Class Definitions

The Boeing Company recognizes Regional Jets (RJ's), Single Aisles, Twin Aisles, Very Large Jets (VLJ's), and Freighters as five classes of commercially operated airliners. For the SUGAR contract (with exception to the future scenario), these classifications will be simplified into Regional, Medium, and Large classes. The simplification also serves the purpose of separating the vehicle classes from the species discriminating names Twin Aisle and Single Aisle. Passenger airplanes dominate the commercial market and tend to push airplane technology forward. Freighters are historically fallouts from passenger driven designs and are thus excluded from the SUGAR study. These class definition changes are illustrated in Figure 1.2.

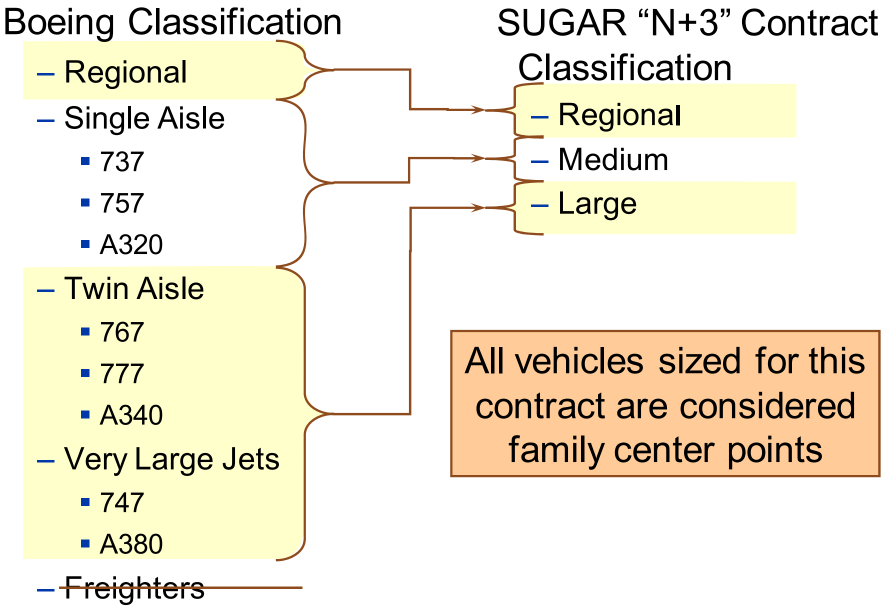


Figure 1.2 – SUGAR Vehicle Class Definitions

2.0 – Future Scenario

A 20 year forecast of the commercial airline current market outlook (CMO)[7] has been published for 40 years and shared with airlines, journalists, bankers, investment analysis, governments, suppliers and educators. The forecast includes all commercial aircraft 30 seats and over in all regions of the world. It is the only complete forecast that combines a top down and bottom up analysis.

Historically the CMO has a good record of predicting aggregate air travel demand, however at disaggregated levels it has somewhat under predicted the demand for the future number of new airplanes in various size categories. This under-prediction is comprised primarily of an under-forecasting of demand for the single-aisle market and the ability of twin-aisle airplanes to open up new long-range city pairs with a higher number of frequencies. In addition, the distortion of market forces with the introduction of Regional Jets and associated scope clause also impacted demand in these size categories. Much of the misestimated demand for large airplanes (e.g.747, A380) was predicated on historical behavior and regulatory régimes in force at the time. These impacts have been reduced as these phenomena have been incorporated into the knowledge base and tools underpinning the CMO.

The CMO tools, described in Section 2.1, were exercised for the SUGAR contract and provide specific forecasts for the 2030 and 2055 timeframes which are discussed in Section 2.2.

2.1 – Forecasting Tools

Prior to understanding how Boeing’s market forecasting tools work, one must understand the underlying dynamics of the airline industry. The airline operating environment is challenging and is driven by pressures that are hard to predict including volatile oil prices, a varying world economy, shifting regulatory policies, geopolitical events, slowing traffic growth, congestion, and environmental pressures.

Typically, world airline revenue is approximately one percent of Gross Domestic Product (GDP). This relationship varies by country and is shown in Figure 2.1. While airline revenues remain a constant percentage of GDP, travel demand grows over time.

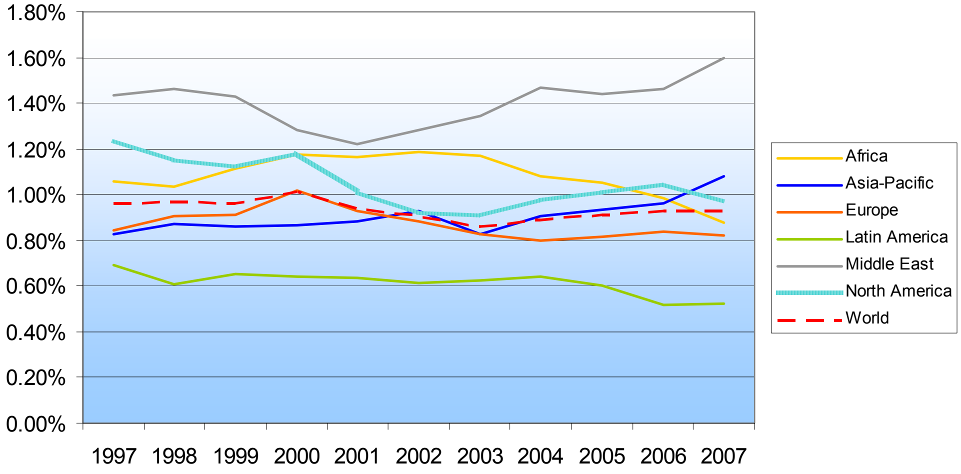


Figure 2.1 – Airline Revenue as Percentage of GDP

Trade, measured as imports and exports, typically grows one and a half to two times faster than GDP. The ratio of GDP to Available Seat Miles (ASM), or travel share, grows with increased trade. A steady positive trend of travel share with time is illustrated in Figure 2.2.

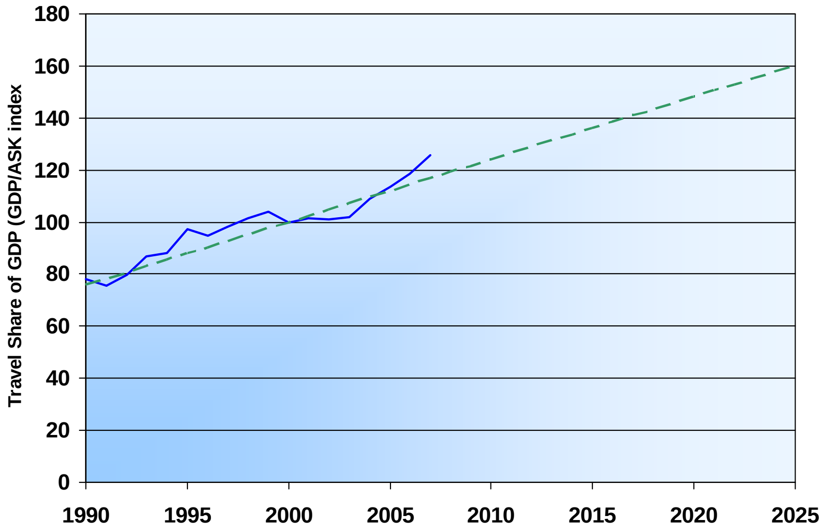


Figure 2.2 – Time Trend Travel Share of GDP

These relationships are used in conjunction with a world model that predicts the GDP growth of twelve economic regions (Figure 2.3). These regions were formed to best represent major world traffic flows and do not always match political or geographic regions. This defines 64 traffic flows both internal to the region and between regions. Recognition of the impact of liberalization of air services on airline competition and the subsequent stimulation of traffic as the value of air travel increases are also modeled and incorporated into the demand model.

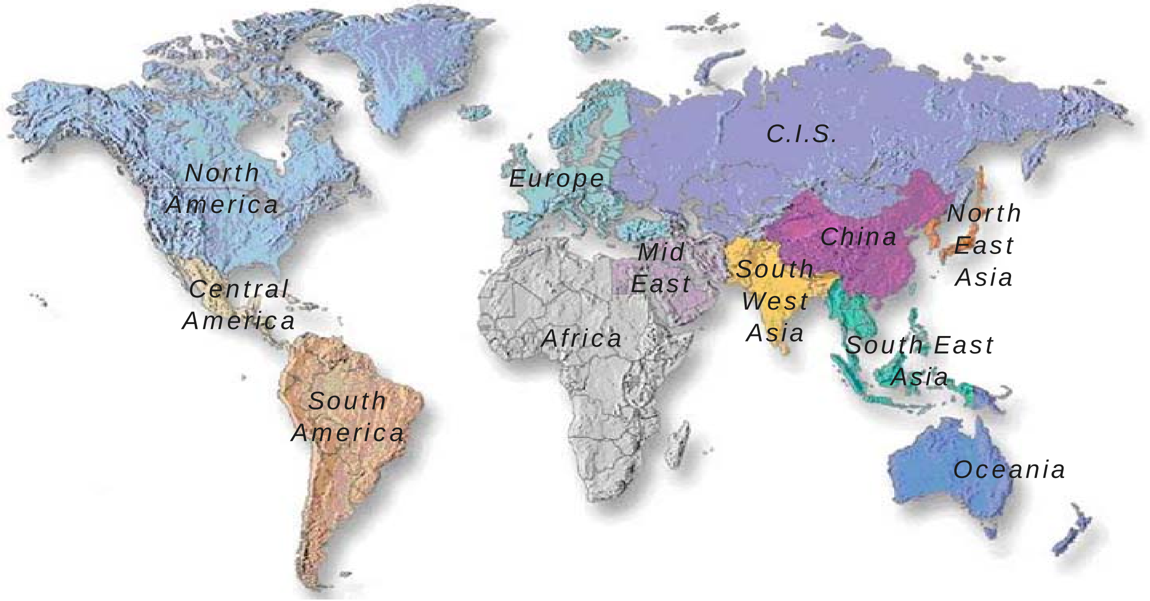


Figure 2.3 – Traffic forecasted within and between 12 world regions

The GDP forecasted demand is met by forecast airline operators. 149 individual airlines (including cargo, charter, regional, low cost carriers (LCC), and subsidiary carriers) are modeled based on their existing fleet, operational models, and financial situation. Predictions estimate how airlines react to forecast demand. Factors that would affect airline decisions are illustrated in Figure 2.4 and primarily depend on the duration of the forecasted demand and the financial impact on the airline. The airline models also try to predict what additional new markets would be served by each airline.

Demand modeling also includes effects of transportation mode shifts, infrastructure, air traffic management (ATM), and operations. Transportation mode shifts (e.g. air-rail in Europe, rail-air in India) both positive and negative to air travel in the short-haul markets are estimated and incorporated. Infrastructure in general is assumed to lag demand, there is a build-up of pressure to improve the infrastructure before it is improved. NextGen ATM is included in the model, but is assumed to not be as efficient as planned. Metroplex operations are not explicitly in the forecast but they are also not excluded from being a solution to pent-up demand from infrastructure lag. Environmental concerns are modeled as a broadening cap and trade arrangement lead by Europe, followed by USA and Asian countries. This equates to an increasing cost of flying and, by holding %GDP constant, leads to less demand for travel than would be otherwise expected.

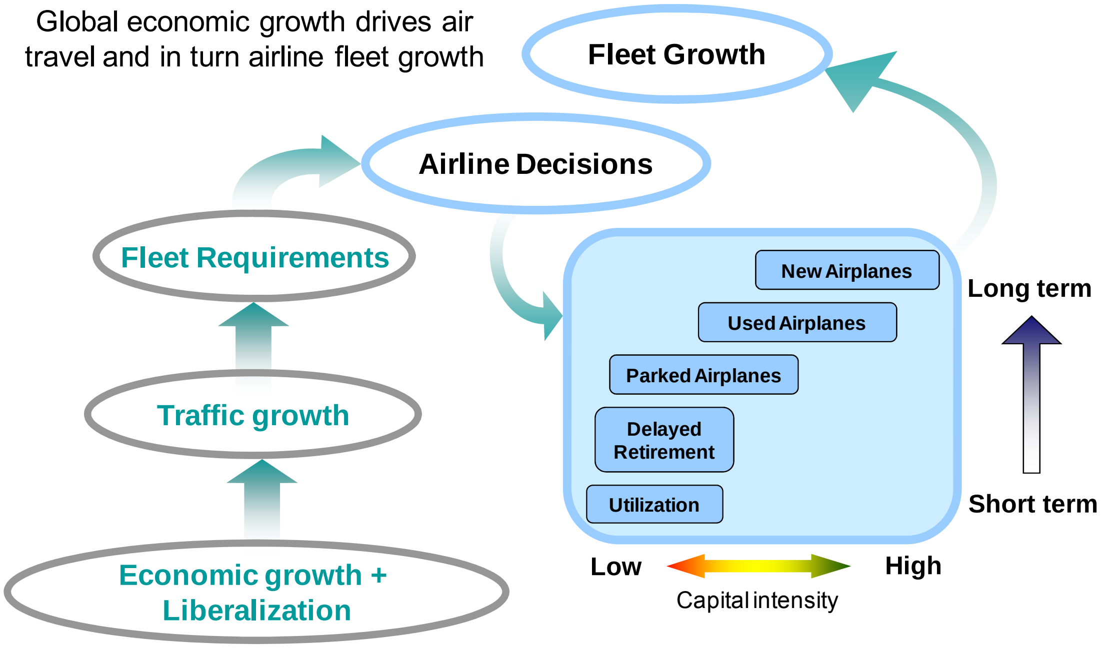


Figure 2.4 – Underlying Dynamics of the Airline Industry

The CMO is driven by economics. Boeing’s product forecasters create a bottom-up scenario at the airline level by adding services (frequency, city pairs, and capacity) to balance the top-down traffic forecast (driven by GDP) on a regional flow basis (Figure 2.5).

The product forecast used for the process is derived by examining data about the current and projected fleet. Figure 2.6, an example of this data, shows the number of tickets sold in a day for every origin-destination pair (international and domestic). Highlighted areas have low traffic density and thus limited product availability. These are created by geography, (few fly to the middle of an ocean), and probability, (the odds of needing to fly to exactly the opposite side of the world). This data is an example of what is used to determine which product characteristics show consistent and stable demand over time; this stability is utilized to forecast what the market will look like in 2030 and beyond.

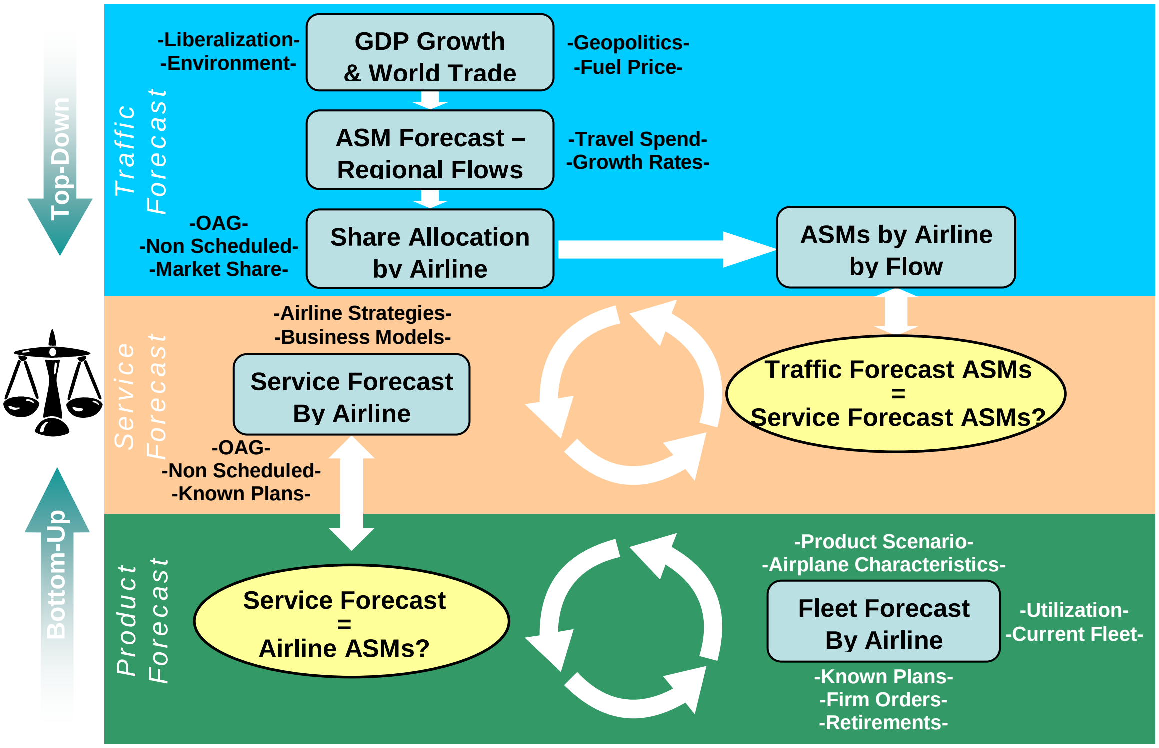


Figure 2.5 – CMO Process

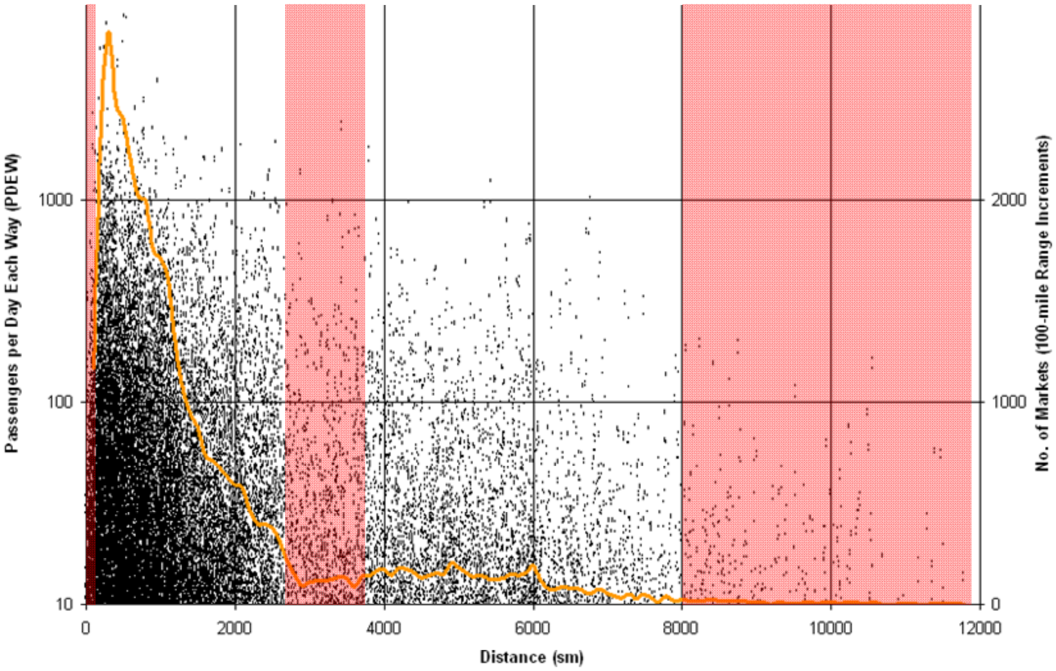


Figure 2.6 – World Ticketed Origin and Destinations

2.2 – Current Market Outlook

Market forecast results are shown in Figure 2.7, and indicate that strong long term growth will continue. Short term economic fluctuations are not expected to significantly change the long term growth trends.

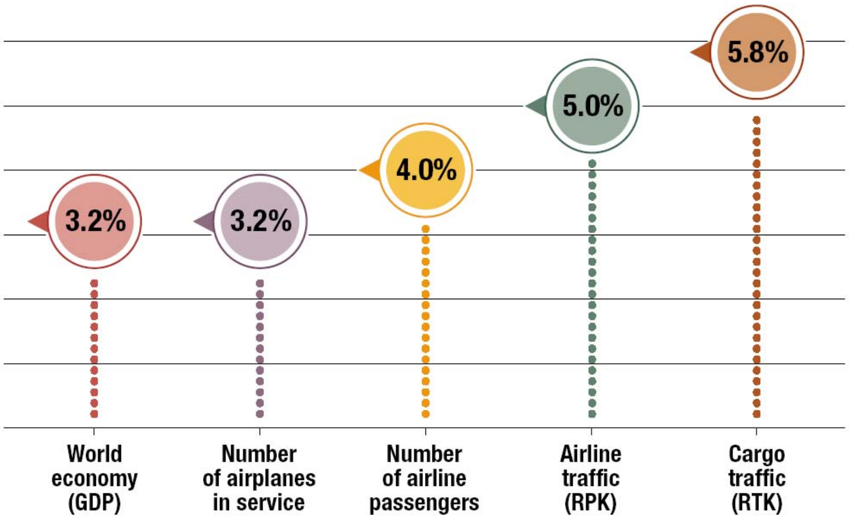


Figure 2.7 – 2010 to 2030 Forecast: Strong Long Term Growth

Over the past 20 years, air travel grew by an average of 4.8 percent each year, despite two major world recessions, terrorist acts, the Asian financial crisis of 1997, the severe acute respiratory syndrome (SARS) outbreak in 2003, and two Gulf wars. During 40 years of producing the CMO, Boeing has learned that the resilience of air transport growth comes from its intrinsic importance to the livelihood of people around the world.

On average over the next 20 years, passenger travel will grow at 5.0 percent and cargo at 5.8 percent. The fastest growing economies will lead the transformation into a more geographically balanced market. The average growth in airline passenger numbers will be around 4.0 percent each year. More people will be traveling by air as economies grow. Markets will open up through reduced regulation and increased competition. As these markets expand, new travel opportunities will mostly be on longer-distance flights.

The air transport fleet plays a fundamental role in stimulating and sustaining economic activity. This tie-in is clear, with the 3.2 percent annual fleet growth in line with expected long-term economic growth of 3.2 percent.

Total fleet size as well as the rate of aircraft replacement have been estimated and are shown in Figure 2.8. This shows a large demand for replacing older, less efficient aircraft.

With the projected passenger and cargo growth, the total in-service fleet will nearly double by 2030 growing from 18,000 airplanes to over 32,000. It will take 14,000 new airplanes to meet the growth requirements. In addition, it will take about 11,900 new airplanes to replace retiring airplanes. That’s a total need of about 25,900 new airplanes over the next 20 years.

Approximately 54 percent of the 25,900 new airplanes being delivered over the next 20 years are attributable to growth in the market. The remaining 46 percent of the demand for new aircraft is coming from replacing older airplanes, up from 36 percent last year. This strong replacement demand is being driven by high fuel prices and the introduction of new, very efficient, very capable aircraft. In a tough, competitive environment, airlines are looking for ways to cut costs from their operations. With high fuel prices, it certainly makes more and more sense for airlines to replace their old aircraft with new, fuel efficient airplanes, and we have reflected that trend in our analysis.

Approximately 6,100 airplanes, about 34 percent of the fleet operating today, will still be in operation 20 years from now.

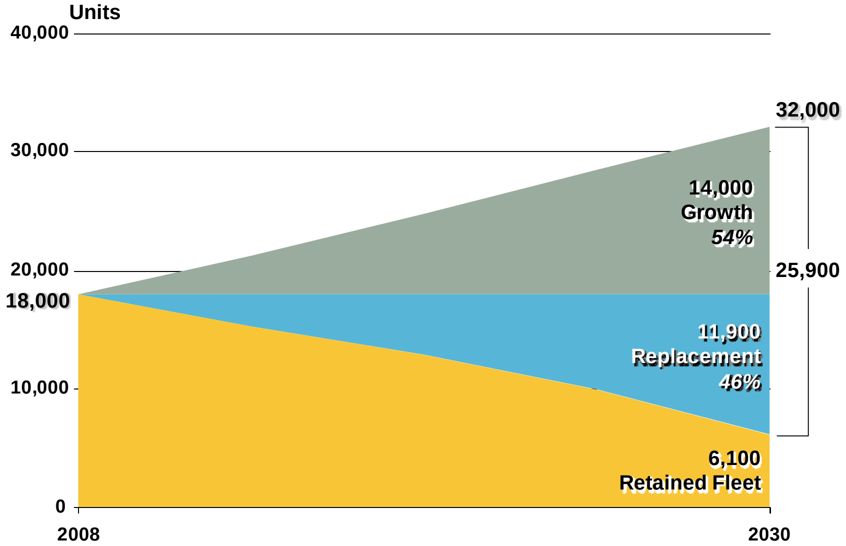


Figure 2.8 – Increasing Demand for Replacing Older, Less Efficient Aircraft

The projected fleet compositions for 2008, 2030, and 2055 are listed in Table 2.1. The table shows the rate of fleet retirement based on aircraft technology level and also helps illustrate the time it takes for a new airplane to comprise a significant percentage of the market. A new medium sized aircraft with an entry to service of 2030 will comprise about 50% of the fleet in 25 years. This trend is consistent with other sized aircraft though the actual percentage varies.

The CMO also predicts the required airplane size for the estimated entry to service. The size is driven by many factors. Technology and the environment, depending on specifics, may pull toward either larger or smaller vehicles. Seat mile economics and airport congestion generally drive toward larger aircraft. Crew costs, direct markets, turn time, competition, and the overall passenger experience drive toward smaller aircraft.

Figure 2.9 shows the weekly frequencies of airplanes with relation to their size. Future markets, fuel prices, infrastructure, and environmental issues are predicted to force an up-gauging in the small airplane market driving small and medium regional jets into large regional jets and small single-aisle categories. Single aisle and regional jets comprise 90% of airplane frequencies, a trend which should continue into 2055.

Detailed future fleet information is needed for aircraft sizing. The CMO was used to predict the number of aircraft in the fleet in 2030 as discussed in the previous paragraphs. It was also used to generate more specific data about each airplane class shown in Table 2.2. The data in the table is a mixture of design goals and operational characteristics generated with the assumption that vehicles will fly the same speed they fly today and in the current air traffic management system.

The number of seats, average trip distance, and maximum trip distance are used as design parameters for the airplane.

Table 2.1 – SUGAR Fleet Mix by Year and Aircraft Class

Series Class	Generation	2008	2030	2055
Regional	N+3	0	0	2,000
	N	0	1,000	1,250
	N-1	1,800	1,575	150
	N-2	1,350	100	0
	N-3	75	0	0
	Total	3,225	2,675	3,400
Medium	N+3	0	0	20,000
	N+1&2	0	9,000	18,000
	N	0	1,500	1,000
	N-1	6,050	11,350	1,000
	N-2	4,400	300	0
	N-3	950	0	0
	Total	11,400	22,150	40,000
Large	N+3	0	0	5,000
	N+1&2	0	1,000	3,350
	N	0	4,400	5,000
	N-1	1,550	1,700	250
	N-2	1,800	125	0
	Total	3,350	7,225	13,600
Grand Total		18,000	32,000	57,000

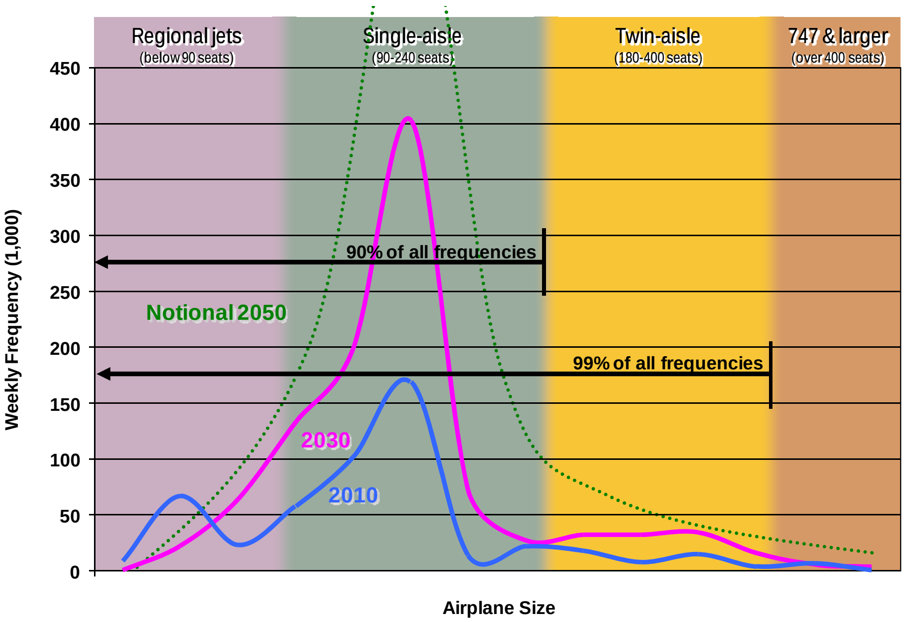


Figure 2.9 – Weekly Frequency vs. Airplane Size

Since the air traffic management system is unconstrained for SUGAR the airplanes are allowed to fly slower than what is listed in the chart. The effects of flying slower are hard to estimate. It can be argued that slowing down will reduce demand because flights will get longer or that demand will increase because flights will cost less. It is expected that slowing down one class will push demand onto other classes of vehicles. These types of market changes are very hard to simulate and are beyond the scope of this study. For SUGAR the assumption is that the fleet daily air miles (fleet size times daily miles), or demand, remains fixed independent of speed. Slowing a vehicle class down will result in an increased fleet size inversely proportionate to the change in speed. Since the total fleet daily air miles remains fixed, each airplane would fly less cycles in a day and thus burn less fuel for the day. On a fleet basis, the fuel burn benefit for slowing down is proportional to the individual airplane fuel burn benefit.

Table 2.2 – CMO 2030 Aircraft Fleet Information

	Regional	Medium	Large
Number of Aircraft	2,675	22,150	7,225
Family Midpoint # of Seats	70	154	300
Avg Distance	575	900	3,300
Max Distance	2,000	3,500	8,500
Avg Trips/day	6.00	5.00	2.00
Avg MPH	475	500	525
Fleet Daily Air Miles (K)	8,500	100,000	55,000
Daily Miles	3,200	4,500	7,600
Daily Hours	6.92	9.23	13.96

Aircraft utilization, desired operational city pairs, and airline driven economics drive a minimum speed for aircraft. Figure 2.10 shows this minimum speed per aircraft class and was derived from the future scenario study. The minimum speed of the medium and large categories is being driven primarily by geography and utilization, less than these speeds would have a large impact on the airline networks and value of travel (these impacts are beyond the scope of this study).

- Minimum Speed Drivers:
  - Desired City Pairs
  - Flight Crew Rules
  - Aircraft Utilization
- Current Class Speeds:
  - Regional: ~ 0.70 – 0.75 Mach
  - Medium: ~ 0.75 – 0.80 Mach
  - Large: ~ 0.80 – 0.85 Mach

SUGAR will estimate the best speed to fly at or above the MINIMUM speed allowed by the future scenario

- Regional: Optimum
- Medium: 0.70 Mach
- Large: 0.80 Mach

Figure 2.10 – Minimum Economic Aircraft Speed

2.3 – Future Scenario Update: Configuration Economic and Mobility Impact

The Future Scenario was generated assuming a technology development path similar to our historical long term trend. Since 1970 the air transportation system is about 70% more efficient, this improvement has come from airspace management, airline operations, airplane design, and material technology. The underlying assumption of progress aligns with this trend. Projecting forward to 2030-2035 yields ~35% improvement from the current system. It is important to remember that in 1970 the world was a much different place, and one would be hard pressed to imagine all of the advancements that have been delivered over that time. After the configurations discussed later in this report were analyzed, it was determined that, when combined with air traffic control improvements, the assumptions in the Future Scenario are similar to the results achieved by the Refined SUGAR, SUGAR High, and SUGAR Ray. Therefore, the technologies and designs studied are in-line with the assumptions made at the beginning of this study, so the existing Future Scenario is still valid for the SUGAR advanced concepts. Even though these aircraft fly slower than what is suggested by Table 2.2, their gate to gate time is actually a little faster due to improvements in direct routing and taxi times (Figure 6.3). The city pairs the aircraft can serve are not greatly impacted because the cruise Mach number was held to Mach 0.70. Overall, the data in the table remains valid.

The SUGAR Volt concept uses less fuel but assumes significant changes in airport infrastructure to handle the charging and transportation of modular batteries. A separate analysis of energy and battery cost associated with this concept is recommended.

Recent changes in the World economy, although significant, are still thought to be captured by the long term trends assumed in the Future Scenario. The influence of oil price fluctuations on Boeing forecasts have also been studied, and tend to influence all forms of transportation, reducing the unique impact on aviation.

The baseline Future Scenario is driven by many factors, like technology investment, regulation of air travel, as well as basics like airport and airspace infrastructure. There is a basic assumption that government and industry worldwide will continue to invest to allow air travel to compete with other transportation modes and continue to act as a catalyst for trade and business development in the future. If this assumption were to be removed, then the Future Scenario would change greatly.

For this alternate Future Scenario, the resulting travel demand can be evaluated and there is a 10-15% decrease in travel that depends on the rate of technology investment in other modes, i.e. would they slow down their investment because they have less competition. The decrease in travel is equivalent of not needing ~10,000 airplanes during the 20 years after the change in technology assumption, or ~7,000,000 passengers per day. More speculatively, the effect on trade and global economic development could slow GDP by 0.3%, but this effect has not been accounted for.

In this alternate Future Scenario, the cost of flying is up, while the level of service is down; this is a compounding effect that reduces travel demand further and squeezes profits across the industry. The profit squeeze reduces investments and slows development compounding the issue. The total effect of this is not captured in the forecast of the reduction in fleet need because it quickly spirals out of control until there is no more air travel; we know that something would change and equilibrium would be restored.

In this alternate Future Scenario, seat mile economics and scarce infrastructure drive toward larger aircraft, while direct markets, competition, and the overall passenger experience suffer. This alternate Future Scenario is not considered likely, but is discussed here only to serve as an indication of the value of the technology work that is being conducted at NASA, Boeing, the engine companies, and universities.

3.0 – Advanced Concept Selection

The Boeing Company solicited input from the Georgia Tech (Ga. Tech) Aerospace Systems Design Laboratory (ASDL) to facilitate a workshop for concept selection for the SUGAR aircraft. Working closely with Boeing and General Electric, ASDL formalized a custom process and created tools specifically created for the concept selection activity based on past experience in similar programs.

The overall goal of the workshop was to downselect a few operational, airframe and engine concepts for further analysis and study. The workshop required coordination between the partners prior to the actual events of the workshop to create the interactive tools which would aid in workshop activities.

3.1 – Process Overview and Background

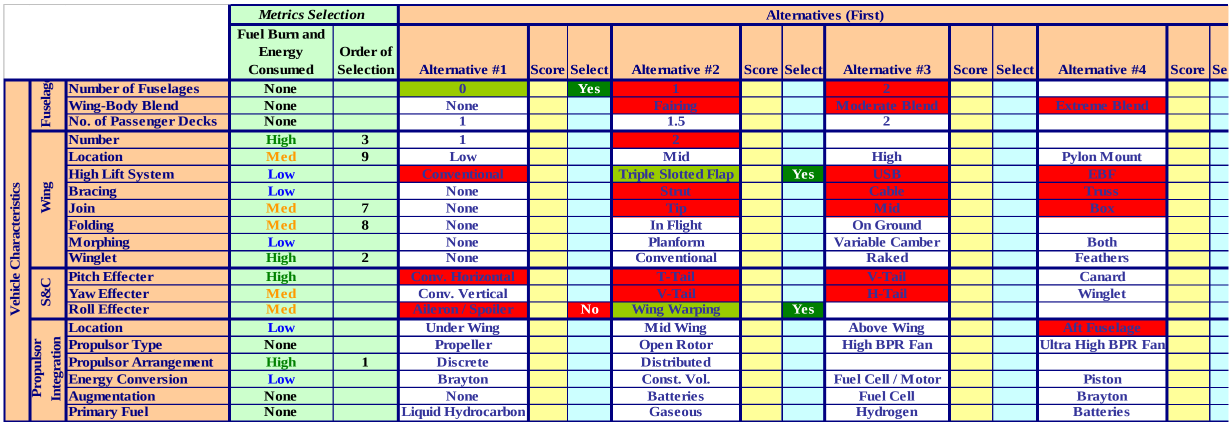
The workshop for SUGAR concept selection was centered on using an Interactive Reconfigurable Matrix of Alternatives (IRMA) as a tool to aid in the discovery of configurations. IRMA is a systematic qualitative procedure that is unique to the conceptual design process developed by ASDL. It was created to provide an “audit-trail” to define reference systems upon which quantitative analysis could be performed in a traceable, structured and systematic manner. IRMA builds on the concept of a Morphological Analysis created by Fritz Zwicky. Zwicky states that “within the final and true world image everything is related to everything, and nothing can be discarded a priori as being unimportant.”[8]

Given the complexity of the new systems, there are millions of possible alternatives in the hyperspace of requirements, technologies and responses. Not all these alternatives can be quantitatively compared within the practical time limits imposed by the program management. To overcome this issue, a qualitative brain-storming exercise has been developed by ASDL to prioritize and down-select the important requirements and alternatives with feedback from disciplinary experts and program management. This allows the quantitative process of the down-selected alternatives to be much more manageable.

The IRMA is a combination of Systems Engineering techniques such as Matrix of Alternatives, Multi-Attributes Decision Making (MADM) and Technique for Ordered Preference by Similarity to Ideal Solutions (TOPSIS)[9]. Figure 3.1 depicts the Interactive Reconfigurable Matrix of Alternatives (IRMA) which was created for the SUGAR workshop. These tools provide a process for functionally decomposing the problem, identifying alternatives and technologies to meet the functions, and identifying the solutions that meet the top level needs. These tools and processes provide a mechanism for encouraging collaborative communication at the early stages of conceptual design.

The general procedure for selecting a system through the Morphological Matrix of Alternatives is as follows:

- Functionally decompose the existing system
- For each function, list all the possible ways in which it might be satisfied
- Examine the matrix for the possible new permutations.



			Metrics Selection		Alternatives (First)											
			Fuel Burn and Energy Consumed	Order of Selection	Alternative #1	Score	Select	Alternative #2	Score	Select	Alternative #3	Score	Select	Alternative #4	Score	Se
Vehicle Characteristics	Fuselag	Number of Fuselages	None		0		Yes	1			2					
		Wing-Body Blend	None		None			Fairing			Moderate Blend			Extreme Blend		
		No. of Passenger Decks	None		1			1.5			2					
	Wing	Number	High	3	1			2								
		Location	Med	9	Low			Mid			High			Pylon Mount		
		High Lift System	Low		Conventional			Triple Slotted Flap		Yes	USB			EBF		
		Bracing	Low		None			Strut			Cable			Truss		
		Join	Med	7	None			Tip			Mid			Box		
		Folding	Med	8	None			In Flight			On Ground					
		Morphing	Low		None			Planform			Variable Camber			Both		
		Winglet	High	2	None			Conventional			Raked			Feathers		
	S&C	Pitch Effecter	High		Conv. Horizontal			T-Tail			V-Tail			Canard		
		Yaw Effecter	Med		Conv. Vertical			V-Tail			H-Tail			Winglet		
		Roll Effecter	Med		Aileron / Spoiler		No	Wing Warping		Yes						
	Propulsor Integration	Location	Low		Under Wing			Mid Wing			Above Wing			Aft Fuselage		
		Propulsor Type	None		Propeller			Open Rotor			High BPR Fan			Ultra High BPR Fan		
		Propulsor Arrangement	High	1	Discrete			Distributed								
		Energy Conversion	Low		Brayton			Const. Vol.			Fuel Cell / Motor			Piston		
		Augmentation	None		None			Batteries			Fuel Cell			Brayton		
		Primary Fuel	None		Liquid Hydrocarbon			Gaseous			Hydrogen			Batteries		

Figure 3.1 – Interactive Matrix of Alternatives for Conceptual Design Formulation

The last step offers great ambiguity which the ASDL developed IRMA process is attempting to solve. The IRMA process contains a dynamic dashboard for visualizing the effects of each decision. When a selection is made, incompatible options are filtered out thereby facilitating down-selection. The interactive nature of the IRMA tool allows for decision makers to understand the impact of decisions at the initial point of decision making. In a collaborative group such as seen at the SUGAR workshop, this tool provides a mechanism for understanding the impacts of the order of decisions as well as facilitating discussions among group members.

3.2 – Pre-Workshop Steps

In order to create an IRMA and have a successful workshop for selecting advanced vehicle concepts, a fair amount of systems engineering activities must occur prior to the workshop. Figure 3.2 depicts the necessary general steps to creating the IRMA in preparation for the workshop. This section will describe the details and major outcomes of each step.

These steps are carried through by a subset of workshop participants who have demonstrated technical competence in systems engineering techniques as well as the technical aspects for the problem at hand. The subgroup for the development of the SUGAR IRMA consisted of representatives from The Boeing Company as well as representatives from General Electric. The representatives from General Electric provided input and guidance supporting engine technologies and integration issues.

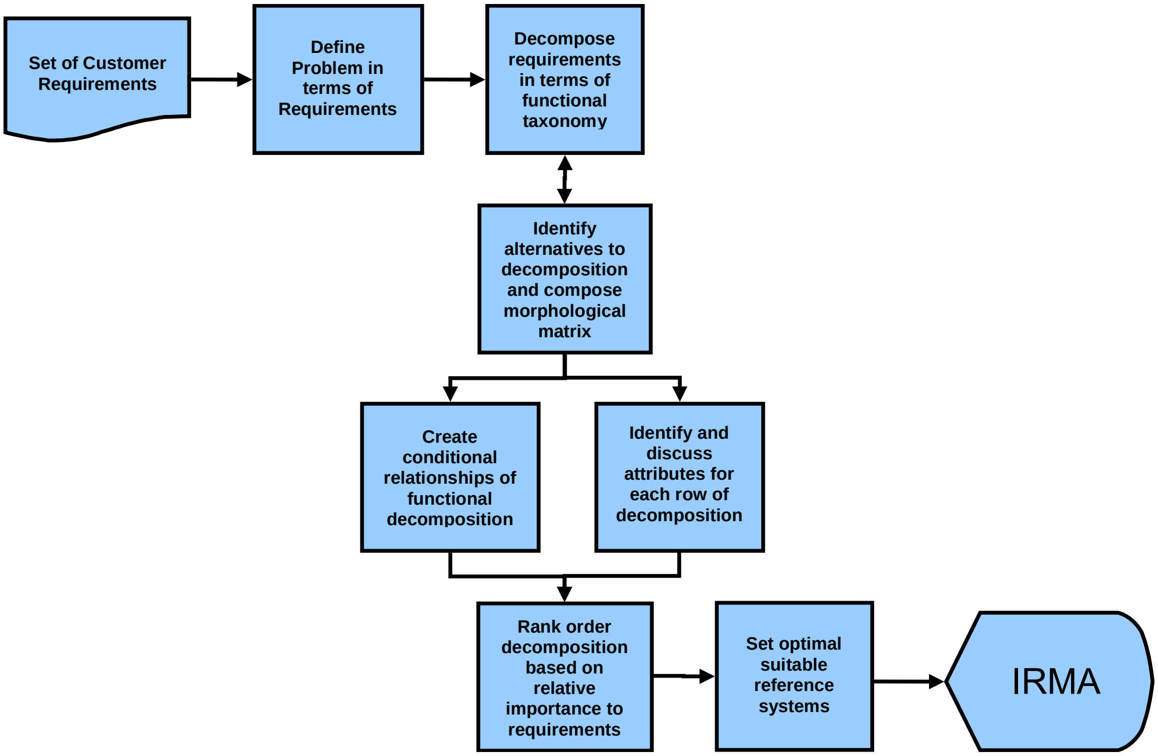


Figure 3.2 – Pre-Workshop Activity Sequence

Pre-workshop Step 1: Identify a set of customer requirements

Preparation for the workshop begins first with understanding the needs of the customer. Section 1.0 and 2.0 discusses the current outlook for the commercial aircraft market and illustrates the need for a more efficient, environmentally friendly fleet. In response to this, NASA has issued an aggressive set of goals to drive next generation aircraft design. Table 1.1 shows the various goals NASA has set for future aircraft design. The SUGAR initiative strives to develop N+3 vehicle concepts to meet the most aggressive set of goals: reduction of aircraft noise, NOx emissions, takeoff field length, and fuel burn. These requirements, coupled with the current market outlook, provide the initial constraints for the SUGAR initiative and direct IRMA construction.

Pre-workshop Step 2: Define problem in terms of requirements

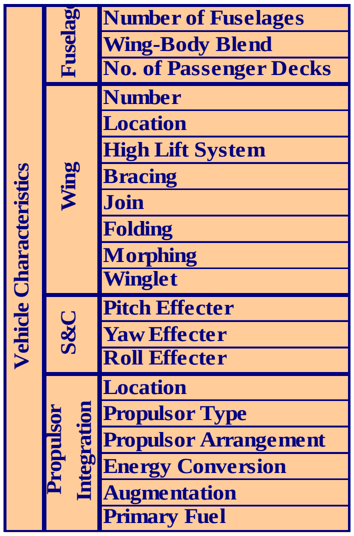
Once the customer has issued a set of requirements, and the overall project goal has been established, the requirements must be translated such that the problem can later be mapped to realizable engineering characteristics. Section 2.0 discusses how the aircraft fleet is changing and how aircraft will be used in the future. This information, coupled with NASA's goals, helps formulate the overall problem: to design advanced concept, improved performance aircraft which can fit the changing market while also meeting aggressive environmental standards. Therefore, the problem can be understood as one primarily involving aircraft architecture; changes to the aircraft architecture will either enhance or detract from the vehicle performance relative to one or more of NASA's goals. In order to thoroughly address vehicle performance, the specific vehicle systems that most affect performance should be identified and targeted as important areas for the conceptual design process. The Boeing team noted that design changes made to the aircraft fuselage, wing, stability and control system, and propulsion system would most impact the vehicle’s performance. The problem then becomes one that involves conceptual design tradeoffs of the vehicle characteristics.

Pre-workshop Step 3: Decompose requirements in terms of functional taxonomy

Once the targeted areas of vehicle architecture have been defined, it is important to break down the architecture in terms of its functional components. This is the first step in building the morphological matrix essential to IRMA. Using the sub-categories defined by Boeing (i.e. fuselage, wing, stability and control, propulsion) as a starting place, the vehicle can be functionally broken down into its parts. These functional “parts” will serve as points of decision for each concept created. Design decisions are then made at this level of detail, ensuring that the concepts can be built from the “bottom up” with much freedom to generate the N+3 concepts that will best address NASA’s goals.

In order to begin vehicle decomposition, it is important to know the vehicle components which make up each subsystem as these generate decision making points in the IRMA. For example, a few of the design points that make up the wing subsystem are the number of wings, wing location, the type of high lift system, and the type of wing bracing.

The functional decomposition was completed by Boeing and GE in keeping with the fuselage, wing, stability and control, and propulsion categories. A complete visualization of the finished functional taxonomy can be seen in Figure 3.3.



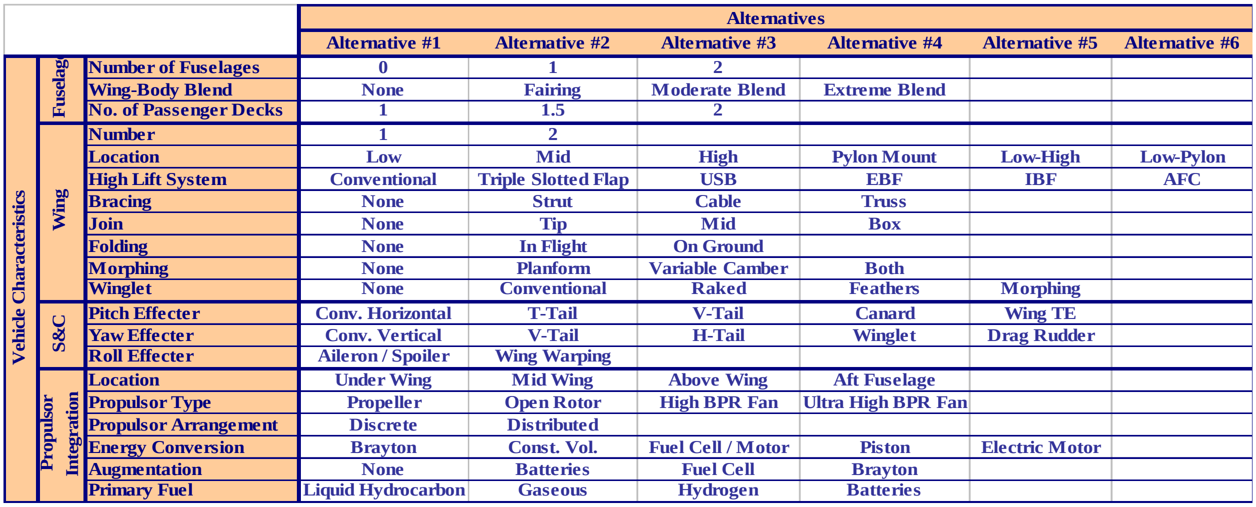
Vehicle Characteristics	Fuselag	Number of Fuselages
		Wing-Body Blend
		No. of Passenger Decks
	Wing	Number
		Location
		High Lift System
		Bracing
		Join
		Folding
		Morphing
		Winglet
	S&C	Pitch Effecter
		Yaw Effecter
		Roll Effecter
	Propulsor Integration	Location
		Propulsor Type
		Propulsor Arrangement
		Energy Conversion
		Augmentation
		Primary Fuel

Figure 3.3 – Functional Decomposition of Vehicle Characteristics

Pre-workshop Step 4: Identify alternatives to decomposition and compose morphological matrix

Once the functional taxonomy is complete, each entry to the decomposition must be given possible alternatives that could function in a vehicle design. For example, an airplane may realistically have 1 or 2 wings. Therefore these are the two alternatives which would populate the “number of wings” category. Similarly, the realistic options for “wing morphing” would be to have no wing morphing, variable camber morphing, planform morphing, or simultaneous variable camber and planform morphing. It is important to populate the list with as many alternatives as one can think of, also allowing for capabilities which may not be developed now but are projected to be fully developed by the N+3 timeframe. These alternatives serve as possible “choices” in the IRMA, guiding the users in creating vehicle concepts. The alternatives are populated across a row for each entry created in the functional taxonomy. Once the alternatives have been entered, the morphological matrix is complete and the backbone for the IRMA is set.

The complete morphological matrix created by Boeing and GE for the SUGAR workshop is shown in Figure 3.4.



			Alternatives					
			Alternative #1	Alternative #2	Alternative #3	Alternative #4	Alternative #5	Alternative #6
Vehicle Characteristics	Fuselag	Number of Fuselages	0	1	2			
		Wing-Body Blend	None	Fairing	Moderate Blend	Extreme Blend		
		No. of Passenger Decks	1	1.5	2			
	Wing	Number	1	2				
		Location	Low	Mid	High	Pylon Mount	Low-High	Low-Pylon
		High Lift System	Conventional	Triple Slotted Flap	USB	EBF	IBF	AFC
		Bracing	None	Strut	Cable	Truss		
		Join	None	Tip	Mid	Box		
		Folding	None	In Flight	On Ground			
		Morphing	None	Planform	Variable Camber	Both		
		Winglet	None	Conventional	Raked	Feathers	Morphing	
	S&C	Pitch Effecter	Conv. Horizontal	T-Tail	V-Tail	Canard	Wing TE	
		Yaw Effecter	Conv. Vertical	V-Tail	H-Tail	Winglet	Drag Rudder	
		Roll Effecter	Aileron / Spoiler	Wing Warping				
	Propulsor Integration	Location	Under Wing	Mid Wing	Above Wing	Aft Fuselage		
		Propulsor Type	Propeller	Open Rotor	High BPR Fan	Ultra High BPR Fan		
		Propulsor Arrangement	Discrete	Distributed				
		Energy Conversion	Brayton	Const. Vol.	Fuel Cell / Motor	Piston	Electric Motor	
		Augmentation	None	Batteries	Fuel Cell	Brayton		
		Primary Fuel	Liquid Hydrocarbon	Gaseous	Hydrogen	Batteries		

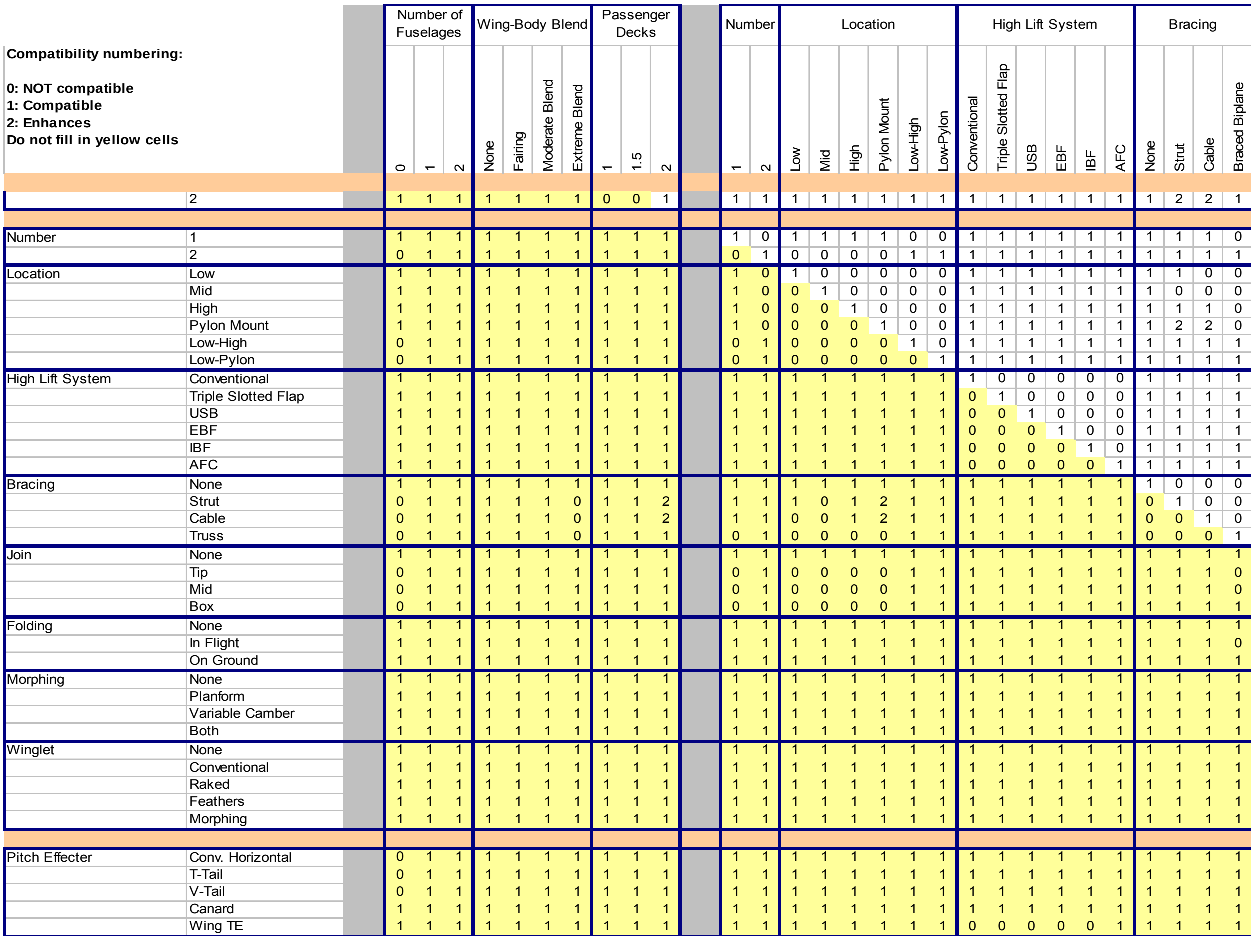
Figure 3.4 – SUGAR’s Morphological Matrix

Pre-workshop Step 5.1: Create conditional relationships of functional decomposition

Once the morphological matrix is complete, the dynamic nature of the matrix must be set up. This is done through the creation of a compatibility matrix which summarizes the conditional relationships within the functional decomposition. The goal of conditional relationships is to eliminate alternatives that are physically incompatible with each other. For example, if the user initially selected a flying wing configuration with no fuselage, it would be unnecessary and physically impossible, to have any type of wing bracing or join. Therefore, the alternatives under these categories on other rows of the matrix would be removed as alternatives for the vehicle configuration.

It is important to note that the incompatibilities being dealt with merely reflect those vehicle attributes which are impossible by the laws of physics or by engineering standards. These incompatibilities do not reflect combinations of attributes which may be uncommon or suggested against. This allows for more freedom in generating concepts. It is important that the users also apply their engineering judgment when making decisions to ensure the designs are not only physically possible, but also logical, as incompatibilities cannot account for engineering logic.

The compatibility matrix should be filled in by those who helped populate the morphological matrix. It is helpful if each individual fills out the compatibility matrix for those attributes which fall under their discipline specialty. The compatibility matrix is symmetrical and at minimum, consists of the numbers 1 and 0. A 0 indicates that two alternatives are incompatible while a 1 indicates they are compatible. The compatibility covers alternatives in the same row as the attribute in question as well as those alternatives in other rows that affect other aspects of the vehicle architecture. A section of the compatibility matrix created for the SUGAR workshop is shown in Figure 3.5.



Compatibility numbering:

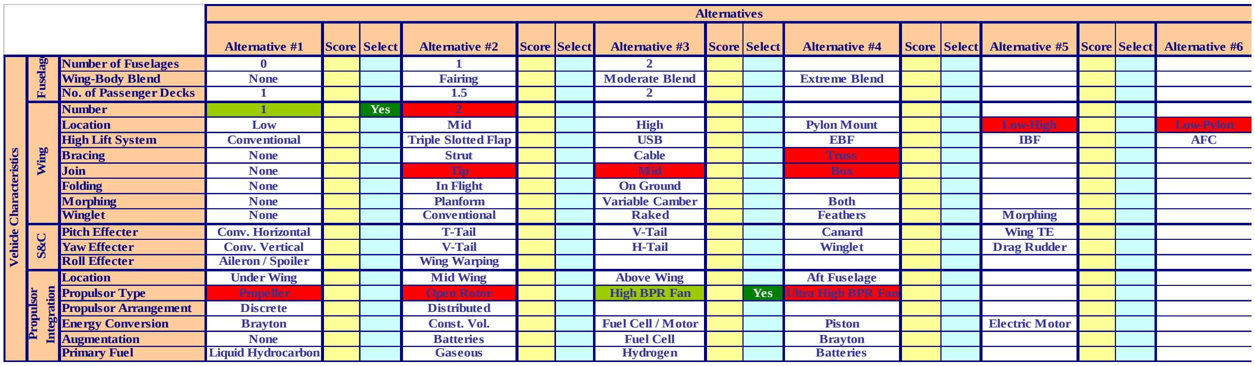
0: NOT compatible
1: Compatible
2: Enhances
Do not fill in yellow cells

		Number of Fuselages			Wing-Body Blend				Passenger Decks			Number		Location						High Lift System						Bracing			
		0	1	2	None	Fairing	Moderate Blend	Extreme Blend	1	1.5	2	1	2	Low	Mid	High	Pylon Mount	Low-High	Low-Pylon	Conventional	Triple Slotted Flap	USB	EBF	IBF	AFC	None	Strut	Cable	Braced Biplane
	2	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1
Number	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	0
	2	0	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Location	Low	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0
	Mid	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	0	0	0	1	1	1	1	1	1	1	0	0	0
	High	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1	0
	Pylon Mount	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	0	0	1	1	1	1	1	1	1	2	2	0
	Low-High	0	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1
	Low-Pylon	0	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
High Lift System	Conventional	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1
	Triple Slotted Flap	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	1	1	1	1
	USB	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0	0	0	1	1	1	1
	EBF	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	1	0	0	1	1	1	1
	IBF	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	0	1	1	1	1
	AFC	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1
Bracing	None	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0
	Strut	0	1	1	1	1	1	0	1	1	2	1	1	1	0	1	2	1	1	1	1	1	1	1	1	0	1	0	0
	Cable	0	1	1	1	1	1	0	1	1	2	1	1	0	0	1	2	1	1	1	1	1	1	1	1	0	0	1	0
	Truss	0	1	1	1	1	1	0	1	1	1	0	1	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	1
Join	None	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Tip	0	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0
	Mid	0	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0
	Box	0	1	1	1	1	1	1	1	1	1	0	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
Folding	None	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	In Flight	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
	On Ground	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Morphing	None	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Planform	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Variable Camber	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Both	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Winglet	None	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Conventional	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Raked	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Feathers	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Morphing	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Pitch Effecter	Conv. Horizontal	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	T-Tail	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	V-Tail	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Canard	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Wing TE	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1

Figure 3.5 – Part of SUGAR's Compatibility Matrix

Additionally, the matrix can be enhanced by using the number 2 to indicate when two alternatives are not only compatible, but also that using those two alternatives together provides a benefit to using just one or the other. When an alternative is selected, any alternatives that will couple with the previously selected one and thereby improve performance will be highlighted for the user to view. However, the SUGAR team elected not to incorporate this option into the compatibility matrix.

Once the compatibility matrix is complete, it is linked to the morphological matrix to enable dynamic decision making. The results of the compatibility will automatically be reflected to the user with each choice made during the workshop. This can be seen in Figure 3.6. The red cells indicate those options which have been ruled out due to the incompatibility matrix. Which cells appear red is a result of choices selected previously in the decision making chain (these choices are marked with a green "yes") and helps to drive vehicle concept design. This is a function of IRMA and will be discussed in more detail in the workshop section of this report. Note that Figure 3.6 does not reflect work done at the workshop, it merely indicates the functionality of the built in compatibility matrix.



			Alternatives															
			Alternative #1	Score	Select	Alternative #2	Score	Select	Alternative #3	Score	Select	Alternative #4	Score	Select	Alternative #5	Score	Select	Alternative #6
Vehicle Characteristics	Fuselag	Number of Fuselages	0			1			2									
		Wing-Body Blend	None			Fairing			Moderate Blend			Extreme Blend						
		No. of Passenger Decks	1			1.5			2									
	Wing	Number	1		Yes	2												
		Location	Low			Mid			High			Pylon Mount			Low-High			Low-Pylon
		High Lift System	Conventional			Triple Slotted Flap			USB			EBF			IBF			AFC
		Bracing	None			Strut			Cable			Truss						
		Join	None			Tip			Mid			Box						
		Folding	None			In Flight			On Ground									
		Morphing	None			Planform			Variable Camber			Both						
		Winglet	None			Conventional			Raked			Feathers			Morphing			
	S&C	Pitch Effecter	Conv. Horizontal			T-Tail			V-Tail			Canard			Wing TE			
		Yaw Effecter	Conv. Vertical			V-Tail			H-Tail			Winglet			Drag Rudder			
		Roll Effecter	Aileron / Spoiler			Wing Warping												
	Propulsor Integration	Location	Under Wing			Mid Wing			Above Wing			Aft Fuselage						
		Propulsor Type	Propeller			Open Rotor			High BPR Fan		Yes	Ultra High BPR Fan						
		Propulsor Arrangement	Discrete			Distributed												
		Energy Conversion	Brayton			Const. Vol.			Fuel Cell / Motor			Piston			Electric Motor			
		Augmentation	None			Batteries			Fuel Cell			Brayton						
		Primary Fuel	Liquid Hydrocarbon			Gaseous			Hydrogen			Batteries						

Figure 3.6 – Example of IRMA Dashboard with a couple selections. Red cells indicate incompatible options.

Pre-workshop Step 5.2: Identify and discuss attributes of each row of the decomposition

Once the backbone of the IRMA has been completed, it is important to go over the results of the functional decomposition to ensure it is comprehensive. Additionally, it is important to discuss each attribute and alternative to ensure that the function and meaning of each is understood by all those involved. It is also especially important to identify the benefit or cost of each attribute and alternative, in this case to identify how each affects aircraft performance relative to NASA's goals. Understanding the importance of each attribute is crucial to the next pre-workshop step. Additionally, it allows the users to scrutinize the choices they made in the functional decomposition to ensure that the problem can be adequately addressed with those attributes listed in the matrix.

Pre-workshop Step 6: Rank order decomposition based on relative importance to requirements

Using the discussions begun in step 5.2, it is important to set up the basics for IRMA scoring by identifying the importance of each functional attribute to the problem. IRMA scoring ensures that those decisions which most directly impact the customer requirements get weightings reflecting their importance. For example, fuel burn is highly affected by the aircraft propulsor type. Therefore, the functional attribute "propulsor type" would be given a high rating such that it would count highly towards the overall score of the vehicle concept. Additionally, knowing the propulsor type is an attribute highly affecting fuel burn, the user is given a logical place to start the decision making process. Because of the incompatibility matrix, the order in which decisions are made will affect the vehicle architecture options available towards the end of the decision making chain. Therefore, it is important to begin making decisions with those attributes that will most highly affect the vehicle's performance.

In order to use the rankings effectively in the decision making process, each attribute must be evaluated prior to the workshop. For this instance, each attribute was evaluated for its effect on each one of NASA's goals. The attributes are marked as having a high impact, medium impact, low impact, or no impact on a specific goal. The impact may be positive or negative; a positive or negative influence is accounted for during the workshop when scoring each alternative. The "high-none" scale allows for the user to think of the problem qualitatively rather than quantitatively while still capturing the importance of a specific attribute. Once the attributes have been rated, the stage is set to allow for more logical, effective decision making, allowing those decisions which are more critical to vehicle performance relative to a certain goal to occur early on in the chain of decisions.

This step is performed both pre-workshop and during the workshop. Conducting this exercise prior to the workshop helps users ensure that the matrix is complete and its entries are understood. Conducting the exercise during the workshop helps check the work done before the workshop and brings all participants together. It is important that the rankings are as accurate as possible, as they end up driving the decision making process heavily.

Pre-workshop Step 7: Select optimal suitable reference systems

Before groups can come together and begin to brainstorm unique vehicle concepts at the workshop, it is important that everyone be given a frame of reference in which they must make decisions. This frame of reference includes a baseline vehicle as well as the type of mission for which the vehicle is being designed.

The baseline vehicle provides a reference system for users when they are scoring alternatives in the workshop. During the workshop, each alternative will be given a score (1-10) reflecting how well they contribute to the customer goals. In this case, the score reflects how well an alternative will improve performance towards specific NASA goal. Knowing the features of the baseline, the user is able to make these decisions relative to existing systems. For example, the baseline alternative may be given a score of 5. Each alterative can then be scored against that, being given a higher score if it improves performance or a lower score if it hinders performance.

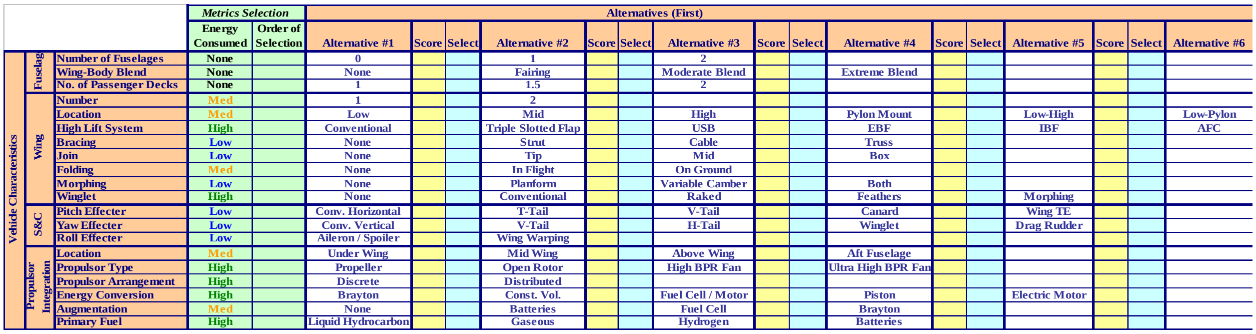
Additionally, choosing a reference mission is important prior to the workshop. The reference mission stipulates such decisions as the class of vehicle being designed and the mission it will be expected to perform. Users will make different design choices for a regional jet than for a long range aircraft. In order to minimize confusion, it is important to stipulate these parameters ahead of time so everyone may understand the context in which they are designing.

The SUGAR team selected a 2008 technology conventional configuration (similar to 737NG) as the baseline aircraft and assumed a medium range aircraft flying at approximately M=0.7 for all vehicle concepts created.

Having these guidelines gives structure to the workshop and ensures the participants are able to effectively contribute to the overall workshop process.

Pre-workshop Step 8: Exercise IRMA

The group is now ready to exercise the IRMA at the workshop. The IRMA will simply aid the group in the decision making process by providing structure and support for the conceptual design process. The steps of the workshop and details on how the IRMA is used to aid dynamic decision making will be discussed in the next section of this report. A complete IRMA, ready for a workshop, is depicted in Figure 3.7. Again, this IRMA is a notional example and does not reflect real decisions made prior to the workshop.



			Metrics Selection		Alternatives (First)															
			Energy Consumed	Order of Selection	Alternative #1	Score	Select	Alternative #2	Score	Select	Alternative #3	Score	Select	Alternative #4	Score	Select	Alternative #5	Score	Select	Alternative #6
Vehide Characteristics	Fuselag	Number of Fuselages	None		0			1			2									
		Wing-Body Blend	None		None			Fairing			Moderate Blend			Extreme Blend						
		No. of Passenger Decks	None		1			1.5			2									
	Wing	Number	Med		1			2												
		Location	Med		Low			Mid			High			Pylon Mount			Low-High			Low-Pylon
		High Lift System	High		Conventional			Triple Slotted Flap			USB			EBF			IBF			AFC
		Bracing	Low		None			Strut			Cable			Truss						
		Join	Low		None			Tip			Mid			Box						
		Folding	Med		None			In Flight			On Ground									
		Morphing	Low		None			Planform			Variable Camber			Both						
		Winglet	High		None			Conventional			Raked			Feathers			Morphing			
	S&C	Pitch Effecter	Low		Conv. Horizontal			T-Tail			V-Tail			Canard			Wing TE			
		Yaw Effecter	Low		Conv. Vertical			V-Tail			H-Tail			Winglet			Drag Rudder			
		Roll Effecter	Low		Aileron / Spoiler			Wing Warping												
	Propulsor Integration	Location	Med		Under Wing			Mid Wing			Above Wing			Aft Fuselage						
		Propulsor Type	High		Propeller			Open Rotor			High BPR Fan			Ultra High BPR Fan						
		Propulsor Arrangement	High		Discrete			Distributed												
		Energy Conversion	High		Brayton			Const. Vol.			Fuel Cell / Motor			Piston			Electric Motor			
		Augmentation	Med		None			Batteries			Fuel Cell			Brayton						
		Primary Fuel	High		Liquid Hydrocarbon			Gaseous			Hydrogen			Batteries						

Figure 3.7 – Notional IRMA before Workshop

3.3 – Workshop Steps

The work prepared prior to the workshop created tools and resources to facilitate a more streamlined execution of the workshop steps. These workshop steps are composed of small group breakout activities and larger group down-selection activities. This workflow is depicted in Figure 3.8. This section will describe in more detail the major accomplishments of each of the steps involved in the workshop and the outcomes.

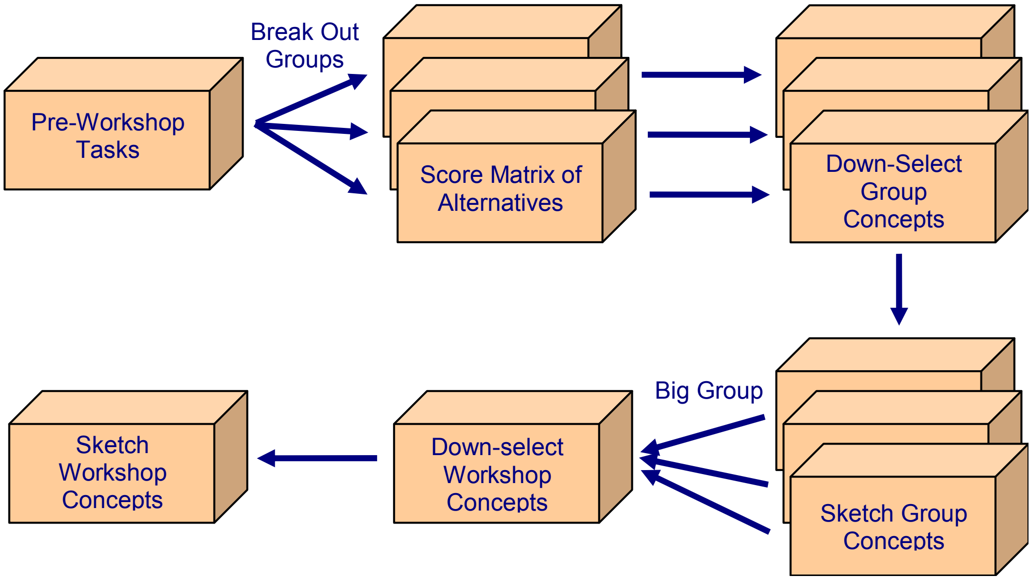


Figure 3.8 – Workshop Workflow Diagram

Workshop Step 1: Participant Planning and Pre-workshop review

The information provided in the pre-workshop activities contributed to the creation of the tools that will be available to the workshop participants. The Interactive Reconfigurable Matrix of Alternatives (IRMA), information on specific technologies, information on the baseline vehicle, information on mission requirements and information for the NASA goals will be provided to each of the teams. The IRMA integrates the decomposition of requirements, the alternatives in the matrix of alternatives and the compatibility matrix in an interactively accessible format.

The workshop participants consist of a subset of the individuals who participated in the pre-workshop activities and other technical experts who may not have been involved in the pre-workshop activities. These participants were selected by their past experience in specific technology areas, configuration design or possess a broad understanding of engineering trades.

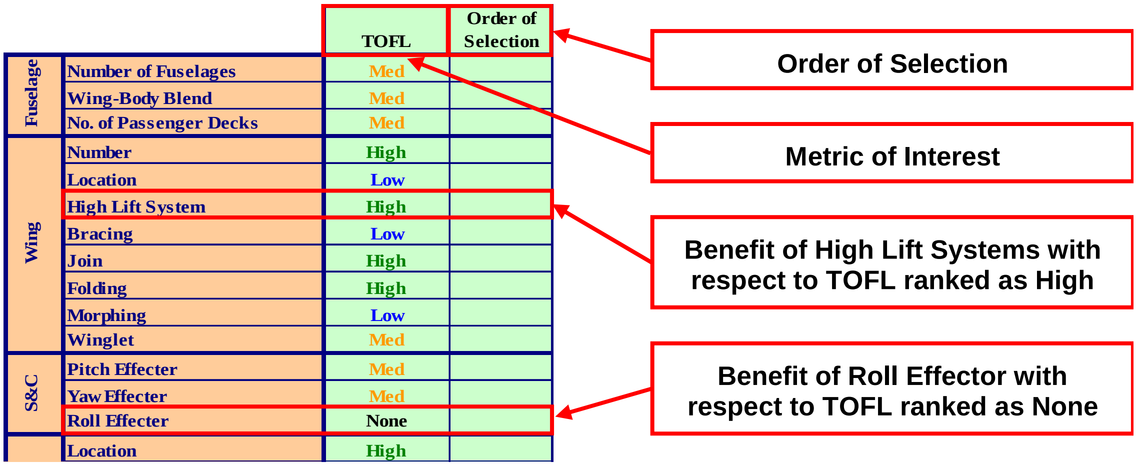
The purpose of the Workshop Step 1 is to orient the participants to the mission that they are designing for and the steps that they will be required to go through during the workshop.

An orientation for the tools that will be available to them along with reference vehicle and mission information. Furthermore, each of the groups will be required to select architectures that relate to each of the functional metrics. These metrics were specified by NASA and refined in the earlier phases of the program.

Workshop Step 2: Score Matrix of Alternatives

The participants were broken up into three groups consisting of an averaged level of experience, both on years of experience and technical expertise. These groups worked together to identify the initial aircraft configurations for each of the NASA Goals or "Metrics of Interest" (MOI).

The teams investigated a single MOI and qualitatively ranked the benefit of each characteristic relative to the MOI. The groups identified the characteristics with high benefits progressing from medium to identifying characteristics with low or no benefit to the MOI. This progressive identification of relative benefit supplies the team with a general "order of selection" to be used in the future. A snapshot of the exercise is depicted in Figure 3.9.



		TOFL	Order of Selection
Fuselage	Number of Fuselages	Med	
	Wing-Body Blend	Med	
	No. of Passenger Decks	Med	
Wing	Number	High	
	Location	Low	
	High Lift System	High	
	Bracing	Low	
	Join	High	
	Folding	High	
	Morphing	Low	
	Winglet	Med	
S&C	Pitch Effecter	Med	
	Yaw Effecter	Med	
	Roll Effecter	None	
	Location	High	

Order of Selection

Metric of Interest

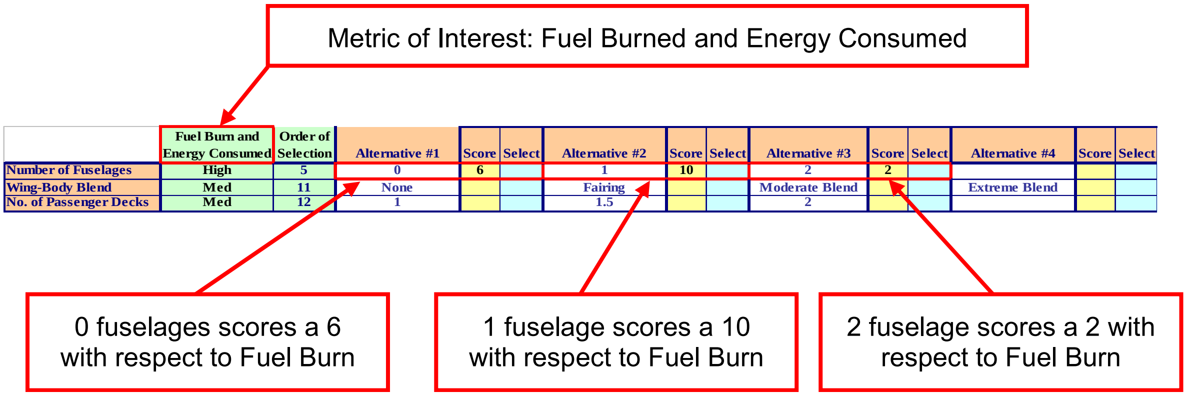
Benefit of High Lift Systems with respect to TOFL ranked as High

Benefit of Roll Effector with respect to TOFL ranked as None

Figure 3.9 – Step 2: Identification of Relative Benefit

Upon identifying the order of selection, the teams will progress in the specified order and rank the alternatives associated with the metrics of interest. This ranking will be used to facilitate discussions for assessing the benefit and tradeoffs between configuration options. For a given metric, starting with the high impact characteristics, score the elements within each row based on their value to the specified metrics where 1 is low and 10 is high. The teams will progress in the specified order of selection ranking each of the alternatives. A snapshot of selected results is depicted in Figure 3.10 below.

The teams repeat step 2 until all the MOI have been evaluated. Upon the completion of identifying the order of selection and the scoring of alternatives, the teams have the necessary information to exercise the IRMA to select concepts.



Metric of Interest: Fuel Burned and Energy Consumed

	Fuel Burn and Energy Consumed	Order of Selection	Alternative #1	Score	Select	Alternative #2	Score	Select	Alternative #3	Score	Select	Alternative #4	Score	Select
Number of Fuselages	High	5	0	6		1	10		2	2				
Wing-Body Blend	Med	11	None			Fairing			Moderate Blend			Extreme Blend		
No. of Passenger Decks	Med	12	1			1.5			2					

0 fuselages scores a 6 with respect to Fuel Burn

1 fuselage scores a 10 with respect to Fuel Burn

2 fuselage scores a 2 with respect to Fuel Burn

Figure 3.10 – Scoring the Alternatives

Workshop Step 3: Down-Select Group Concepts

Beginning with the characteristic labeled #1 in the order of selection column for a specific MOI, the teams will begin to select alternatives for each of the characteristics. The teams utilize the interactive capability of the IRMA tool with the built in compatibility matrix. When the team selects an alternative, the incompatible options in other characteristic rows turn red if they are incompatible with that selection. Ideally, the team will specify the highest ranked alternative on each row for a given MOI, but the incompatibilities may make this impossible. The team will progress in the order of selection, discussing the selection of the alternative. Once there is an option selected in each of the rows, a configuration is complete. The intermediate results are shown in Figure 3.11. This figure shows the filtered out results based on a few selections for a characteristic.

Selections are made according to the order of selection

As selections are made, incompatible elements turn red

	Metrics Selection		Alternatives (First)												
	Fuel Burn and Energy Consumed	Order of Selection	Alternative #1	Score	Select	Alternative #2	Score	Select	Alternative #3	Score	Select	Alternative #4	Score	Select	Alternative #5
Number of Fuselages	High	1	0	2		1	10	Yes	2	5					
Wing-Body Blend	Med	7	None	3		Fairing	4		Moderate Blend	10		Extreme Blend	1		
No. of Passenger Decks	Low	13	1	10		1.5	1		2						
Number	Med	8	1	3		2	10								
Location	None	17	Low	4		Mid	7		High	[illegible]		Pylon Mount	2		Low-High
High Lift System	High	2	Conventional	10	Yes	Triple Slotted Flap	3		USB	4		EBF	1		IBF

Selections are made according to the order of selection

Figure 3.11 – Intermediate Results from the IRMA

The team continues to select alternatives for each of the characteristics in the prescribed order of selection for each of the MOI, discussing each selection, ultimately arriving at a couple of configurations for further investigation. These various configurations represent the corners of the design space and will be used for sensitivity analysis once the workshop process is complete. Figure 3.12 shows the results of the configuration selection for one of the groups participating in the workshop.

		Team Y Fuel Burn #1	Team Y TOFL #1	Team Y Cruise Emissions #1	Team Y LTO NOx #1	Team Y DNL #1
Fuse	**Fuselages**	1	1	1	1	1
	Wing-Body Blend	Fairing	Fairing	Fairing	Fairing	Extreme Blend
	Passenger Decks	1	1	1	1	1
Wing	**Number**	1	1	1	1	1
	Location	High	High	High	High	Mid
	High Lift System	Conventional	AFC	Conventional	Conventional	AFC
	Bracing	Strut	Strut	Strut	Strut	None
	Join	None	None	None	None	None
	Variable Span	On Ground	On Ground	On Ground	On Ground	On Ground
	Morphing	None	None	Variable Camber	None	None
	Tip Devices	Raked	Raked	Raked	Conventional	Raked
S&C	**Pitch Effecter**	Conv. Horizontal	Conv. Horizontal	Conv. Horizontal	Conv. Horizontal	Wing TE
	Yaw Effecter	Conv. Vertical	Conv. Vertical	Conv. Vertical	Conv. Vertical	H-Tail
	Roll Effecter	Aileron/Spoiler	Aileron/Spoiler	Aileron/Spoiler	Aileron/Spoiler	Aileron/Spoiler
Propulsor Integration	**Location**	Below Wing	Mid Wing	Below Wing	Below Wing	Above Wing
	Propulsor Type	Open Rotor	Open Rotor	Open Rotor	Propeller	Fan
	Propulsor /core	Single	Multiple	Single	Single	Single
	Energy Conversion	Const. Vol. Combustion	Brayton	Electric Motor	Const. Vol Combustion	Brayton
	Augmentation	None	None	Brayton	Fuel Cell	None
	Primary Fuel	Liquid Hydrocarbon	Liquid Hydrocarbon	Batteries	Liquid Hydrocarbon	Hydrocarbon

Figure 3.12 – Team Y's Configuration Results from IRMA process

Workshop Step 4: Sketch group concepts

Identifying specific alternatives for each of the characteristics alone lends itself to a myriad of interpretations for integration and sizing effects. In this conceptual phase of the program, performing a sizing algorithm on the alternatives is premature. In order to bring the concept to life and understand different individual's interpretations of the integration aspect of the design choices, each member of the group will sketch each of the proposed aircraft.

The result is a collage of interpretations of drawings. The teams then compared individual sketches for each of the different aircraft and reach group consensus on what the aircraft should look like. Based on the results of the discussions, the team will redraw the concepts incorporating any changes. An example of one of the group's original interpretations and final drawing is depicted below in Figure 3.13.

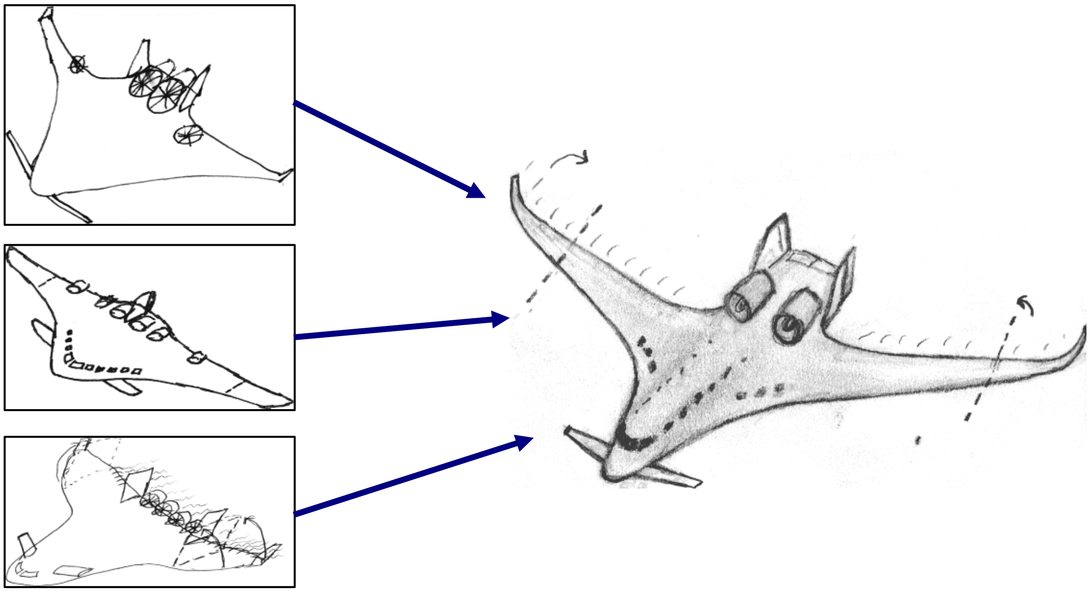


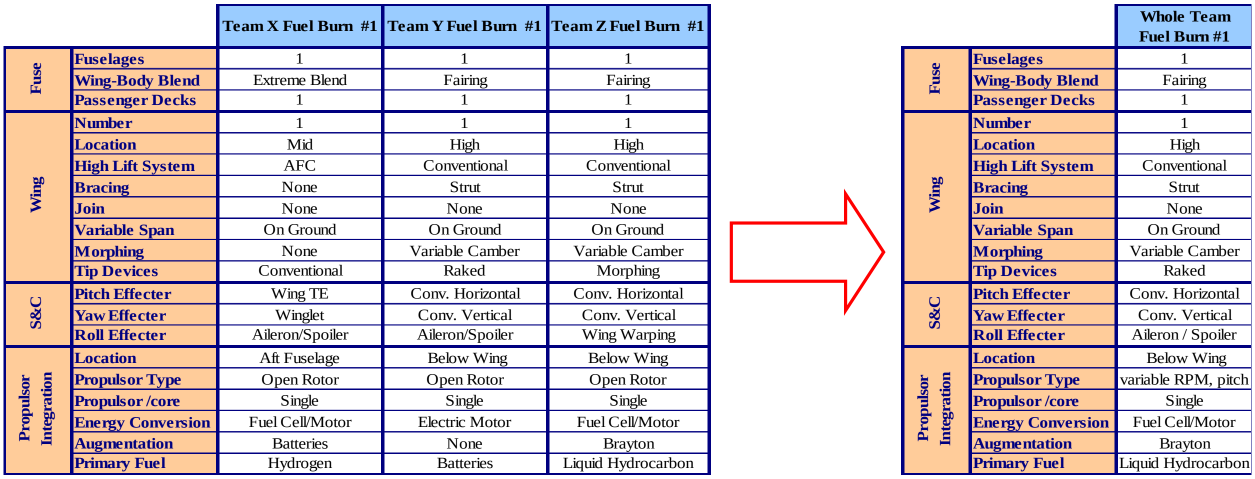
Figure 3.13 – Concept sketches

Workshop Step 5: Down-select among group concepts

At this stage of the workshop, there exist at least three concepts to meet each of the NASA goals. In order to arrive at a select few configurations to apply technologies toward, the teams regroup and present their concepts.

Each team presents their concept sketch and provides discussion for the rational for their configuration selection. Since different alternatives for each of the vehicle characteristics provide advantages and disadvantages alone as well as the integrated, the teams discuss the expected pros and cons for their concepts.

Once all the groups have discussed their concepts, the large group down-selects to one or two concepts per metric. To facilitate the down-select, the group compares the concepts to each of the metrics of interest based on the perceived pros and cons of each concept. The group discusses commonalities among all concepts, configuration selection issues and integration issues which may lead to reassessing the configuration selection. Upon reaching consensus, the large group will arrive at a concept or two for each metric as and repeats the concept selection process to identify a configuration that represents a compromise between all metrics. An example of the results of the large group discussion is depicted below in Figure 3.14.



		Team X Fuel Burn #1	Team Y Fuel Burn #1	Team Z Fuel Burn #1
Fuse	**Fuselages**	1	1	1
	Wing-Body Blend	Extreme Blend	Fairing	Fairing
	Passenger Decks	1	1	1
Wing	**Number**	1	1	1
	Location	Mid	High	High
	High Lift System	AFC	Conventional	Conventional
	Bracing	None	Strut	Strut
	Join	None	None	None
	Variable Span	On Ground	On Ground	On Ground
	Morphing	None	Variable Camber	Variable Camber
	Tip Devices	Conventional	Raked	Morphing
S&C	**Pitch Effecter**	Wing TE	Conv. Horizontal	Conv. Horizontal
	Yaw Effecter	Winglet	Conv. Vertical	Conv. Vertical
	Roll Effecter	Aileron/Spoiler	Aileron/Spoiler	Wing Warping
Propulsor Integration	**Location**	Aft Fuselage	Below Wing	Below Wing
	Propulsor Type	Open Rotor	Open Rotor	Open Rotor
	Propulsor /core	Single	Single	Single
	Energy Conversion	Fuel Cell/Motor	Electric Motor	Fuel Cell/Motor
	Augmentation	Batteries	None	Brayton
	Primary Fuel	Hydrogen	Batteries	Liquid Hydrocarbon

		Whole Team Fuel Burn #1
Fuse	**Fuselages**	1
	Wing-Body Blend	Fairing
	Passenger Decks	1
Wing	**Number**	1
	Location	High
	High Lift System	Conventional
	Bracing	Strut
	Join	None
	Variable Span	On Ground
	Morphing	Variable Camber
	Tip Devices	Raked
S&C	**Pitch Effecter**	Conv. Horizontal
	Yaw Effecter	Conv. Vertical
	Roll Effecter	Aileron / Spoiler
Propulsor Integration	**Location**	Below Wing
	Propulsor Type	variable RPM, pitch
	Propulsor /core	Single
	Energy Conversion	Fuel Cell/Motor
	Augmentation	Brayton
	Primary Fuel	Liquid Hydrocarbon

Figure 3.14 – Large group configuration down-selection

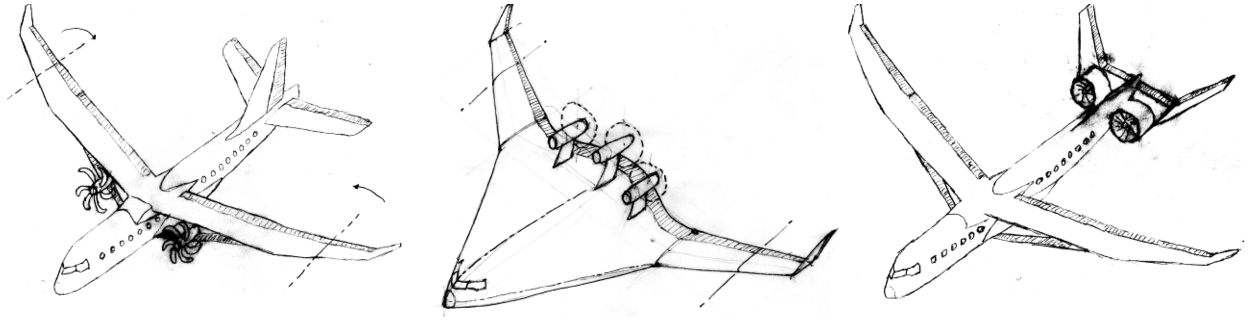
Workshop Step 6: Final workshop configuration and sketch workshop concepts

Upon reaching consensus among the large group, the concepts are reviewed for completeness and sketches are drawn by a selected individual to bring the concepts to life. This final sketching provides a mechanism for discussion as well as a product of the workshop. Figure 3.15 depicts the results from the SUGAR workshop. These drawings were used as a starting point in future steps of the contracted work.

Combined Fuel Burn #1

Combined Fuel Burn #2

Combined DNL #1



Combined DNL #2

Combined TOFL

Combined NOx and Emissions

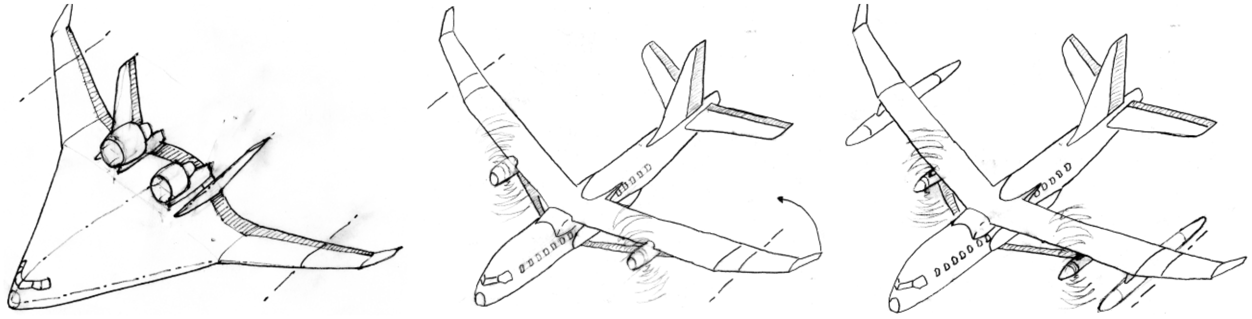


Figure 3.15 – Workshop concept drawings

3.4 – IRMA Process Payoff

By utilizing the ASDL created IRMA process, the SUGAR team was able to develop several alternatives for evaluation utilizing a systematic approach with documented decisions. By exercising the interactive tool, the teams were able to gain an enhanced understanding of the systems selections for the vehicle characteristics and the impacts of selecting a particular alternative without the need of exercising expensive analysis codes. The tool's dynamic nature and extensible, flexible framework allowed for the down-selection process to be rapidly repeated in order to select multiple configuration alternatives. This tool also facilitated discussions related to all major components of the aircraft and the integration issues.

The process used for exercising the tool provided a systematic process to obtain a sufficient set of reference systems and a mechanism for documenting the decisions that were made over the course of the workshop. The resulting files were given to the participants for use in further analysis in the follow on phases of the contract.

3.5 – Post Workshop Selection of Concepts for Detailed Analysis

The Concept Workshop resulted in six advanced concepts (Figure 3.15). It was decided that because of resource limitations, only one HWB concept would be considered and that it would emphasize low noise (Combined DNL #2) rather than performance (Combined Fuel Burn #2). There were two possible architectures for the "Combined NOx and Emissions" concept: One using fuel cells and the other batteries. Therefore, two reference concepts and six advanced concepts were selected for consideration (Figure 3.16).

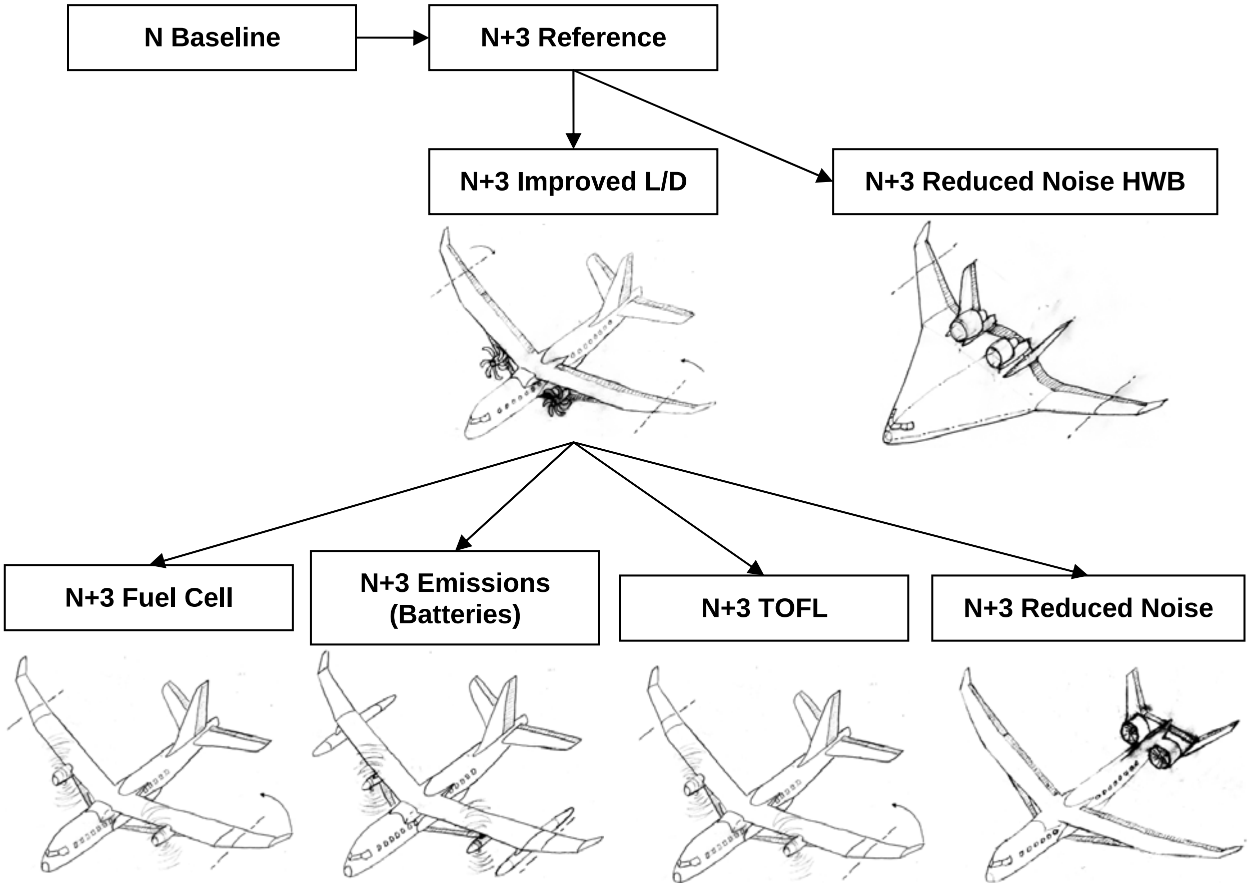


Figure 3.16 – Candidate Configurations for Detailed Analysis

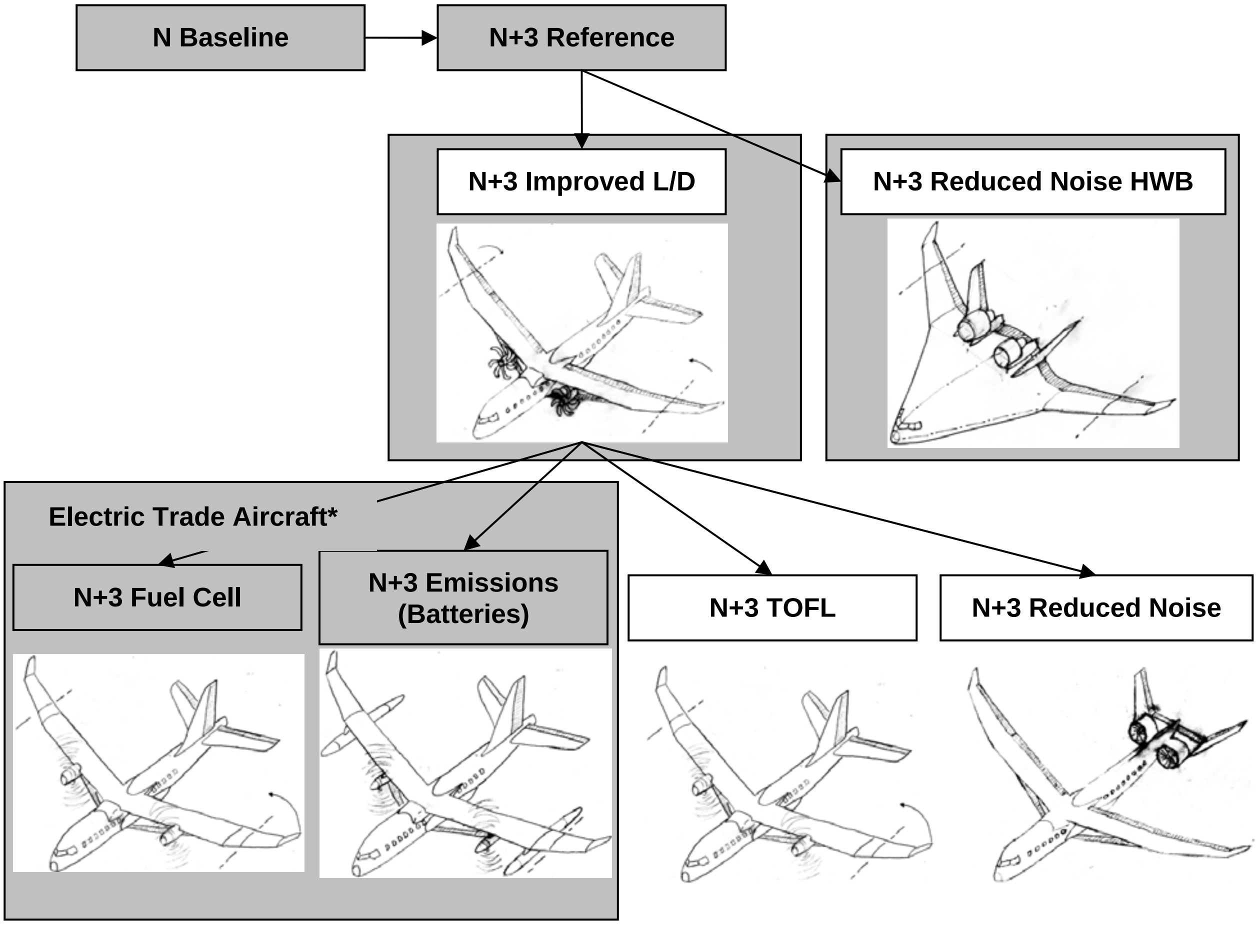
Based on available contract resources, we decided to focus our efforts on the corner points of the design space that appeared the most challenging and to reduce the number of advanced concepts to three. To achieve this, we decided to group the fuel-cell, battery, and hybrid electric aircraft into an "Electric Trade Aircraft". The HWB configuration was judged to be the configuration with the best chance of making the aggressive N+3 low noise goal, so it was selected over a strut braced wing configuration with tail shielding. The dedicated take-of-field-length (TOFL) optimized aircraft was dropped in favor of looking at TOFL sensitivities for one or more of the other configurations (Figure 3.17). All of the eliminated configurations have merit, and should be considered for inclusion in future studies. The five aircraft selected for detailed analysis are shown in Figure 3.18, and are summarized below:

1. SUGAR Free – Current technology, similar to 737 class aircraft. Used as Baseline for performance comparisons.
2. Refined SUGAR – Reference conventional configuration with estimated 2030-2035 technologies. This vehicle requires no new additional technology initiatives from NASA. It includes a turbofan engine which will be designed by GE. A variation of this configuration with N+3 advanced technologies will be provided for direct comparison to the advanced concepts.
3. SUGAR High – High span strut-braced wing configuration with advanced 2030-2035 N+3 technologies. Assumes significant technology development beyond the technologies

in the Refined SUGAR concept. Turbofan and open fan propulsion concepts are supplied by GE.

4. SUGAR Volt – Electric Trade Aircraft that builds off of SUGAR High configuration to add electric propulsion technologies. Considers a variety of electric-propulsion architectures (Battery electric only, fuel-cell gas turbine hybrid, battery electric gas turbine hybrid) which are supplied by GE.
5. SUGAR Ray – A HWB configuration that uses a similar suite of advanced technologies as the SUGAR High. Primary design emphasis is on reducing aircraft noise, while maintaining performance similar to the SUGAR High.

In summary, the matrix of configuration and operations alternatives are repeated here (Figure 3.19), with configuration and operations alternatives that are being actively evaluated by the SUGAR study highlighted in green.



* Includes hybrids with conventional Brayton cycle engines

Figure 3.17 – Configuration Groupings and Selections (Shaded)

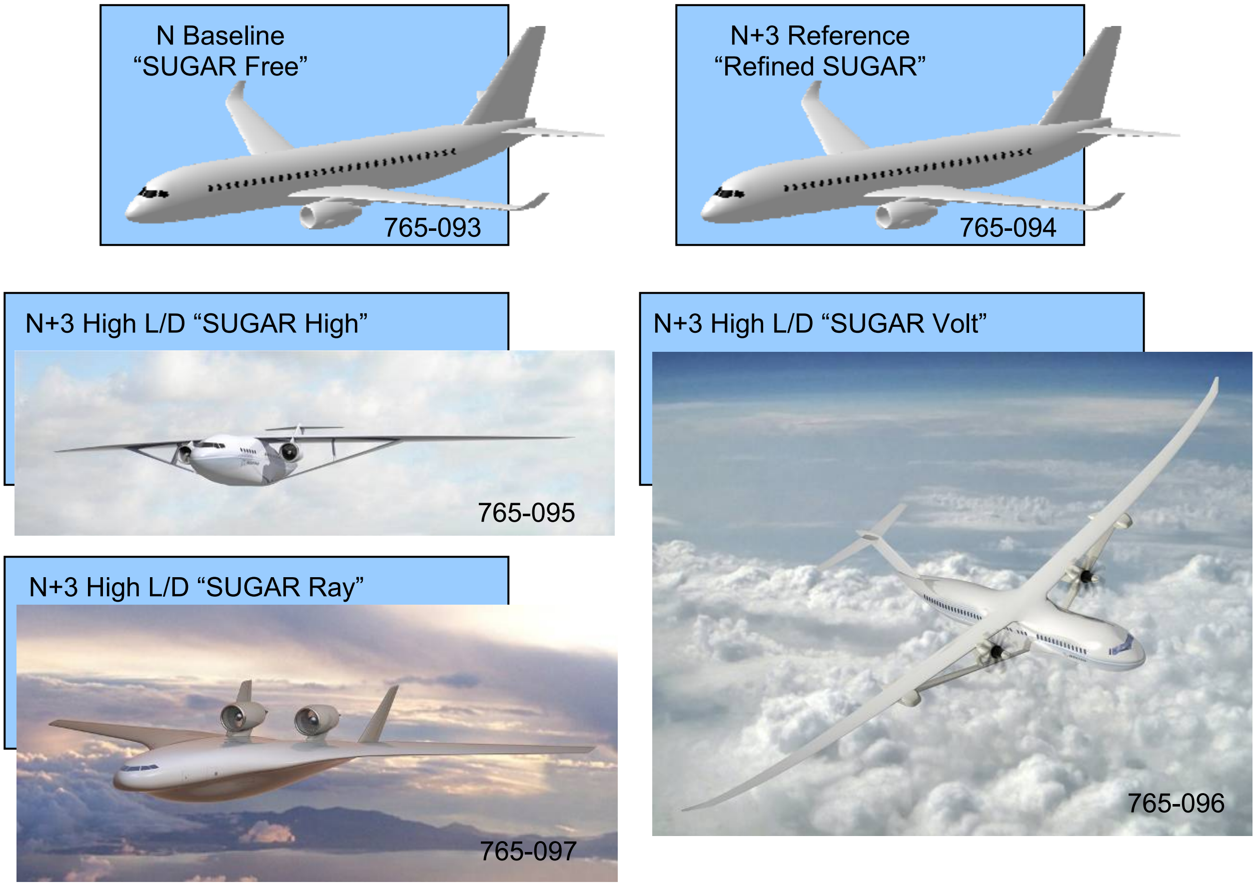
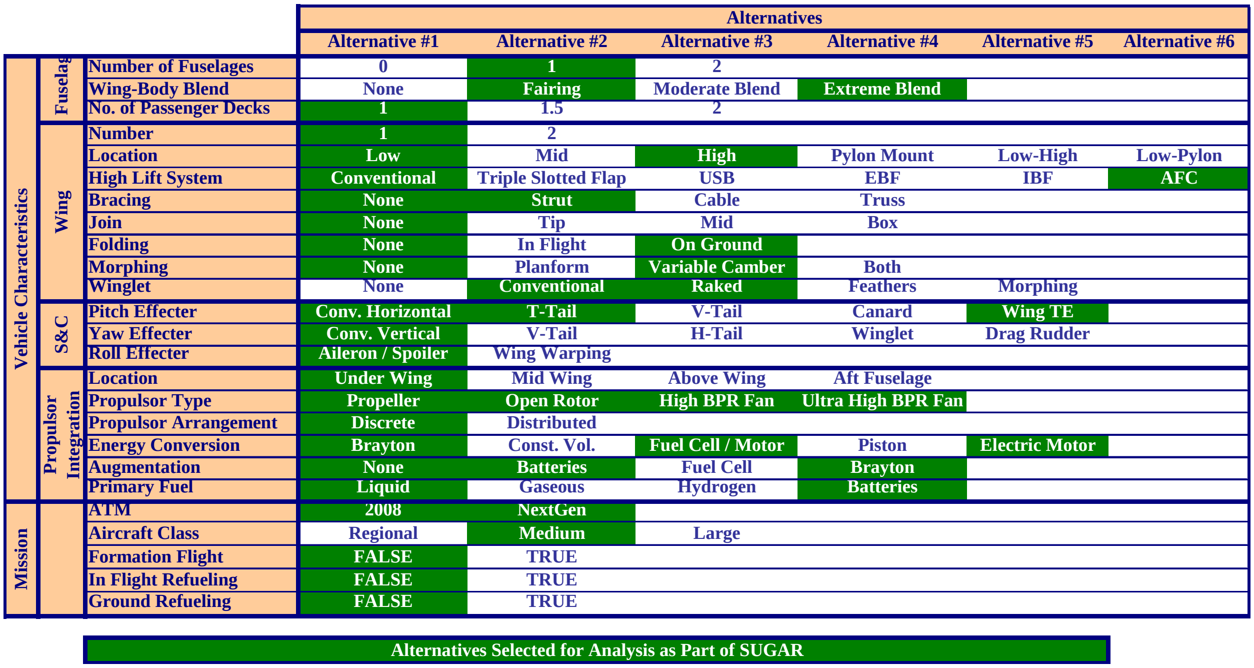


Figure 3.18 – Final Five airplanes selected for further study

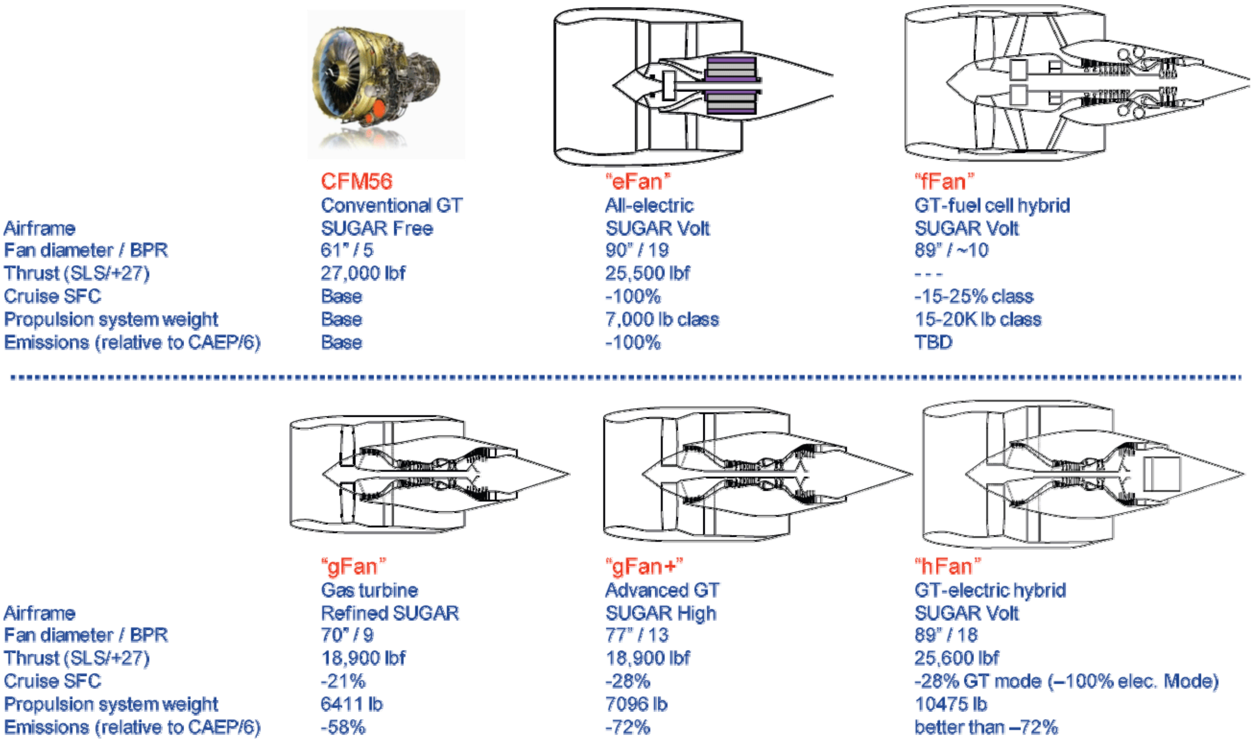


			Alternatives					
			Alternative #1	Alternative #2	Alternative #3	Alternative #4	Alternative #5	Alternative #6
Vehicle Characteristics	Fuselag	Number of Fuselages	0	1	2			
		Wing-Body Blend	None	Fairing	Moderate Blend	Extreme Blend		
		No. of Passenger Decks	1	1.5	2			
	Wing	Number	1	2				
		Location	Low	Mid	High	Pylon Mount	Low-High	Low-Pylon
		High Lift System	Conventional	Triple Slotted Flap	USB	EBF	IBF	AFC
		Bracing	None	Strut	Cable	Truss		
		Join	None	Tip	Mid	Box		
		Folding	None	In Flight	On Ground			
		Morphing	None	Planform	Variable Camber	Both		
		Winglet	None	Conventional	Raked	Feathers	Morphing	
	S&C	Pitch Effecter	Conv. Horizontal	T-Tail	V-Tail	Canard	Wing TE	
		Yaw Effecter	Conv. Vertical	V-Tail	H-Tail	Winglet	Drag Rudder	
		Roll Effecter	Aileron / Spoiler	Wing Warping				
	Propulsor Integration	Location	Under Wing	Mid Wing	Above Wing	Aft Fuselage		
		Propulsor Type	Propeller	Open Rotor	High BPR Fan	Ultra High BPR Fan		
		Propulsor Arrangement	Discrete	Distributed				
		Energy Conversion	Brayton	Const. Vol.	Fuel Cell / Motor	Piston	Electric Motor	
		Augmentation	None	Batteries	Fuel Cell	Brayton		
		Primary Fuel	Liquid	Gaseous	Hydrogen	Batteries		
Mission		ATM	2008	NextGen				
		Aircraft Class	Regional	Medium	Large			
		Formation Flight	FALSE	TRUE				
		In Flight Refueling	FALSE	TRUE				
		Ground Refueling	FALSE	TRUE				

Alternatives Selected for Analysis as Part of SUGAR

Figure 3.19 – Alternatives Selected for Analysis

A total of five advanced engine designs were delivered for the SUGAR study and are summarized in Figure 3.20. Each of these engines was designed to the thrust requirements for their respective point-of-departure vehicle designs (Section 5.1.3) and each is shown approximately to scale. The engines were given the informal designations “eFan”, “fFan”, “gFan”, “gFan+”, and “hFan”. Starting at the top left of the figure, the baseline engine for this study is a conventional gas turbine (GT), the CFM56 with a 61” fan diameter and 27,000 pound takeoff thrust rating. The “eFan” is an all-electric propulsor that is basically an electric motor connected to a high bypass fan via a gearbox. The electric power required to drive this propulsor is derived from a source external to the propulsor itself.



	CFM56	“eFan”	“fFan”
	Conventional GT	All-electric	GT-fuel cell hybrid
Airframe	SUGAR Free	SUGAR Volt	SUGAR Volt
Fan diameter / BPR	61” / 5	90” / 19	89” / ~10
Thrust (SLS/+27)	27,000 lbf	25,500 lbf	- - -
Cruise SFC	Base	-100%	-15-25% class
Propulsion system weight	Base	7,000 lb class	15-20K lb class
Emissions (relative to CAEP/6)	Base	-100%	TBD

	“gFan”	“gFan+”	“hFan”
	Gas turbine	Advanced GT	GT-electric hybrid
Airframe	Refined SUGAR	SUGAR High	SUGAR Volt
Fan diameter / BPR	70” / 9	77” / 13	89” / 18
Thrust (SLS/+27)	18,900 lbf	18,900 lbf	25,600 lbf
Cruise SFC	-21%	-28%	-28% GT mode (–100% elec. Mode)
Propulsion system weight	6411 lb	7096 lb	10475 lb
Emissions (relative to CAEP/6)	-58%	-72%	better than –72%

Figure 3.20 – GE Engine Family for Consideration in SUGAR Vehicles

The “fFan” is a fuel cell-gas turbine hybrid concept featuring a single spool gas generator attached to the same shaft as an electric motor. A portion of the compressor discharge air is pulled from the primary flowpath via a scroll system and fed to a fuel cell stack external to the propulsion nacelle (not shown). The exhaust effluent from the fuel cell is then fed back into the combustor and subsequently expanded in the turbine. The electric power from the fuel cell is used to power the electric motor/fan for some portions of the mission, provide electric power to airframe systems, and (possibly) power external electric propulsion units.

The “gFan” and “gFan+” engines are advanced high bypass 2-spool turbofan engines. The primary difference between the two is that the “gFan+” represents an aggressive push on gas turbine technology whereas the “gFan” is intended to be an extrapolation on were gas turbine technology will be in 2035 given a more moderate (but still aggressive) pace of development. Finally, the “hFan” is a gas turbine-electric hybrid engine capable of operating in an all gas turbine, all-electric, or combined modes depending on mission requirements, where the electric power is assumed to come from a source external to the engine (e.g. batteries).

The “eFan” engines, when integrated on the point-of-departure version of the SUGAR Volt, could not achieve the needed 3,500 nmi mission range without assuming a phenomenal improvement in battery technology relative to today’s state-of-the-art. The “fFan” showed some promise, but was ultimately not as competitive as the “hFan” engine concept. This, in combination with the challenges of realizing a compact, lightweight, high power output, prime-reliable fuel cell subsystem, deterred further work on the “fFan” concept. As such, only the “hFan” was selected for more detailed analysis and sizing on the SUGAR Volt.

Finally, one area holding considerable promise toward meeting the aggressive fuel burn goals of this project is the open fan. Open fan is also desirable from an emissions reduction point of view inasmuch as emissions are correlated to fuel burn. Open fan is less desirable from the point of view of meeting the very aggressive noise goals of this project, though it is clear that considerable progress could be made in this area with concerted effort.

It was clear at the outset that the number of possible engine concepts worthy of study in this project far outstrips the resources available. Furthermore, it was clear that the team would need to set a strategy on how to approach the number of engine concepts to be evaluated versus the depth of analysis. In general, the philosophy of this study has been to study a fewer number of the most promising engine concepts, and to do so at a level of analysis fidelity conducive to drawing useful conclusions from the results.

Thus, the team made a conscious decision early in this study to eschew the detailed evaluation of an open fan in favor of spending additional time and resources developing other “out of the box” concepts such as fuel cell and electric hybrids. Furthermore, open fan is presently being studied by industry and NASA in other venues. It therefore seems logical to focus the bulk of the effort in this project on those concepts that have heretofore received little or no attention.

As a result, the open fan is evaluated in only the most rudimentary way for this project. Specifically, the open fan’s impact on vehicle fuel burn is estimated by treating the open fan as a simple cruise SFC delta and an engine weight delta applied on top of the “gFan+” engine performance and weight estimates. This is sufficient to give some insight as to how the open fan performance benefit might be expected to impact the sized vehicle system. No attempt was made to evaluate open fan noise, as this would have required considerable effort and would have detracted from resources available to develop other concepts.

To recap, propulsion selections and top level technology assumptions are summarized below:

- N Baseline (SUGAR Free)
    - CFM56
    - Fuel burn Baseline
- N+3 Reference (Refined SUGAR)
    - “gFan”
    - High bypass ratio turbofan with 2030 engine technologies
    - SFC reduction goal of 20%
- N+3 High L/D (SUGAR High)
    - “gFan+”

    - High bypass ratio turbofan
    - An open fan variant was also evaluated at a very high level using simple weight and SFC deltas relative to the “gFan+” concept
    - Advanced technologies to improve engine performance relative to Refined SUGAR
    - SFC reduction goal of 25%
- N+3 Electric Trade Aircraft (SUGAR Volt)
    - “hFan”
    - Ducted fan
    - Hybrid gas turbine-battery electric architecture
    - Fuel cell hybrid (“fFan”) and battery electric (“eFan”) versions were evaluated but not selected for further analysis
- N+3 Low Noise HWB (SUGAR Ray)
    - “gFan+” (same as SUGAR High)

4.0 – Advanced Technologies Selection

This section provides a brief overview of the technologies included in this study.

4.1 – Aerodynamics Technologies

A team of aerodynamicists developed a list of technologies that would be applicable to a 2030-2035 technology aircraft. The technologies to be applied to vehicles are shown in Table 4.1. As cost was not considered directly, trade studies were not performed to determine the optimum mix of technologies for each vehicle. Subject Matter Experts (SMEs) determined the matching of the technologies to the configurations.

Table 4.1 – Aero Technology Summary

		Configuration				
		'N' SUGAR Free	**'N+3' Refined SUGAR**	**'N+3' SUGAR High**	**'N+3' SUGAR Volt**	**'N+3' SUGAR Ray**
Aero Technology Areas	**Laminar Flow**	None	Natural / Passive	Natural, Passive and Active Where Appropriate		
	Riblets	None	Fuselage	Fuselage, Wing, Tails, Nacelles Where Appropriate		TBD
	Excrescence Drag	Conventional	Multi-Functional Structures, Reduced Fasteners, Reduced Flap Fairings, Gapless			
	Empennage	Conventional Size	C.G. Control Relaxed Static Stability & Increased C_{LMax} for reduced Size			
	Airfoil Technology	Supercritical		Advanced Super Critical Adaptive Camber w/ Spanload Control		TBD
	Additional Technologies	None		Low Interference Drag Nacelle Low Drag Strut Integration		Airframe Noise Shielding

4.1.1 – Laminar Flow Control

Laminar flow can significantly increase the aerodynamic performance of an air vehicle by reducing viscous drag. Drag Reduction is accomplished by delaying the buildup of two primary transition mechanisms, Stationary Cross-Flow (SCF) and Tollmien-Schlicting (T-S) waves. For the SUGAR study, the following strategies are discussed:

- Natural Laminar Flow (NLF): is achieved through shaping. Wing airfoil design with extended favorable gradients delays the buildup of T-S waves.
- Passive Laminar Flow: is similar to Hybrid Laminar Flow but does not require power for a suction system. The delta pressure needed for suction is designed into the airplane.
- Hybrid Laminar Flow (HLFC): employs suction in a non-structural region ahead of the front spar and design for favorable gradients to sustain laminar flow over the wing box. Power is still needed for the suction system.

- Active Laminar Flow: is achieved through integrating the suction system with the structural wing box to ensure laminar flow. This requires power and plumbing for the suction system.

As shown in Table 4.1, different levels of laminar flow designs will be applied to each configuration. The trade between the strategies depends on the design features of the configuration. No trade studies will be performed to determine which level of laminar flow is to be applied and the chosen amount will be determined by SMEs.

Kruger flaps were chosen for the low speed leading edge device. This provides the high lift needed for low speed and is an enabler for laminar flow at cruise. The Kruger also stows below the wing behind the attachment line providing a clean uninterrupted upper surface for laminar flow in cruise.

In the Aerodynamic drag buildup, the laminar surface area must be calculated to apply the proper drag reduction relative to turbulent values. Transition Reynolds Number of 12 to 17 million (variation with span) was used to determine the extent of the laminar run in the streamline direction. An eight-degree turbulent wedge created by the intersection of the body and the leading edge of the wing establish the inboard wing boundary for laminar flow. It is also assumed that NLF can achieve the same transition Reynolds number as HLFC. These assumptions were used in the Aerodynamic buildups.

4.1.2 – Riblets

Riblets have been studied for fuselage drag reduction in the past. They offer drag reduction but traditionally are not damage tolerant. The lower surface of wings may also benefit but these surfaces typically encounter more extreme environments resulting in riblet delamination. In these studies, aircraft using the technology will assume features are manufactured into the vehicle wing skin or take the place of paint resulting in no weight change. A 7% drag benefit on skin friction drag will be applied to each component using this technology (based on wind tunnel and flight tests).

4.1.3 – Excrescence Drag

Application of multi-functional structures, reduction in fasteners, reduced flap fairings, and sealed surfaces will result in a 20% reduction of excrescence drag. Structures enables a portion of this savings, the rest comes from reduced flap fairings resulting from optimized high lift systems.

4.1.4 – Empennage

Reducing the tail size for horizontals and verticals attained through active CG management and increased design lift coefficient results in drag reduction. This is reflected in the configuration geometry and is not explicitly carried as an aerodynamics increment.

4.1.5 – Airfoil Technology

Advanced supercritical airfoil technology will be applied to the baseline and reference vehicles. The SUGAR High and SUGAR Volt configurations will benefit from higher cruise lift coefficients compared to conventional configurations. A 3% reduction in airplane drag is assumed from wind tunnel derived database levels for a given lift coefficient based on wing design studies.

4.1.6 – Additional Aero Technologies

Additional technologies include low drag strut integration, low interference drag nacelle, and airframe noise shielding. For the strut-braced wing a 4.8% drag improvement was used over empirical methods. Low interference nacelle assumes an interference drag free installation. Airframe noise shielding is an Aerodynamic technology which enables future takeoff and approach operations.

4.2 – Structural Technologies

A team of structural engineers developed a list of technologies that would be applicable to a 2030-2035 technology aircraft. The technologies, and vehicles they can be applied on, are shown in Table 4.2. As cost was not considered directly, trade studies were not performed to determine the optimum mix of technologies for each vehicle. The application of the technologies was left to the aircraft designers and discipline experts.

Table 4.2 – Structural Technologies Summary

		Configuration				
		‘N’ SUGAR Free	**‘N+3’ Refined SUGAR**	**‘N+3’ SUGAR High**	**‘N+3’ SUGAR Volt**	**‘N+3’ SUGAR Ray**
Structural Technology Areas	**Materials / Manufacturing**	Aluminum	Adv. Composites incl. Hybrid Polymer, Adv. Metals, Adv. Joining, Adv. Ceramics			
	Health Management	None On-Board	On-board Structurally Integrated SHM, Advanced NDE/NDI			
	Loads & Environments	None	Max. Flight Control Int.	Maximize Flight Control Integration, Active/Passive Aeroelastic Response for Load Control		
	Design & Criteria	Deterministic	Reliability Based, Robust/Unitized, Multi-Functional Structures, Support for NLF			
	Adaptive Structures for Control Systems	Conventional	Conformal, Gapless, Simplified HL	Conformal, Gapless, Adaptive, Spanwise Load Control, Simplified HL		
	Energy Management	No Structural Integration	Structurally Integrated Thermal and Electrical Energy Management			
	Coatings	Conventional Paint and Corrosion Prev.	Enable Lightweight Materials	Enable Lightweight Materials, Energy Harvesting, Thermal Management, Drag Reduction		
	Interiors	Standard	More Lightweight			
	Additional Structures Technologies	None	Environmentally Compliant Manufacturing, Structurally Integrated Systems (Wiring)	Lightweight Wing Folds, Adv. Lightweight High Lift Systems, Adaptive Wing Camber, Adv. Material Forms		Lightweight Wing Folds, Adaptive Wing Camber, Adv. Material Forms, Adv. Non-Circular Fuse., Adaptive Inlets/Nozzles

4.2.1 – Materials and Manufacturing

There are many areas of material development including Advanced Composites, Metals, Joining, and Ceramics technologies. The estimated structural weight reductions for advanced materials are shown in Table 4.3. These are based on expected improvements in critical material properties and the distribution of the dominant material properties.

Table 4.3 – Advanced Material Applications and Improvements

Component	Weight Reduction	Material Type
Strength Dominated Structure	15%	Advanced Composites
Stiffness Dominated Structure	25%	Advanced Composites
Metallic Structure	10%	Advanced Metals
Landing Gear	25%	Advanced Materials (MMC / CMC)
All Structure	15%	Advanced Joining
High Temperature Structure	25%	Advanced Ceramics

4.2.2 – Structural Health Management (SHM)

This is an enabling technology required for the weight reductions claimed in Sections 4.2.1 and 4.2.3. The technology works in close conjunction with non-deterministic design criteria by permitting reduced conservatism in the structural design criteria. The amount of structural weight that can be reduced depends upon the critical structural sizing criteria and the damage assumptions built into those criteria. The primary structural weight savings results from the enhanced knowledge of the probability of occurrence of damage scenarios coupled with quantitative knowledge of actual damage events. This permits damaged structure to be designed for Design Limit Load (DLL) or in some cases for 70% of DLL. Full application of this technology to save weight will require significant changes to current aircraft design requirements and methods.

The weight penalty for this SHM system itself is estimated to add 0.005 pounds per square foot to all wing and fuselage wetted areas. This SHM weight is based on our experience using current technology piezoelectric guided wave technology, but assumes in the 2030 time frame we take full advantage of advanced structurally integrated wiring technology (Direct Write) to reduce SHM system weight allowing for large area coverage at very high sensor density. Structural weight reduction is estimated to be dependent upon SHM sensor density as shown in Figure 4.1. The weight savings are estimated at 5% - 30% away from fastener holes, 5% - 12% near edges and fastener attachment holes. It is expected that bonded/welded structural joining will result in a large reduction in the use of fasteners.

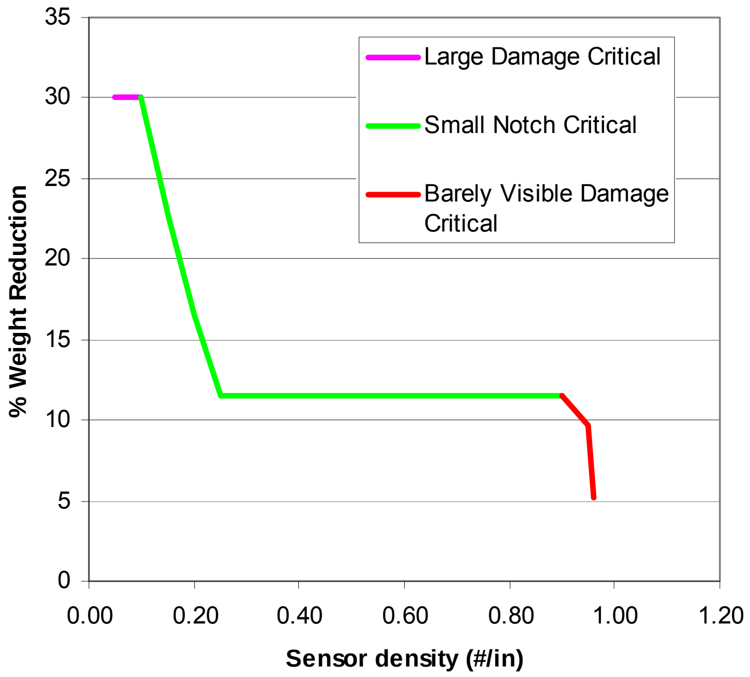


Figure 4.1 – Structural Weight Reduction Expeccted from SHM

4.2.3 – Loads and Environments

Load alleviation is currently being used on Boeing's latest aircraft. Conservatively extrapolating this technology to 2030 would yield about a 15% reduction in wing weight due to Gust Load Alleviation and Maneuver Load Alleviation. A significant technology push in this area will provide the ability to integrate active aeroelastic response control into the flight controls and enable the tailoring of spanwise load control into the flight controls. This is likely a larger benefit to high aspect ratio configurations and 25% reduction is estimated for the high aspect ratio configurations.

4.2.4 – Design and Criteria – Reliability Based Loads and Design

Structural Health Management (SHM) technology will work in conjunction with a transition from current deterministic structural design methods to probabilistic analyses, also known as Reliability Based Design. This will have the dual advantage of quantifying the actual reliability of a structure in terms of both probability distributions of load levels and probability distributions of load carrying capability. SHM sensors will provide real time data to validate both probability distributions (applied load levels) and the current load carrying capabilities of the structures. The joint probability of these distributions will define reliability of the structure and dictate restrictions as required to assure safe operation of the aircraft. Taking advantage of these technologies will require a significant shift in structural design requirements and practices that can only be achieved through an extended evolution of these criteria to assure continued airworthiness throughout the transition.

4.2.5 – Adaptive Structures and Control Systems

Adaptive structures and control systems are assumed to allow a 50% reduction in complex high lift systems and a 20% reduction in simple high lift systems. High Lift and control surface systems currently comprise approximately 50% of the weight of typical commercial aircraft wings. It is estimated that conformal wing shape change (adaptive structures, sometimes known as morphing) will provide benefits that include reduced weight for high lift systems primarily through simplification of these structures. Additional benefits include significantly reduced noise through elimination of slat and flap gaps and possibly reduced drag due to elimination of gaps and joints between flaps and control surfaces and the main wing surface. Elimination of such gaps will also support the drag reduction estimates by supporting enhanced laminar flow. Because of the reduced need for extensive high lift systems for the high aspect ratio concepts, only 20% reduction is estimated for SUGAR High and Volt.

4.2.6 – Integrated Energy Management

Integrated energy management provides reduced overall aircraft weight through the use of electrical and thermal management approaches that are highly integrated with aircraft structure. Electrical power distribution systems in addition to wiring weight include parasitic structural weight required to attach wiring to the structure as well as weight penalty due to the required structural penetrations. As subsystems thermal loads continually increase, conducting those heat loads will require increasingly complex thermal energy management technologies. Using structure as thermal conduction paths will reduce overall aircraft weight.

4.2.7 – Coatings

A 50% Reduction in paint weight has been estimated base on use of advanced coatings and appliqué. Advanced coatings also enable the use of advanced metals.

4.2.8 – Interiors

A 5% reduction in insulation weight is estimated using advanced insulation materials and through integration of insulation with structure. A 20% reduction in weight of interior walls and seats is also estimated.

4.2.9 – Multi-functional Structures Technologies

Multi-functional design and integrated systems/structures technology has been estimated to yield a 50% reduction in wiring weight. Further reductions are expected through structural integration of thermal and electrical energy management systems and components and of lightning protection.

4.2.10 – Additional Structures Technologies

Additional technologies include environmentally friendly manufacturing processes, and features such as lightweight wing folds for large span aircraft and adaptive structural features such as variable geometry wing tips, adaptive wing camber and adaptive engine inlets and nozzles. Large unitized structures will reduce the weight of joints. Hybrid composite and metallic structures with advanced joining technology will permit the usage of the best materials depending upon application.

4.3 – Subsystem Technologies

Boeing technology engineers compiled a list of anticipated subsystem technologies that could be available in the 2030 timeframe (Table 4.4). Industry experts have chosen technologies to include based on their engineering judgment and experience.

Table 4.4 – Subsystems Technology Summary

		Configuration				
		‘N’ SUGAR Free	‘N+3’ Refined SUGAR	‘N+3’ SUGAR High	‘N+3’ SUGAR Volt	‘N+3’ SUGAR Ray
Subsystems Technology Areas	**Power Management**	Conventional	Adaptive			
	Power Generation	Eng. Primary APU Gnd. & Bkup.				
	APU	Conventional	Conventional or Diesel			
	Actuators	Hydraulic	Hydraulic & EMA	EMA		
	Control Architecture	Cable / Pulley	Maximize Use of Fiberoptics			
	Thermal Technology	Conventional	Lightweight			
	Electro Magnetic Effects / Lightning	Conventional	More Tolerant Systems and Dual Use Structure			
	Fuel	Jet-A	Low Sulfur Jet-A / Synthetic / Biofuels			
	Flight Avionics	Conventional	NextGen ATM Capable			
	Wiring	Copper & Aluminum	Copper & Aluminum with Current Return Networks	High Conductivity, Lightweight		
	Computing Networks	None	Integrated			

4.3.1 – Power Demand, Generation, and Management

Power is required for aircraft systems. Power demands are driven by payloads and TOGW. ECS loads drive power requirements for steady state and are dependent primarily on the payload and cabin altitude constraints while landing gear, and control system power loads are aircraft weight and technology driven. Passenger comfort enhancements like lower cabin altitude, in flight entertainment systems, and reduced recirculation ECS all increase power demand. However, peak power demand may be reduced by intelligent power management systems.

It should be noted that for all ‘N+3’ airplanes the ECS is expected to be completely electrified incorporating more advanced generations of the “787 No-Bleed Electrical Systems Architecture”. The primary motivation for the no-bleed architecture is fuel burn reduction, as well as improved airplane maintenance and dispatch reliability. The architecture incorporates highly efficient electrical cabin pressurization scheme utilizing adjustable speed electrical motors, as well as electrical wing ice protection, engine starting, and driving the high capacity hydraulic pumps if required. The engine start function is accomplished via starter/generators that act as the starter motors for the engines, as well as providing electrical power when the respective engine is running.

Table 4.5 shows the power requirements for each configuration. It also shows the peak power reduction attained by the use of advanced energy management. The advanced concepts show greater use of electrical power with a reduction in hydraulic power and engine bleed. Additional system requirements for aircraft certification have historically increased total electrical power demand.

Table 4.5 – Installed Aircraft Power (Bleed, Hydraulic, Electric)

	Configuration							
Aircraft Systems	**‘N’ SUGAR Free**			**‘N+3’ Refined SUGAR**		**‘N+3’ SUGAR High,**	**‘N+3’ SUGAR Volt**	**‘N+3’ SUGAR Ray**
	Bleed (lb/s)	Hyd. (Hp)	Ele. (KVA)	Hyd. (Hp)	Ele. (KVA)	Ele. (KVA)	Ele. (KVA)	Ele. (KVA)
Total (Peak / Avg)	1.05	109 / 50	180 / 140	60 / 34	600 / 500	670 / 575	780 / 600	670 / 575
Adaptive Peak Pwr. Reduction	~	~	~	~	10%	10%	10%	10%
Reduced Total (Peak / Avg)	1.05	**109 / 50**	**180 / 140**	**60 / 34**	**540 / 500**	**600 / 575**	**700 / 600**	**600 / 575**
Engine	CFM-56 Equivalent			2030 Reference Turbine		2030 Adv. Electric		

4.3.2 – Auxiliary Power Unit

The APU for SUGAR Free is a conventional turbine type. The N+3 advanced concepts use either an advanced conventional turbine, Diesel Cycle APU, or a Fuel Cell power center. At this time, it is not clear which approach will be the best. Table 4.6 shows the expected use and power output for each configuration’s APU.

Table 4.6 – APU Power and Weight

	Configuration				
	‘N’ SUGAR Free	**‘N+3’ Refined SUGAR**	**‘N+3’ SUGAR High**	**‘N+3’ SUGAR Volt**	**‘N+3’ SUGAR Ray**
APU Use	APU Gnd. & Bkup.				
APU Type	Turbine	Turbine or Diesel Cycle			
APU Power (KVA)	90	254	308		

4.3.3 – Actuators

Actuators are hydraulic for SUGAR Free. Without NASA funding a shift toward a hybrid system would occur by 2030. This system would use both electro-hydraulic and electrical mechanical actuators. With NASA funding, an all EMA system could be attained and is used on the three advanced configurations. Any hydraulic system in the ‘N+3’ configurations would operate at 5,000 PSI yielding a 20% weight savings over an ‘N’ 3,000 PSI system.

Table 4.7 – Control Systems Architecture

	Configuration		
Aircraft Load	**'N' SUGAR Free**	**'N+3' Refined SUGAR**	**'N+3' SUGAR High, Volt, Ray**
Hydraulic Pressure	3,000 PSI	5,000 PSI	None
Hydraulic Systems	Two Systems	Single System	None

4.3.4 – Control Architecture

It is anticipated that redundant, multiplexed, fiberoptic networks will provide data to remote mounted actuator systems in the N+3 timeframe.

4.3.5 – Thermal Technology

N+3 aircraft will utilize lightweight heat exchanger technology, as well as light weight heat transfer media to utilize the excess heat generated in some areas of the airplane in areas that require heating.

4.3.6 – Electromagnetic and Lightning Effects

Flight safety requires lightning protection and advanced composite structures must include special provisions.

4.3.7 – Fuel

For this study, it is assumed that N+3 aircraft will operate on conventional Jet-A, synthetic, or biofuels that are essentially “drop-in” fuels. It is assumed that there is no fuel system penalty or aircraft performance change due to the use of alternative fuels.

4.3.8 – Flight Avionics

The aircraft will include avionics required to utilize Advanced Air Traffic Management. Due to improvements in avionics technology, this is not expected to add significant avionics weight to N+3 aircraft.

4.3.9 – Wiring

Current return networks will be required to reduce the weight penalty to wiring due to light weight composite materials that are generally non-conductive. For ‘N+3’ airplanes, significant wire weight reduction may be achieved by utilizing newer generations of the current return technology utilized in the 787.

4.3.10 – Computing Networks

Integrated computing networks using multiplexed fiber optic transport technology will reduce the weight of data and processing subsystems.

4.4 – Propulsion Technologies

An overview of the general propulsion technologies applied to the various engines designed for the SUGAR aircraft is shown in Table 4.8. The engine designed for the Refined SUGAR vehicle contains a suite of technologies that represent a moderately aggressive push forward in gas turbine technology including improved combustion emissions technology, improvements in both cold section and hot section materials/processes, and the use of CMC turbine blade/vane technology. In addition, a suite of acoustics technologies are included as well as a suite of mechanical technologies needed to enable attainment of the aerothermodynamic cycle.

The SUGAR High technologies represent an aggressive push on gas turbine technology and generally include all the technologies of the refined SUGAR in addition to those noted in the column. In particular, the SUGAR High features a next-gen CMC material/process, additional noise technologies, and a variety of additional mechanical technologies.

The SUGAR Volt considered three engine concepts, one being an all-electric propulsor, the second being a fuel cell-gas turbine hybrid, and the third being a gas turbine-electric hybrid. All use a common suite of electric propulsor technologies including advanced lightweight motors, motor controllers, and power conditioning equipment. The fuel cell concept includes an advanced solid oxide fuel cell. Both the fuel cell hybrid and the gas turbine-electric hybrid concepts utilize the same basic suite of gas turbine technologies as the SUGAR High.

The SUGAR Ray utilizes the propulsion system from SUGAR High.

Table 4.8 – Propulsion Technologies Applied to Various Engine Concepts

		Configuration				
		‘N’ SUGAR Free	**‘N+3’ Refined SUGAR**	**‘N+3’ SUGAR High**	**‘N+3’ SUGAR Volt**	**‘N+3’ SUGAR Ray**
Propulsion Technology Areas	**Engine Cycle**	CFM56	Very high BPR turbofan with 2030 engine technologies	Very high BPR turbofan with Advanced engine technologies	Battery, Fuel Cell/Gas Turbine Hybrid (SUGAR High Tech Level)	SUGAR High
	Combustor	Conventional	Advanced low-emissions combustor	Variable Flow Splits, Ultra-compact low emissions combustor	SUGAR High + on fuel cell reformer	SUGAR High
	Materials	Conventional	Adv. PMCs, TiAl, Adv disk material/process, Adv shaft mat’l, CMC blades/vanes	Refined SUGAR Mat’ls + MMC’s, Advanced CMC mat’ls & processes	SiC MOSFET, motor controller, lightweight magnetics & ferrites, CMC’s	SUGAR High
	Acoustic	Conventional	Adv. inlet/nozzle treatment, Adv. liner mat’ls, Adv. Chevrons, Blade & OGV optimization	Refined SUGAR Techs. + Active noise control/fluidics, Non-Ax symmetric nozzles, Unique/shielded installations, others (as needed)		
	Mechanical	Conventional	High DN Bearings, Adv. High Temp Seals	Additional advanced systems (as needed)		

5.0 – Vehicle Development and Analysis

5.1 – Vehicle Requirements

A set of top level requirements for the SUGAR vehicles was generated from the future scenario and was previously shown in Table 2.2. These top level requirements were turned into specific payload-range requirements which are illustrated in Figure 5.1. The figure has several points of interest called out.

1. The airplane is required to fly the average range at max payload (also maximum zero fuel weight). Max payload is required to be 15,200 pounds heavier than the payload from point 2 for a Medium sized airplane.
2. The airplane is required to fly the maximum range at the average number of seats using 200 pounds per passenger and no revenue payload. This point must be achieved using less than 90% of the useable fuel.
3. This point will be used to calculate vehicle fuel burn performance and TOFL performance for the SUGAR program. This represents the point that represents how an operator would most commonly operate the vehicle class.

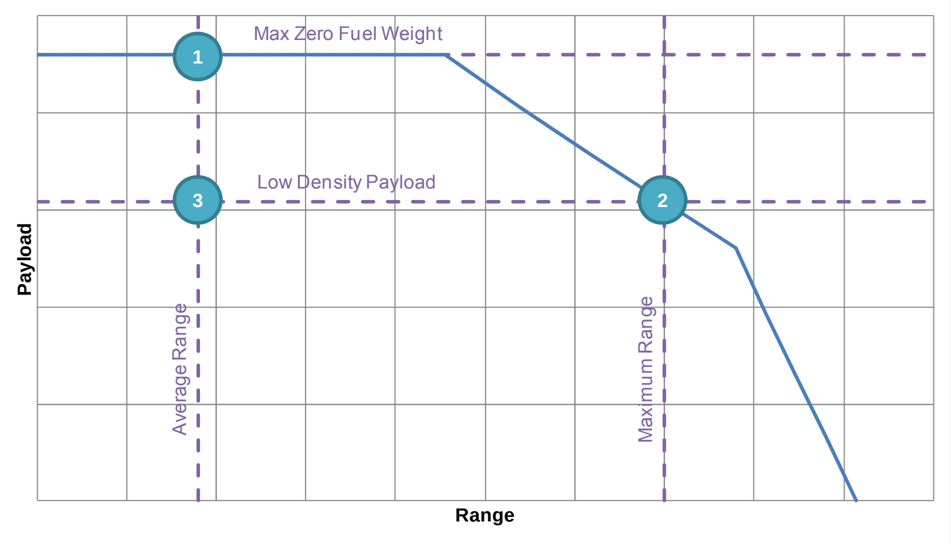


Figure 5.1 – Payload-Range Requirements

Both point 1 and 2 are required for sizing because airplane characteristics may change which point is critical.

5.1.1 – Configuration Synthesis Ground Rules

Critical requirements shape conceptual airplane configurations. Several configuration rules have been utilized for the SUGAR study.

Overall Configuration: When an advanced concept is developed, it is often difficult to determine which performance advancements are attained because of the configuration layout and which are obtained due to technology improvements. In response to NASA's request, the team has developed an N+3 reference airplane to help separate the performance improvements. The N and N+3 reference vehicles are required to topologically be 737 like layouts (also known as tube-and-wing). Both will have turbofans, low wings, conventional tail layouts, etc. All the advanced concepts are allowed to take whatever form makes the integration developed during the Georgia Tech workshop possible.

Interior Arrangement: The interior layout of the all configured aircraft will be generated using the appropriate rules for the vehicle size. For regional aircraft this is a single class arrangement with relatively short seat pitch. For medium aircraft, dual class seating will be used. For Large configurations, long range tri-class rules will be used.

Span: Airport infrastructure is the primary reason for airplane span limitations. The future scenario predicts an increase of flight operations in the 2030 timeframe and airports are already congested. Increasing the distance between gates, assuming the airport cannot expand, would reduce the number available thus reducing throughput. Secondly, a considerable amount of infrastructure already exists that would have to be replaced if spans were increased beyond that of the current fleet. Span constraints are not just an issue at the gate. They are also an issue on runways and taxiways.

Airport regulations dealing with span limitations are described in an FAA Advisory Circular[10]. In order to accurately assess the impact of increasing airplane span beyond 118' a survey of which airports currently served by 737/A320 class airplanes would be affected is necessary. This would determine how much of current and projected service a larger span airplane would be unable to perform and how big an impact that would have on its utility and marketability. Table 5.1 shows all of Boeings commercial products FAA / ICAO designations.

The SUGAR team has decided that all Regional airliners should be Group I or II, a typical Medium airliner would be Group III, and that a Large airliner would be Groups IV thru VI. Greater spans are allowed on advanced concepts provided a folding mechanism is used to meet the gate constraints. All folding is done AFTER landing or BEFORE takeoff. The airport operations aspect of takeoff and landing with high span has been ignored in this study and its impact should be addressed in future studies.

Table 5.1 – Airport Compatibility Group Codes

AIRCRAFT	**FAA / ICAO DESIGNATION**					
CODE	**I / A**	**II / B**	**III / C**	**IV / D**	**V / E**	**VI / F**
SPAN LIMITS	0 – 49’ 0 – 15m	49 – 79’ 15 – 24m	79 – 118’ 24 – 36m	118 – 171’ 36 – 52m	171 – 214’ 52 – 65m	214 – 262’ 65 – 80m
707				IV / D		
720				IV / D		
717			III / C			
727			III / C			
737			III / C			
747					V / E	
757				IV / D		
767				IV / D		
777					V / E	
DC-8				IV / D		
DC-9			III / C			
DC-10				IV / D		
MD-11*				IV	E	
MD-80			III / C			
MD-90			III / C			

* NOTE: MD-11 is the only aircraft that doesn’t remain in the same category between FAA and ICAO. This is due to wingspan conversion from English to Metric units.

Tail Strike Angle: Tail strike angle is left unconstrained at this point. This will fall out of the vehicle analysis and ultimately be set by takeoff and landing requirements.

Tip Strike Angle: Since a stability and control analysis will not be performed, an assumed tip clearance angle will not be allowed below eight degrees when measured at the maximum tail down angle.

A summary of the configuration ground rules is provided in Table 5.2.

Table 5.2 – Configuration Ground Rules

		“N” Reference Vehicle	“N+3” Reference Vehicle	“N+3” Advanced Concepts
Max Span	Regional	79 ft		Ground folding if larger than span constraint
	Medium	118 ft		
	Large	262 ft		
Configuration		Conventional		Unconstrained
Tail Strike Angle		Unconstrained		
Tip Strike Angle		8°		

5.1.2 – Choosing a Cruise Speed

Changing to an advanced air traffic management system allows the cruise speed for future aircraft to be optimized without constraints imposed by heritage vehicles. There are several ways to determine what speed an aircraft should fly and which one is chosen depends heavily on the goal of the operator. For simplicity, the following discussion assumes that the engine thermal efficiency does not change with speed. Four of the possible speeds (Figure 5.2) that can be chosen are discussed below:

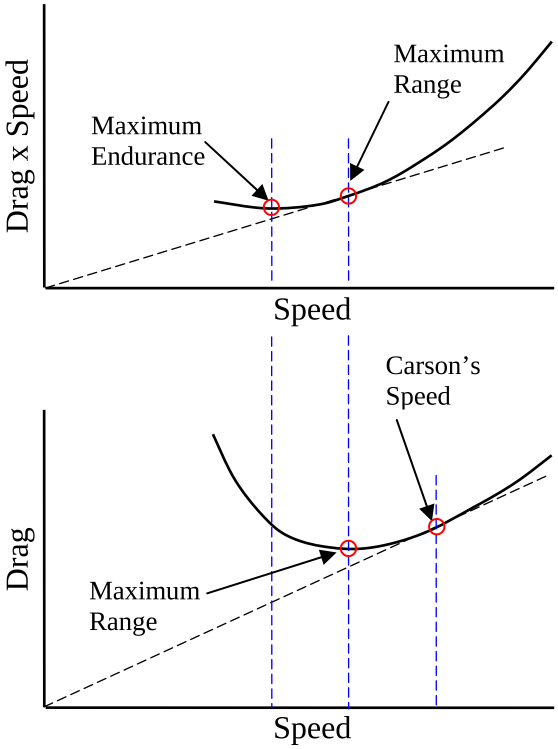


Figure 5.2 – Approximation of Maximum Endurance and Maximum Range, and the Definition of Carson's Speed

Maximum Endurance is the speed which yields the lowest energy used per unit time (lowest power). This isn't a speed of interest for SUGAR because it doesn't account for the need to travel a distance.

Maximum Range is the speed which gives the lowest energy per unit distance. It can be shown that this is achieved at maximum lift-to-drag ratio. This does not take into account the value of time.

Carson's Speed[11] is the "most productive use of excess fuel for cruising purposes"[11]. Carson argues that airplanes are operated at speeds well in excess of one that would achieve maximum lift-to-drag ratio (or maximum range) because they have excess power from the takeoff and climb. Carson also states that flying at this speed is equivalent to flying at the airplanes maximum lift-to-drag ratio times speed (M*L/D at fixed altitude). This is the heritage speed at which airliners fly which Carson states is "the least wasteful way of wasting fuel."[11]

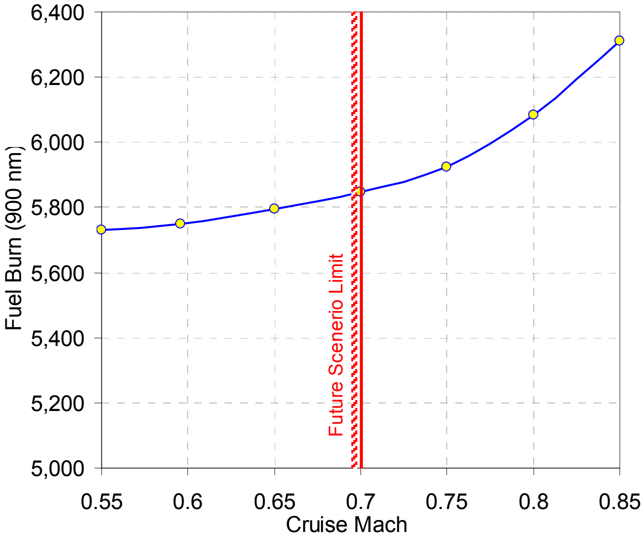


Figure 5.3 – Fuel Burn vs. Mach Number for a family of high span airplanes optimized at different cruise speeds

The Boeing Current Market Outlook does include the impacts of speed. For a vehicle to be economically competitive, our future scenario forecasts a minimum cruise speed for vehicles based on their size classification. This is shown in Figure 2.10 in the future scenario section.

The paragraphs about Maximum Endurance, Maximum Range, and Carson's speed are from an aerodynamic standpoint and do not account for changes that can be imparted by engine-airframe matching (the thermal efficiency of the fuel energy converted to thrust energy as a function of speed and altitude). At first glance, the speed for maximum range appears to be a good choice for SUGAR vehicles, since a wide range of engine possibilities exist. Using an initial sizing process (discussed in Section 5.1.3) several vehicles were optimized for varying cruise Mach numbers. Initial cruise altitude (ICA) was allowed to vary but was limited to 43,000 ft. The fuel burn for these optimized aircraft is shown in Figure 5.3. Each vehicle is optimized to minimize fuel burn for the given Mach number. The curve clearly shows an advantage for slowing down.

For this study we will adhere to the lower limit of Mach 0.70 for Medium sized airplanes as suggested by the Boeing Current Market Outlook (CMO).

5.1.3 – Initial Sizing and Points of Departure

To size the advanced configurations, an initial sizing tool was developed based on a combination of textbook aerodynamic methods, Douglas heritage compressibility tables, textbook mass properties methods with span and strut corrections, a scaled engine deck, and simplistic stability and control for tail sizing. The analysis was calibrated to a known airplane and then used for sizing wing area and aspect ratio, while respecting span constraints and vehicle performance requirements (Section 6.1.2). The tool accepts factors for technology impacts such as weight factors and laminar flow percentage.

SUGAR Free (765-093) is a 2008 technology conventional configuration sized for the 2008 reference mission rules (discussed in Figure 6.2). The sizing for SUGAR Free is particularly important because it sets the baseline performance for all of the advanced configurations analyzed for the contract. Simply analyzing or using the performance of an existing airplane would not be acceptable for this study because it would not be sized for the mission defined by the future scenario (either in number of passengers or range). Early in the analysis of SUGAR Free (765-093) it became clear that any span less than the constraint was a penalty. This leaves wing area, thickness to chord ratio, and sweep as the highest level optimization variables of interest. Figure 5.4 shows the wing area trade using aspect ratio as a surrogate for wing area (span is fixed). Table 5.3 shows the input parameters and information on the selected initial sizing point for the configuration. Note that the effective aspect ratio and span include the virtual span added from a winglet. The actual span was held to the constraint of 118 feet.

Table 5.3 – Initial Sizing: 765-093 SUGAR Free Results

Conditions and Assumptions:	Vehicle Specifications:
Mach: 0.78	Effective AR: 10.5
Max Range (nm): 3,500	Area: 1,440
TOFL: 7,000	Effective Span: 123
ICA: 37,000	t/c Root: 0.145
Strut: NO	t/c Tip: 0.094
ROC at ICA (fpm): 300	Taper Ratio: 0.18
C_L Takeoff: 2.4	C_L Cruise: 0.625
Reserves: N	Sweep: 20.0°
SFC Delta: 0%	L/D: 18.45
Laminar: NO	ICA: 37,000
Riblets: NO	OEW: 101,642
Indirect Routing: 5%	TOGW: 175,635
Tail Size Factor: 1.05	SLS Thrust: 56,315
	Fuel Burn (900nm): 12,681

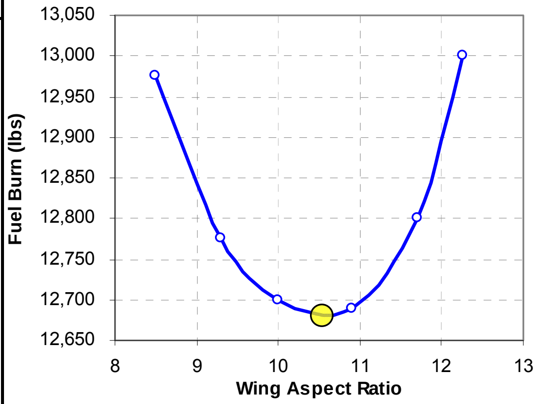


Figure 5.4 – Initial Sizing: 765-093 – SUGAR Free Aspect Ratio Trade

Refined SUGAR (765-094) was sized in a similar way to SUGAR Free. The span constraint left the same parameters for optimization. The optimization did allow for Mach number to be traded with a lower bound set by the future scenario analysis (Section 2.0) to Mach 0.70. The results are shown in Table 5.4 and Figure 5.5.

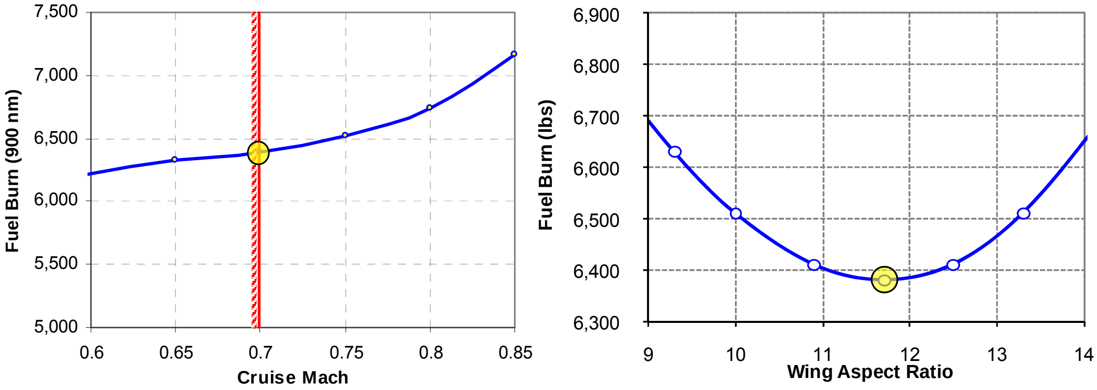


Figure 5.5 – Initial Sizing: 765-094 – Refined SUGAR Aspect Ratio and Mach Number Trade

Table 5.4 – Initial Sizing: 765-094 Refined SUGAR Results

Conditions and Assumptions:		Vehicle Specifications:	
Mach:	0.70	Effective AR:	11.7
Max Range (nm):	3,500	Area:	1,293
TOFL:	7,000	Effective Span:	123
ICA:	38,500	t/c Root:	0.145
Strut:	NO	t/c Tip:	0.094
ROC at ICA (fpm):	300	Taper Ratio:	0.20
C_L Takeoff:	2.4	C_L Cruise:	0.718
Reserves:	N+3	Sweep:	15.0°
SFC Delta:	20%	L/D:	20.54
Laminar:	YES	ICA:	38,408
Riblets:	YES	OEW:	81,612
Indirect Routing:	0%	TOGW:	136,412
Tail Size Factor:	1.00	SLS Thrust:	37,799
		Fuel Burn (900nm):	6,388

All the advanced concepts have more degrees of freedom as the wing span is allowed to grow past the constraint. However, they are required to fold any structure extending beyond 118 feet. The wing fold weight is scaled from existing proprietary data based on a known commercial design. The initial sizing results for SUGAR High (765-095) are shown in Table 5.5. The initial sizing points to very high span even with weight penalties for the wing fold. As expected, the configuration wants to fly as slow as possible and is more sensitive to speed than Refined SUGAR.

Table 5.5 – Initial Sizing: 765-095 SUGAR High Results

Conditions and Assumptions:		Vehicle Specifications:	
Mach:	0.70	Effective AR:	24
Max Range (nm):	3,500	Area:	1,700
TOFL:	7,000	Effective Span:	202
ICA:	44,000	t/c Root:	0.130
Strut:	YES	t/c Tip:	0.85
ROC at ICA (fpm):	300	Taper Ratio:	0.20
C_L Takeoff:	2.4	C_L Cruise:	0.733
Reserves:	N+3	Sweep:	8.0°
SFC Delta:	25%	L/D:	27.31
Laminar:	YES	ICA:	44,000
Riblets:	YES	OEW:	85,100
Indirect Routing:	0%	TOGW:	138,576
Tail Size Factor:	0.85	SLS Thrust:	35,325
		Fuel Burn (900nm):	5,342

SUGAR Volt (765-096) has a very similar layout to the SUGAR High and is used as a trade study platform for alternative propulsion systems. An optimization of wing area and aspect ratio was performed for battery, fuel cell, and hybrid battery-Brayton cycle propulsion systems. The curves of Figure 5.6 thru Figure 5.9 represent the best solutions after optimizing each case.

Figure 5.6 illustrates that ranges of up to one thousand nautical miles may be possible with advanced battery technology but at significant penalty to takeoff gross weight (TOGW). Recall that SUGAR Free had a TOGW of less than 180,000 pounds. Even at 300,000 pounds the battery powered airplane cannot make the range requirement with very aggressive energy densities. The battery powered airplane produces no in flight emissions, burns no fuel, and could potentially be very quiet. However, it was discarded from this study based on its inability to meet range requirements for a medium sized airliner. It could be attractive for Regional airplanes for missions less than 1000 nm.

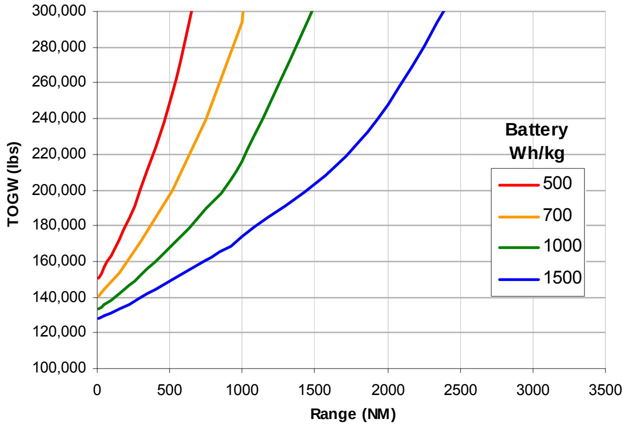


Figure 5.6 – Takeoff Gross Weight vs. Range for Battery Powered SUGAR Volt

A fuel cell powered version of the Volt was also traded. Once again, aspect ratio and area were optimized for varying levels of fuel cell performance. It is shown in Figure 5.7 that, while able to perform the mission, the vehicle performance was not better than the SUGAR High fuel burn reduction for the fuel cell performance range considered.

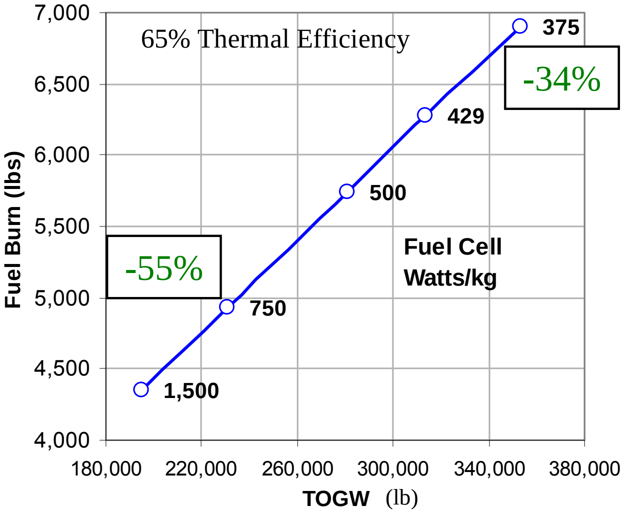


Figure 5.7 – Fuel burn from a Fuel Cell Powered SUGAR Volt

The Hybrid Brayton-Battery propulsion system shows the greatest promise in reducing vehicle fuel burn. The propulsion system is envisioned to have both a Brayton core and an electric motor powering a propulsor (fan or open fan). The airplane performs takeoff and climb using power from both systems, but throttles down one of the systems during cruise. Jet fuel powers the Brayton core and batteries power the electric motor. Maximizing propulsive energy use from batteries is desirable when trying to reduce fuel burn. However, batteries have much lower energy density, limiting range under battery power alone. A key feature of this concept is the ability to use modular batteries, so that the same vehicle can trade battery and fuel depending on the mission. Generally, more fuel and fewer batteries are used for long ranges, and less fuel and more batteries are used for short ranges. For all but the shortest missions, the aircraft has the same takeoff weight, as illustrated in Figure 5.8.

By designing the vehicle to carry more battery weight (increase the design TOGW), greater distances can be flown using energy from batteries. This results in lower jet fuel burn, but higher TOGW. Lower gross weights result in shorter range capability when cruising on electric propulsion only. Figure 5.9 shows the anticipated fuel burn verses range for vehicles of 215,000 pounds of gross weight with varying levels of battery technology. For a 900 nautical mile mission (the average mission length and the range fuel burn reduction will be measured) 90% fuel burn reductions may be attainable at modest levels of battery technology. Table 5.6 shows the initial sizing point from the figure which will be used for the SUGAR Volt initial sizing point.

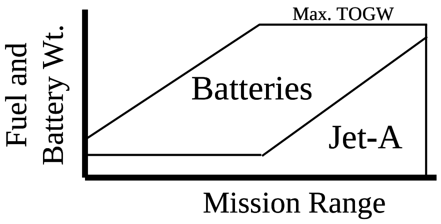


Figure 5.8 – Hybrid Brayton-Battery Airplane Carries More Batteries as Range is Increased Until MTOW is Reached

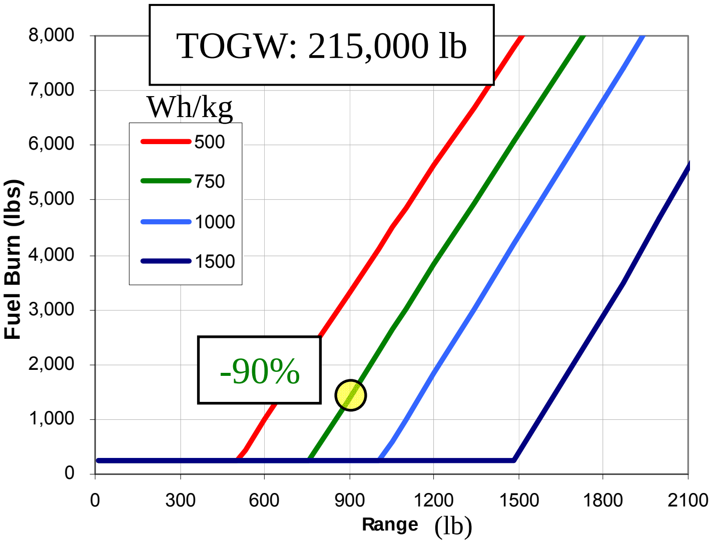


Figure 5.9 – Initial Sizing: 765-097 – SUGAR Volt Fuel Burn

Table 5.6 – Initial Sizing: 765-096 SUGAR Volt Results

Conditions and Assumptions:		**Vehicle Specifications:**	
Mach:	0.65	Effective AR:	24
Max Range (nm):	3,500	Area:	2,473
TOFL:	7,000	Effective Span:	244
ICA:	42,000	t/c Root:	0.130
Strut:	YES	t/c Tip:	0.85
ROC at ICA (fpm):	300	Taper Ratio:	0.18
C_L Takeoff:	2.4	C_L Cruise:	0.833
Reserves:	N+3	Sweep:	8.0°
SFC Delta:	25%	L/D:	32.43
Laminar:	YES	ICA:	42,000
Riblets:	YES	Battery Weight:	26,314
Indirect Routing:	0%	TOGW:	215,000
Tail Size Factor:	0.85	SLS Thrust:	24,810
		Fuel Burn (900nm):	1,490

5.2 – Vehicle Development and Analysis Tools

5.2.1 – Aerodynamic Buildup Methods

CASES (Computer Aided Sizing and Evaluation System), a heritage empirical Douglas application, was used to develop the low and high speed aerodynamic buildups for SUGAR. The CASES standard high speed buildup is comprised of parasite, induced, compressibility, and trim drag. This is illustrated in Figure 5.10. These components are built up using Boeing empirical data and vortex lattice methods. When a configuration is outside the empirical database, methods are substituted as appropriate. For example, vehicles of high span adjust the use of vortex lattice methods to calculate induced drag. Hybrid wing body (HWB) does not use the CASES database. HWB reference drag buildup uses wing-body CFL3D RANS.

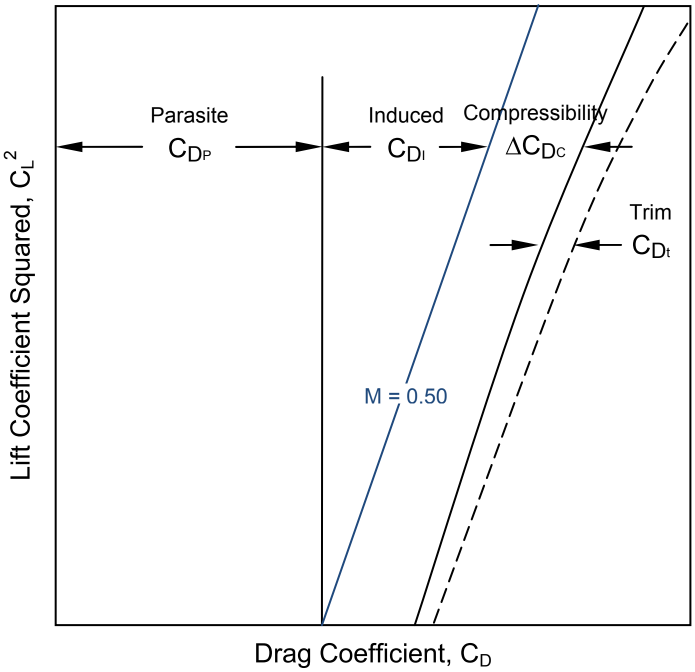


Figure 5.10 – Standard CASES High Speed Buildup

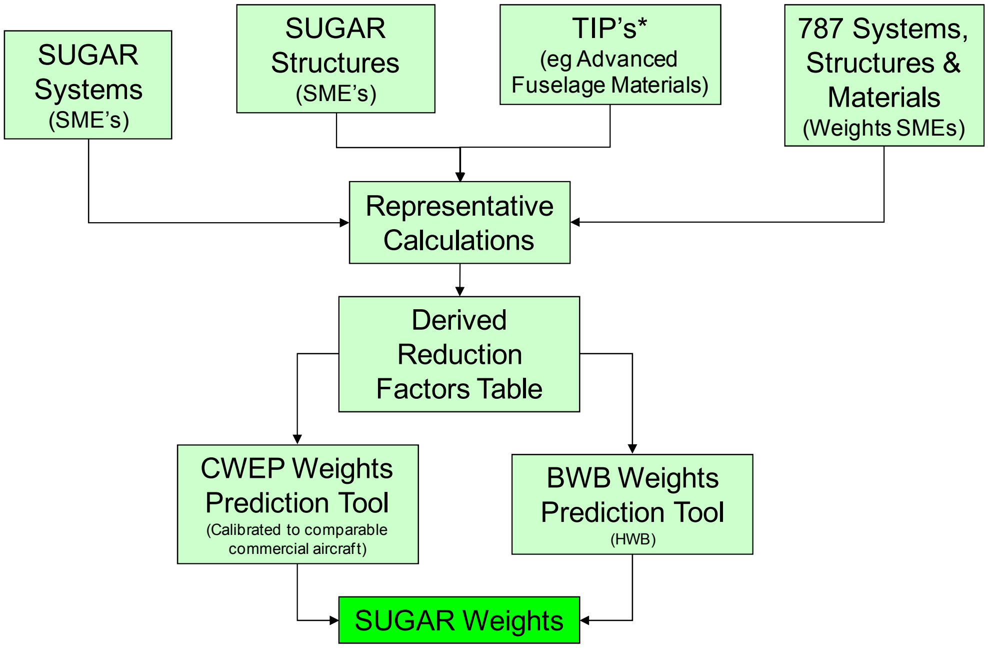
After the initial CASES buildup is attained, additional increments are applied for technology enhancements such as laminar flow. These additional increments are based on engineering knowledge about technology applicability and are applied via spreadsheet adjustments. Powered increments may also be applied for configurations with propellers or open fans.

CASES is also used for the low speed buildup. The total lift coefficient is calculated as a function of the taxi lift coefficient, lift coefficient at ground angle limit, and the maximum free air lift coefficient. The total drag coefficient is comprised of empirically defined components including, parasite, twist, profile, induced, and trim. The resulting polars may be adjusted for vehicles outside the database such as powered lift or vehicles with propellers, open fans, or HWB's.

It should be noted that CASES databases are based on trapezoidal wing projected reference system. Non-Dimensional quantities for all high and low speed buildups use this area as the reference. HWB is an exception using the gross wing reference area.

5.2.2 – Mass Properties Methods

This section describes the process shown in Figure 5.11 below. SUGAR Mass Properties were derived from N+3 technology enhancements incorporated into Boeing proprietary mass modeling tools. N+3 technology enhancements were rigorously reviewed with technology and weights Subject Matter Experts (SME's) to understand and obtain design and integration philosophies. These data were applied to existing detail weights to derive the reduction factors shown in Table 5.7. These factors were used in aircraft level empirical weight prediction tools for performance sizing.



* Technology Integration Programs

Figure 5.11 – Mass Properties Methods Flowchart

CWEP, a Boeing proprietary weights parametric estimating tool, is based on empirical data of current and existing commercial transports. It was calibrated to a SUGAR Free class aircraft using extensive in-house data. Refined SUGAR weights were estimated by applying the weight reduction factors of Table 5.7 to this model.

The BWB weights prediction tools are based on in-house generated BWB data derived from engineering analysis.

Table 5.7 – Mass Properties Reduction Factors

Affected Group	Change in Weight
Wing Bending Material	-26 %
Tails	-15%
Fuselage	-12%
Landing Gear	0.6% of TOGW
Nacelle Structure	-2%
On Board Structural Health Management	+100 lb
Insulation	-5%
Light Weight Seats	-20%
Paint	-44 lb
Advanced Heat Exchanger	-50%
Signal Wiring Reduction	-50%

5.2.3 – Propulsion Methods

Performance of the eFan, gFan, gFan+, and hFan engines was estimated using NPSS cycle models. The component performance calculations for the typical gas turbine components were based on GE standard calculation methods. Simplified PD representations were developed for non-standard components, notably the electric motor and motor controller, such that the impact of those components on overall engine performance could be estimated for the eFan and hFan concepts (the fFan concept was not evaluated to this level of analysis fidelity). The component performance levels assumed were based on GE historical data for current engines with projections for advances in the N+3 timeframe. Additional component performance corrections were included based on specific technology concepts included in the basic engine design, as needed. Cycle performance for the fFan concept was estimated via simple spreadsheet-type calculations based on available fuel cell component performance data.

Engine weight and flowpath geometry were estimated using GE internal tools. These tools utilize a combination of physics-based analysis and historical correlations. These tools design to the level of estimating turbomachinery vector diagrams at the pitch line with corrections for hub and tip of each stage. Thus, the aeromechanical design is consistent with the cycle and suitable for further refinement if selected. Engine weights were adjusted to reflect materials technology assumptions. Electric motor and motor controller weights were scaled from a current state-of-the art machine with corrections to account for the assumed N+3 technology timeframe.

Engine emissions were estimated based on GE internal correlations with adjustments to account for the future progression of technology. Noise was estimated by anchoring to a known comparable baseline. Estimates on noise deltas for specific noise reduction technologies were then applied to this baseline at both the engine and airframe levels to arrive at an overall estimate of vehicle noise levels.

A detailed evaluation of open fan engine concepts was beyond the intended scope of this study due to resource constraints. However, this does not mean that the open fan isn’t promising for this application and it is desirable to at least give some insight into the potential benefit available from open fan concepts. Thus, the open fan was treated as a cruise SFC delta and an engine weight delta applied to the gFan+ engine concept. It should be noted that the open fan is expected to be somewhat more challenging with respect to meeting the very aggressive N+3 noise goals. No attempt was made to assess the noise implications of open fan in this project.

5.3 – 765-093 – SUGAR Free (2008 Baseline Configuration)

The configuration that serves as a baseline for all metrics in our study is defined as the 765-093 ‘SUGAR Free’. SUGAR Free is used as a name since the vehicle is free of any future technology advancements and adheres to the ‘N’ ground rules for vehicle development.

5.3.1 – Configuration Layout

The 765-093 configuration is a low wing airplane with turbofan engines mounted on pylons below the wing and conventional tail layout. The wing planform is conventional and of moderate sweep. It features a substantial inboard trailing edge extension (yehudi) that provides reduced wing root thickness/chord ratio at the body and provides the space required to mount the main landing gear. The main landing gear trunnion is supported between the wing rear spar and a landing gear beam.

All major structure is aluminum and the airplane is configured to be consistent with current technology medium sized aircraft.

A three view drawing of the configuration is shown in Figure 5.12.

The fuselage is nominally circular in cross section and is sized to provide a seating arrangement of 6 abreast in economy class. The cabin length is sized to provide an airplane seating capacity in a dual class configuration of 154 passengers. The lower lobe accommodates bulk baggage only. A Layout of Passenger Accommodations (LOPA) is shown in Figure 5.13.

	WING W/TIP Wimpress	V-TAIL Trap	H-TAIL Trap
Area*	1632.20**	284.58	357.14
Aspect Ratio*	9.760**	1.940	6.237
Taper Ratio	0.137**	0.271	0.202
MAC Inches	163.00**	161.24	104.10
Dihedral (Deg.)	6.0	-	6.0
1/4 Chord Sweep (Deg.)*	25.14	33.20	30.00
Root Chord (Inches)	312.30	228.64	151.00
Tip Chord (Inches)	42.90	62.00	30.60
Span (W/O Winglet)*	1388.44	282.00	566.40

* Projected
** W/O Winglet

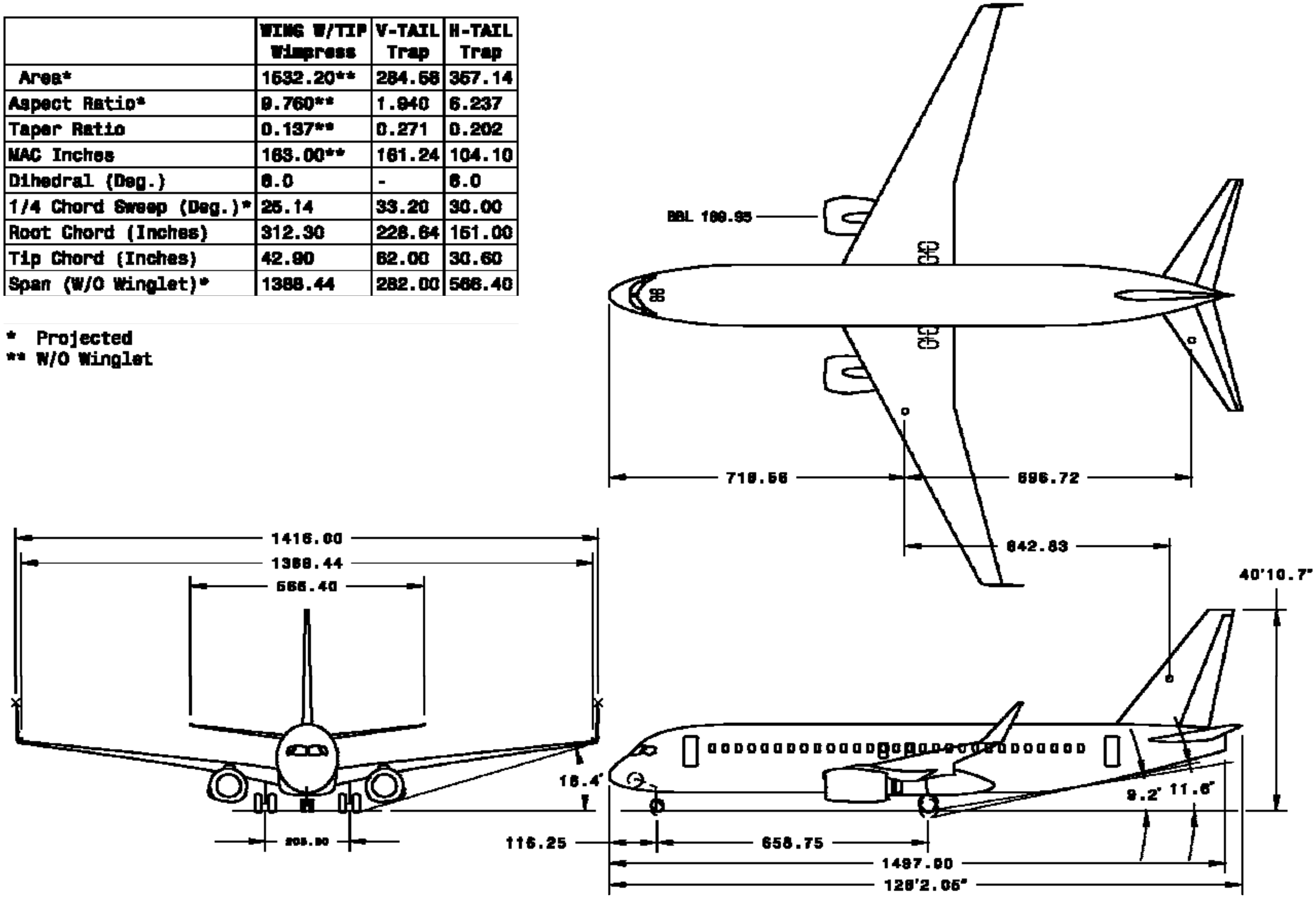
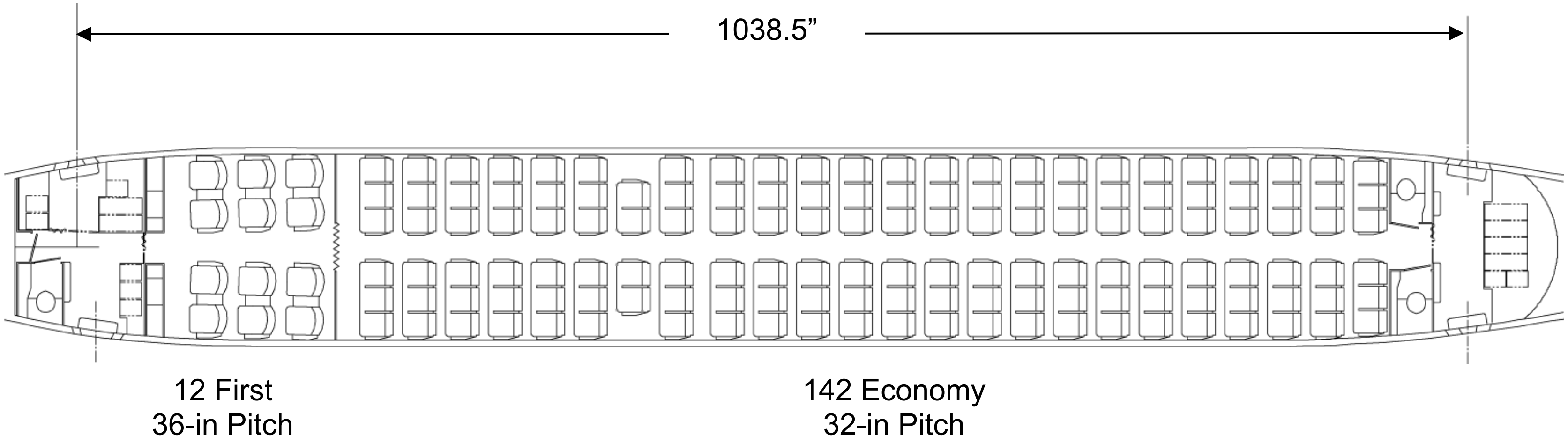


Figure 5.12 – 765-093 3-View Drawing

Interior Arrangement

SUGAR

IAC Short / Medium Range – Dual Class



	Class (%)	Carts (qty)	Cart Ratio (Carts/Pax)	Lavatory Ratio (Pax/Lav)	Closet Ratio (Rod-in/Pax)
First	7.79	3.0	0.250	12	4.00
Economy	92.20	7.0	0.049	71	0.00
Total	100.00	10.0	0.649	–	–

Figure 5.13 – 765-093 LOPA

5.3.2 – Aerodynamic Buildup

High Speed:

The CASES high speed aerodynamic buildup for the 765-093 is shown in Table 5.8 and is summarized in Figure 5.14.

Table 5.8 – 765-093 High Speed Buildup

Configuration	765-093
SWEEP (DEG)	25°
T/C-AVE	0.1258
AIRFOIL TYPE	SUPERCRITICAL
F BUILD-UP (FT^2)	
FUSELAGE	8.8533
WING	8.6164
WINGLET	0.2105
HORIZONTAL	1.9395
VERTICAL	1.6832
N&P	2.9600
CANOPY	0.0405
GEAR PODS	0.0000
ETC BEFORE SUB	0.0400
EXCRESCENCE	2.2883
INTERFERENCE	0.0000
UPSWEEP	0.5076
WING TWIST	0.3415
STRAKES	0.0000
ETC AFTER SUB	-0.6000
FUSELAGE BUMP	0.5000
F-TOTAL (FT^2)	**27.3808**
E-VISC	0.944
CRUISE CD BUILD-UP	
M-CRUISE	0.78
CL-CRUISE	0.625
CRUISE ALTITUDE	35000
CD0	0.01916
CDI	0.01265
CDC	0.00186
CDTRIM	0.00069
CDTOT	0.03436
L/D	**18.189**
ML/D	**14.187**

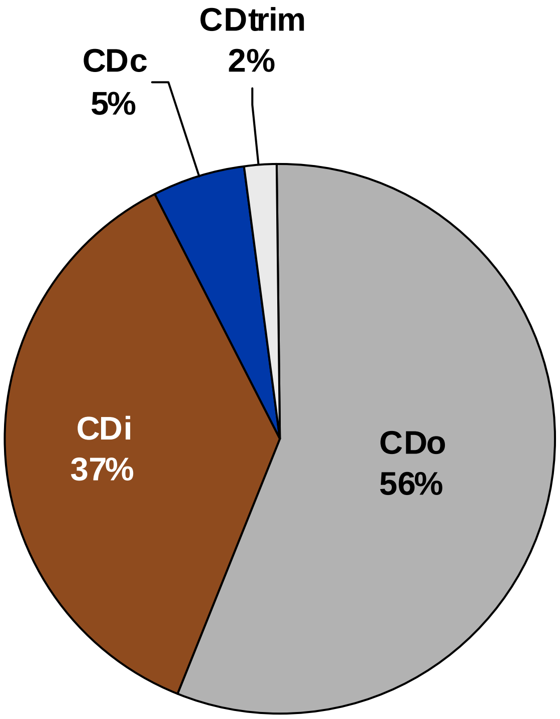


Figure 5.14 – 765-093 High Speed Buildup

It should be noted that the categories ETC BEFORE SUB and ETC AFTER SUB in the parasite drag buildup are used to calibrate the vehicle drag and/or to compensate for the application of advanced technologies. In this case, the appropriate values are used to match the expected performance of an airplane of this configuration. For the advanced concepts, advanced technology increments will also be applied as appropriate. The two categories are required as each is scaled differently as the airplane is sized.

The aerodynamic characteristics reflect the design Mach number of 0.78 for current air traffic management integration. The resulting high speed data is shown in Figure 5.15. The figure illustrates the maximum aerodynamic efficiency (M*L/D) occurring at the design cruise Mach (0.78) and C_L (0.625).

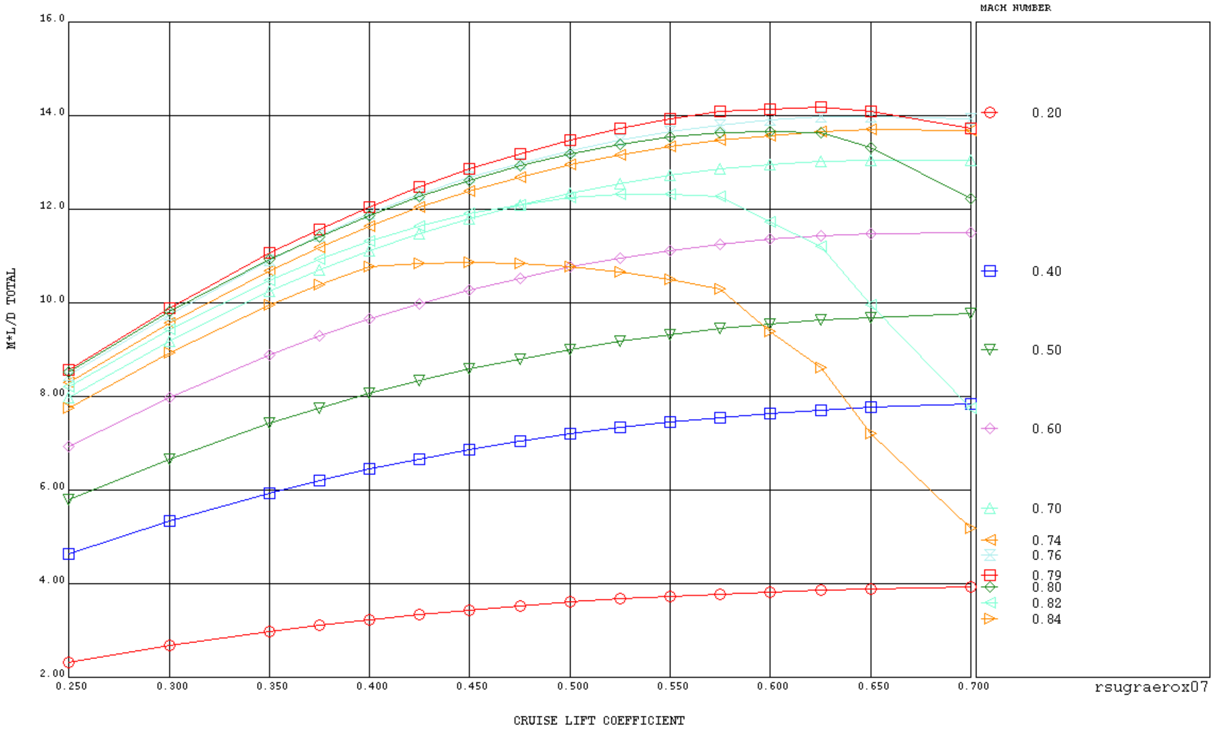


Figure 5.15 – 765-093 - M * L / D Total

Low Speed:

Figure 5.16 through Figure 5.18 show the low speed aerodynamic characteristics for SUGAR Free. Low speed data are trimmed as a function of angle of attack, lift coefficient, and drag coefficient at each flap detent. Low speed high lift devices on wing leading and trailing edges are deployed.

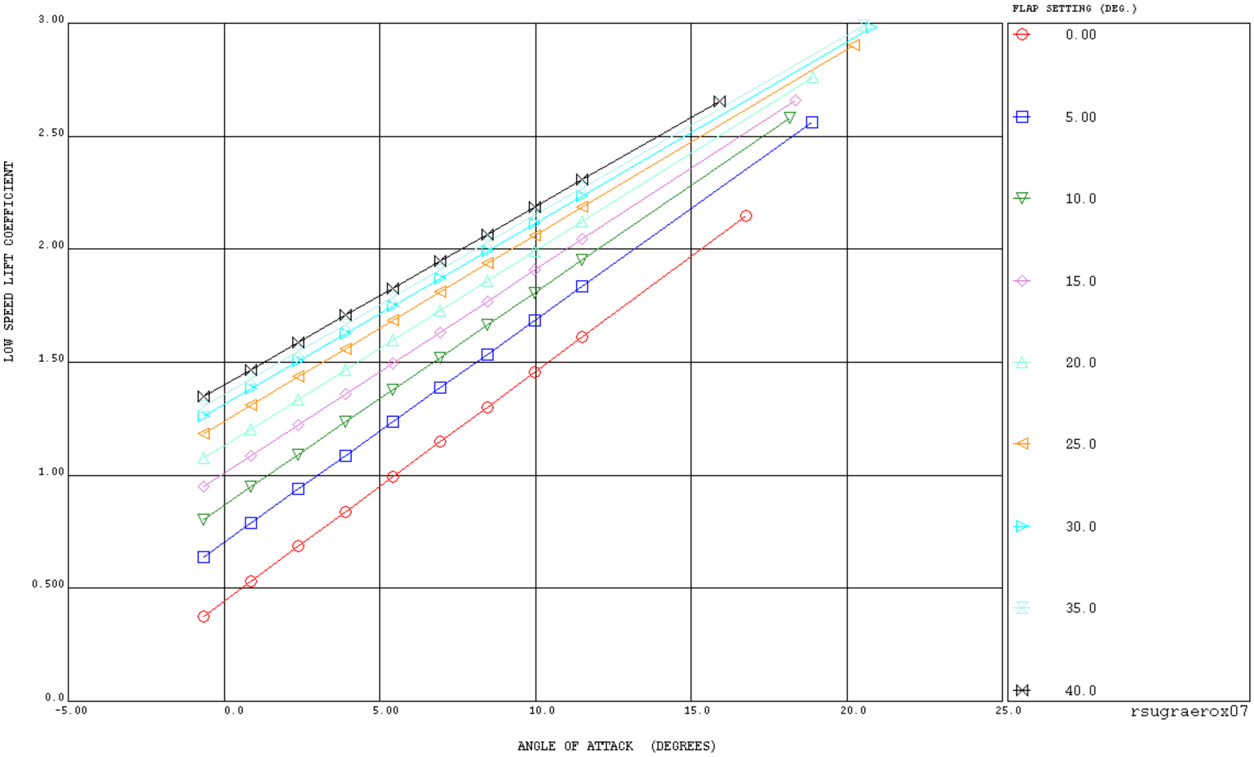


Figure 5.16 – 765-093 - Low Speed Lift Curve; Free Air

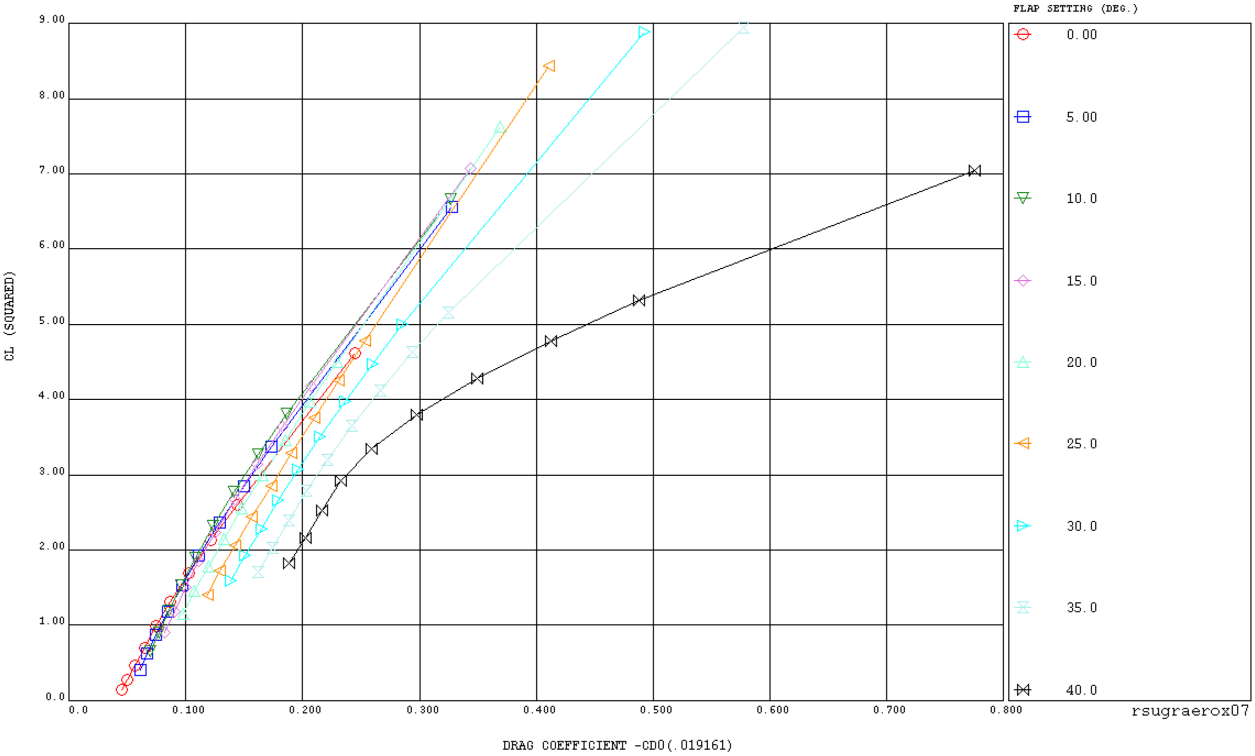


Figure 5.17 – 765-093 - Low Speed Polar; Free Air

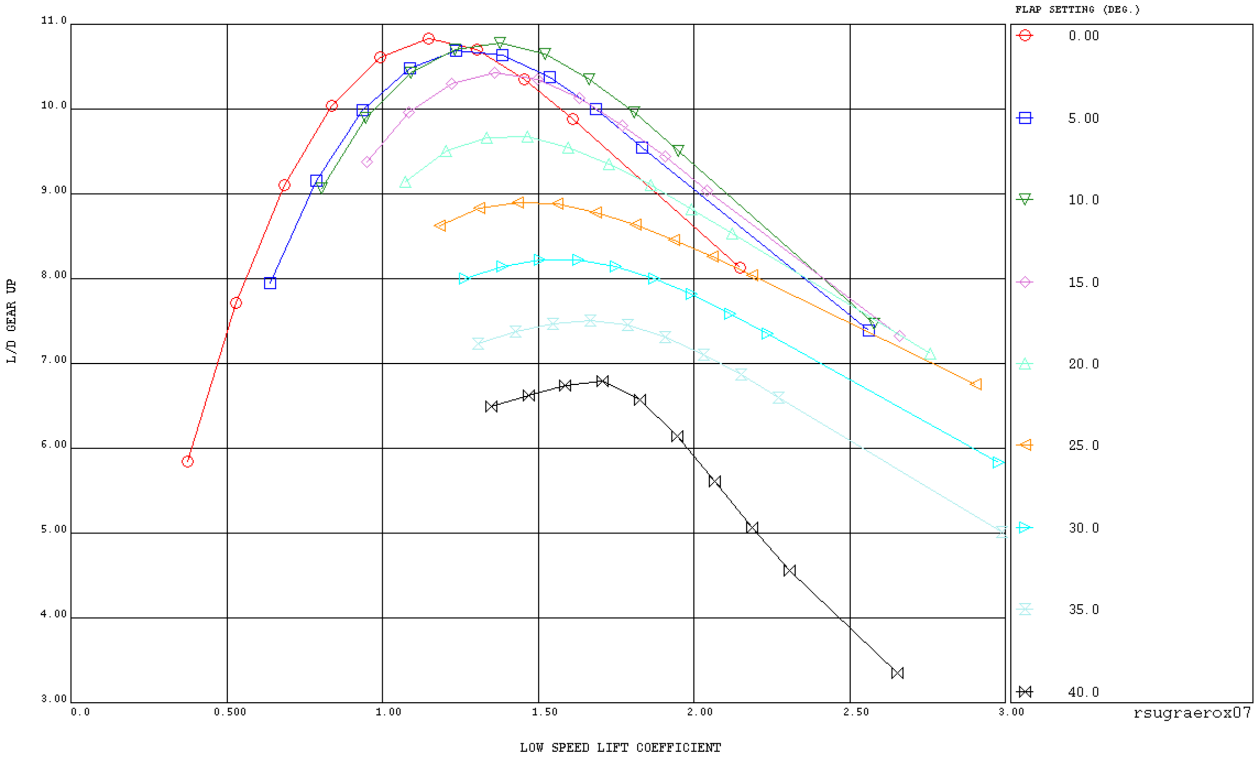


Figure 5.18 – 765-093 - Low Speed Lift / Drag; Free Air

5.3.3 – Mass Properties

The SUGAR Free configuration was calibrated using extensive in-house data to provide a baseline. Table 5.9 below shows the group weight statements and each group's percentages of takeoff gross weight (TOGW). Figure 5.19 shows the SUGAR Free group weights as a percentage of TOGW.

Table 5.9 – 765-093 Group Weight Statement

GROUP	WEIGHT (LB)	% TOGW
WING	**18,728**	**10.7**
BENDING MATERIAL	9,621	5.5
SPAR WEBS	1,290	0.7
RIBS AND BULKHEADS	1,226	0.7
AERODYNAMIC SURFACES	3,351	1.9
SECONDARY STRUCTURE	3,240	1.8
TAIL	**3,779**	**2.2**
FUSELAGE	**18,392**	**10.5**
LANDING GEAR	**6,712**	**3.8**
PYLON	**1,858**	**1.1**
PROPULSION	**14,874**	**8.5**
ENGINE	10,404	5.9
ENGINE SYSTEMS	263	0.1
EXHAUST SYSTEM	3,688	2.1
FUEL SYSTEM	520	0.3
FLIGHT CONTROLS	**3,084**	**1.8**
COCKPIT CONTROLS	252	0.1
SYSTEM CONTROLS	2,832	1.6
POWER SYSTEMS	**4,483**	**2.6**
AUXILIARY POWER PLANT	1,032	0.6
HYDRAULICS	894	0.5
ELECTRICAL	2,557	1.5
INSTRUMENTS	**686**	**0.4**
AVIONICS & AUTOPILOT	**1,533**	**0.9**
FURNISHINGS & EQUIPMENT	**10,866**	**6.2**
AIR CONDITIONING	**1,678**	**1.0**
ANTI-ICING	**118**	**0.1**
MANUFACTURER'S EMPTY WEIGHT (MEW)	**86,790**	**49.4**
OPERATIONAL ITEMS	7,342	4.2
OPERATING EMPTY WEIGHT (OEW)	**94,132**	**53.6**
USEABLE FUEL	45,313	25.8
PAYLOAD	36,190	20.6
TAKEOFF GROSS WEIGHT (TOGW)	**175,635**	**100.0**

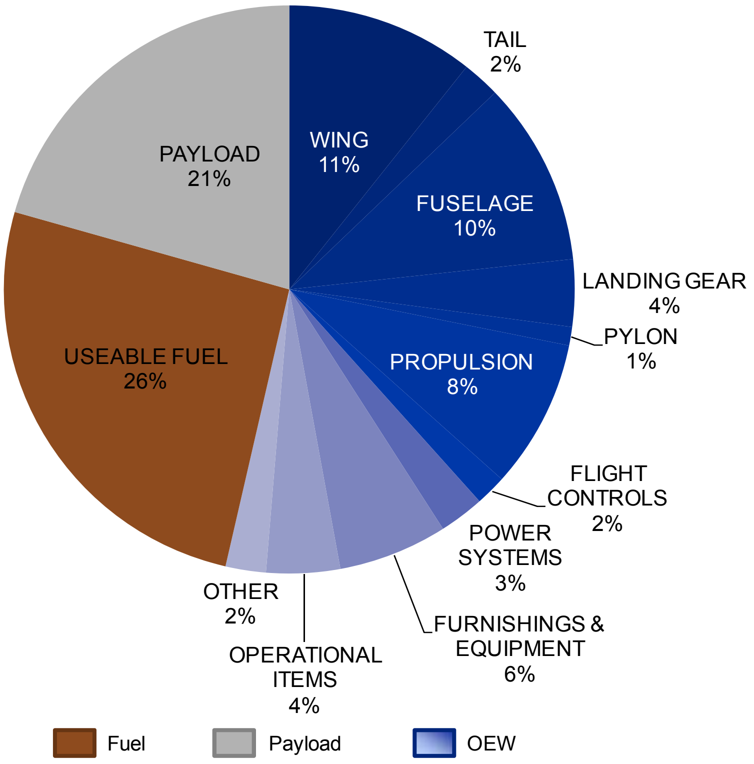


Figure 5.19 – 765-093 Weight Summary

5.3.4 – Engine Data – CFM-56

The engine used for SUGAR Free is a scaled CFM-56-7B shown in Figure 5.20. Basic weight, geometry, and performance information for the scale 1.0 engine is shown in Table 5.10. This engine represents today's state-of-the-art turbofan and is the baseline against which the various advanced engines are compared. It should be noted that the power extraction levels required from this engine are relatively high and would likely require adjustments in the engine to accommodate all operability requirements. No attempt was made in this study to account for these effects in the baseline engine other than to apply the requested power extraction levels.

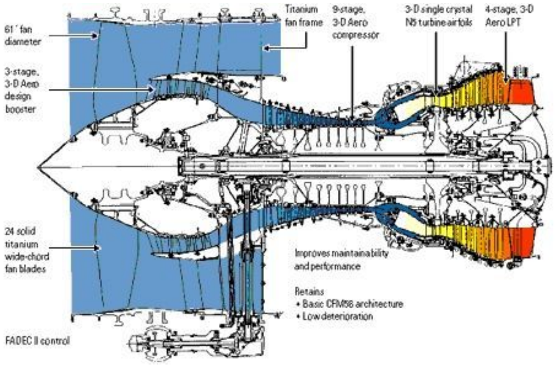


Figure 5.20 – CFM56-7B Engine Walk Around

Table 5.10 – CFM56 Key Weight, Dimensions, and Performance Data

Basic dry weight	5216	lbm
Fan diameter	61	in
Length	98.7	in
Performance	**Thrust, lbf**	**SFC, lbm/lbf-hr**
SLS	27300	- - -
Rolling takeoff	- - -	- - -
Top-of-climb	5962	- - -
Cruise	5480	- - -
Emissions	-30%	relative to CAEP/6
Projected Technologies		
Current CFM56-7B bill of materials		

5.4 – 765-094 – Refined SUGAR (2030 Reference Configuration)

The Refined SUGAR configuration is the 2030 reference. Improvement over the SUGAR Free concept is gained entirely from incremental development of existing technologies.

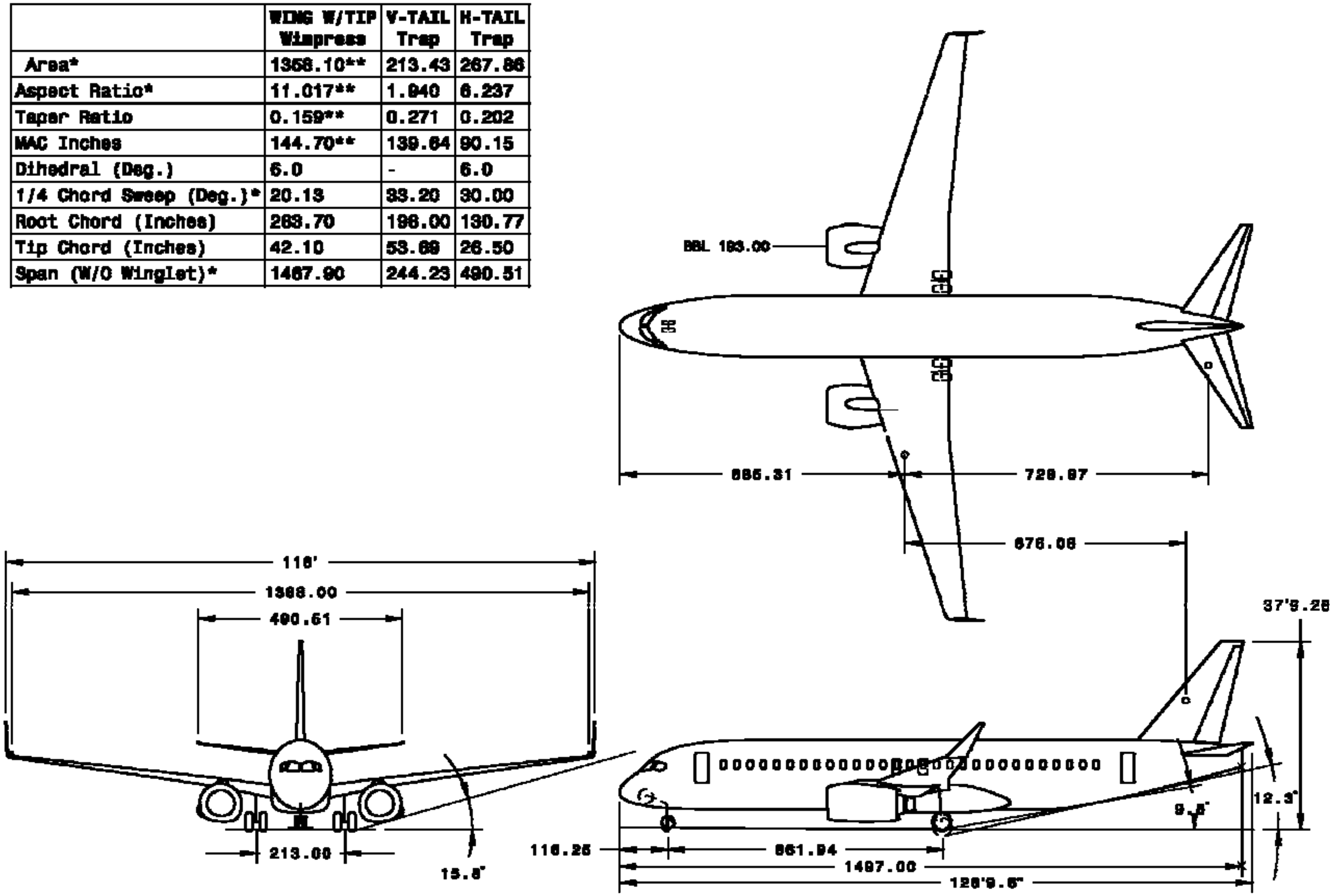
The configuration layout is constrained to be conventional and the technology levels relatively conservative when compared to the three advanced concepts (described in Sections 5.5 through 5.7). The configuration targets lower fuel burn through reduced structural weight and Specific Fuel Consumption (SFC) which should promote reduced noise and emissions (through the scaling down of thrust with weight).

5.4.1 – Configuration Layout

The 765-094 configuration is a low wing airplane with turbofan engines mounted on pylons below the wing and conventional tail layout.

The wing planform is conventional and of moderate sweep. It features a substantial inboard trailing edge extension (yehudi) that provides reduced wing root thickness/chord ratio at the body and provides the space required to mount the main landing gear. The main landing gear trunnion is supported between the wing rear spar and a landing gear beam. A three view drawing of the configuration is shown in Figure 5.21.

The fuselage is nominally circular in cross section and is sized to provide a seating arrangement of 6 abreast in economy class. The cabin length is sized to provide an airplane seating capacity in a dual class configuration of 154 passengers. The lower lobe accommodates bulk baggage only. A Layout of Passenger Accommodations (LOPA) is shown in Figure 5.13) and is the same as the SUGAR Free (765-093).



	WING W/TIP Winpress	V-TAIL Trap	H-TAIL Trap
Area*	1358.10**	213.43	267.88
Aspect Ratio*	11.017**	1.940	6.237
Taper Ratio	0.159**	0.271	0.202
MAC Inches	144.70**	139.64	90.15
Dihedral (Deg.)	6.0	-	6.0
1/4 Chord Sweep (Deg.)*	20.13	33.20	30.00
Root Chord (Inches)	263.70	198.00	130.77
Tip Chord (Inches)	42.10	53.66	26.50
Span (W/O Winglet)*	1467.90	244.23	490.51

Figure 5.21 – 765-094 3-View Drawing

5.4.2 – Aerodynamic Buildup

High Speed:

The high-speed aerodynamic buildup for the Refined SUGAR configuration is summarized in Table 5.11.

Table 5.11 – 765-094 High Speed Buildup

Configuration	765-094
SWEEP (DEG)	15.08°
T/C-AVE	0.1248
AIRFOIL TYPE	SUPERCRITICAL
F BUILD-UP (FT^2)	
FUSELAGE	9.2989
WING	8.1036
WINGLET	0.2173
HORIZONTAL	1.4215
VERTICAL	1.2158
N&P	2.8600
CANOPY	0.0405
GEAR PODS	0.0000
ETC BEFORE SUB	-3.5400
EXCRESCENCE	1.5239
INTERFERENCE	0.0000
UPSWEEP	0.6012
WING TWIST	0.3948
STRAKES	0.0000
ETC AFTER SUB	-0.6500
FUSELAGE BUMP	0.5430
F-TOTAL (FT^2)	**22.0305**
E-VISC	0.966
CRUISE CD BUILD-UP	
M-CRUISE	0.74
CL-CRUISE	0.675
CRUISE ALTITUDE	38408
CD0	0.01713
CDI	0.01290
CDC	0.00159
CDTRIM	0.00065
CDTOT	0.03227
L/D	**20.915**
ML/D	**15.477**

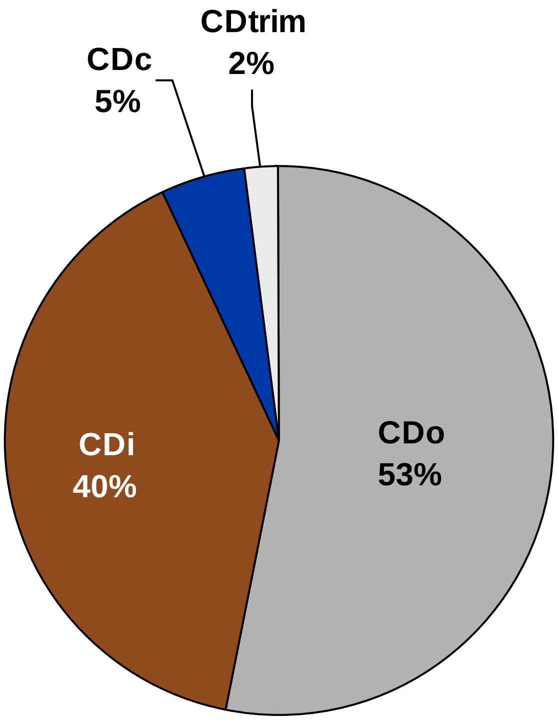


Figure 5.22 – 765-094 High Speed Buildup

For Refined SUGAR, the ETC BEFORE SUB includes technology projections for natural laminar flow over a portion of the wing and riblets on the fuselage, as shown in Figure 5.23.

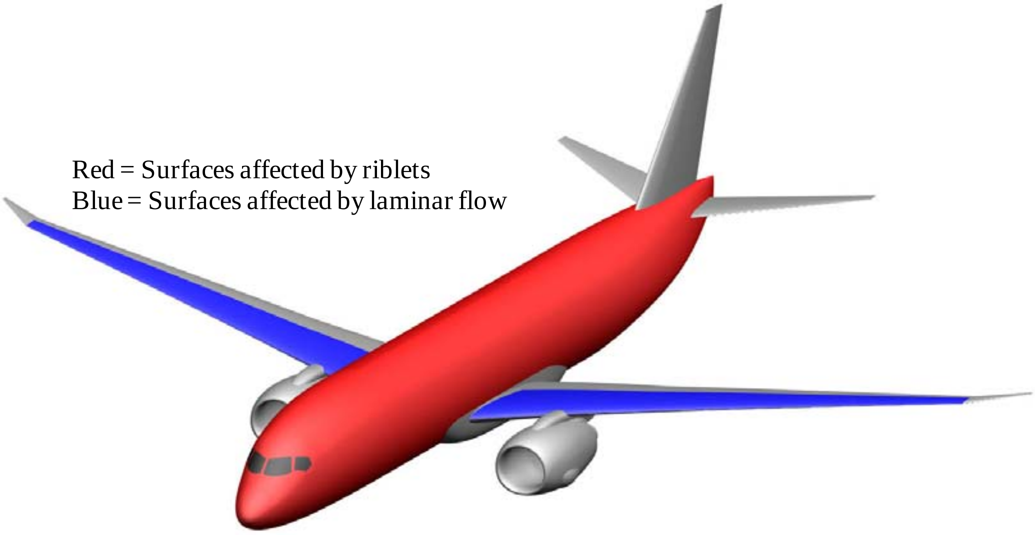


Figure 5.23 – 765-094 Aerodynamic Technologies Application

The resulting high speed data is shown in Figure 5.24. The figure illustrates the maximum aerodynamic efficiency (M*L/D) occurring at a cruise Mach of 0.74 and a CL of 0.625. This is slightly higher than the efficiency at the Mach 0.7 cruise condition.

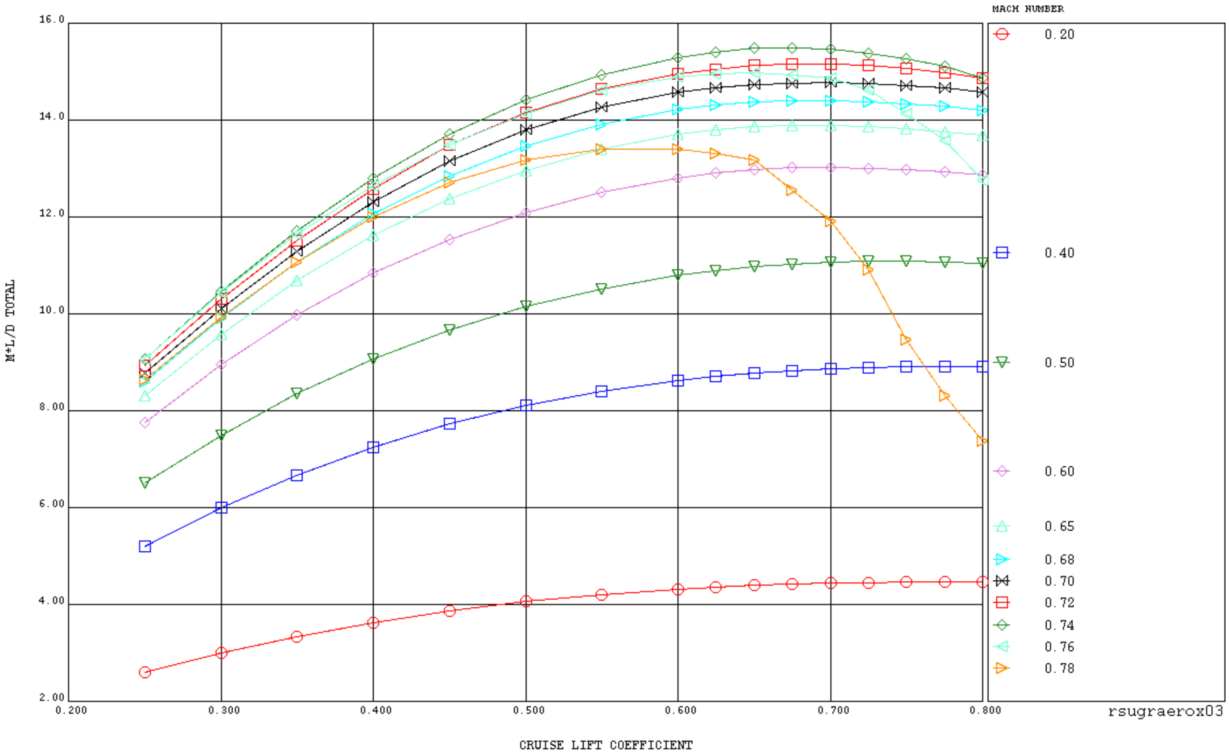


Figure 5.24 – 765-094 - M * L / D Total

Low Speed:

Figure 5.25 through Figure 5.27 show the low speed aerodynamic characteristics for Refined SUGAR. Low speed data are trimmed as a function of angle of attack, lift coefficient, and drag coefficient at each flap detent. Low speed high lift devices on wing leading and trailing edges are deployed.

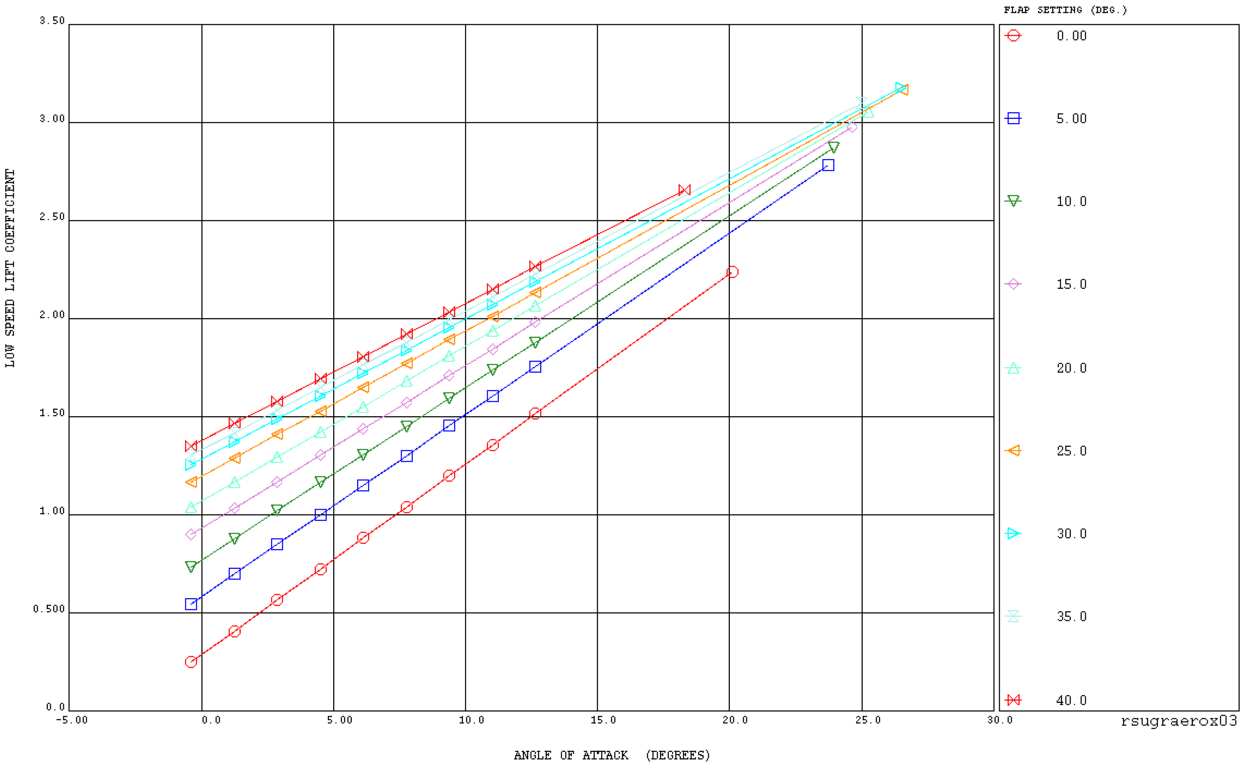


Figure 5.25 – 765-094 - Low Speed Lift Curve; Free Air

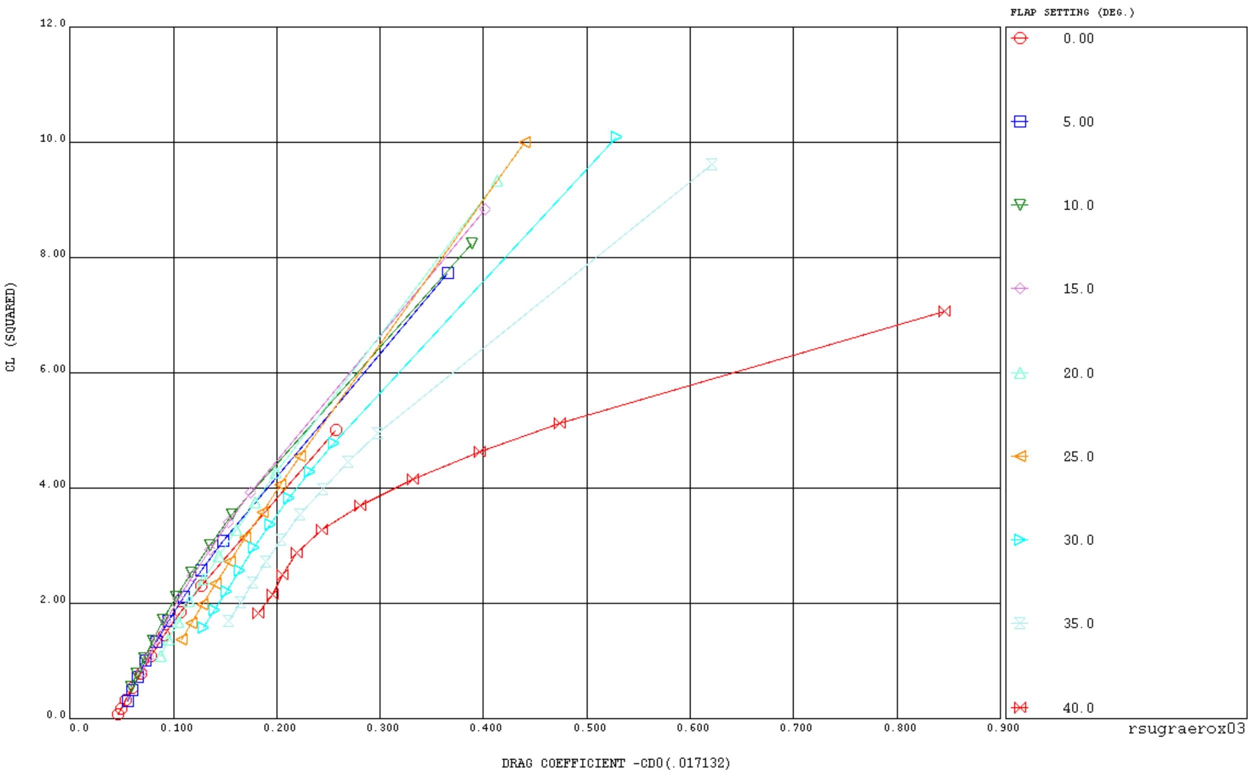


Figure 5.26 – 765-094 - Low Speed Polar; Free Air

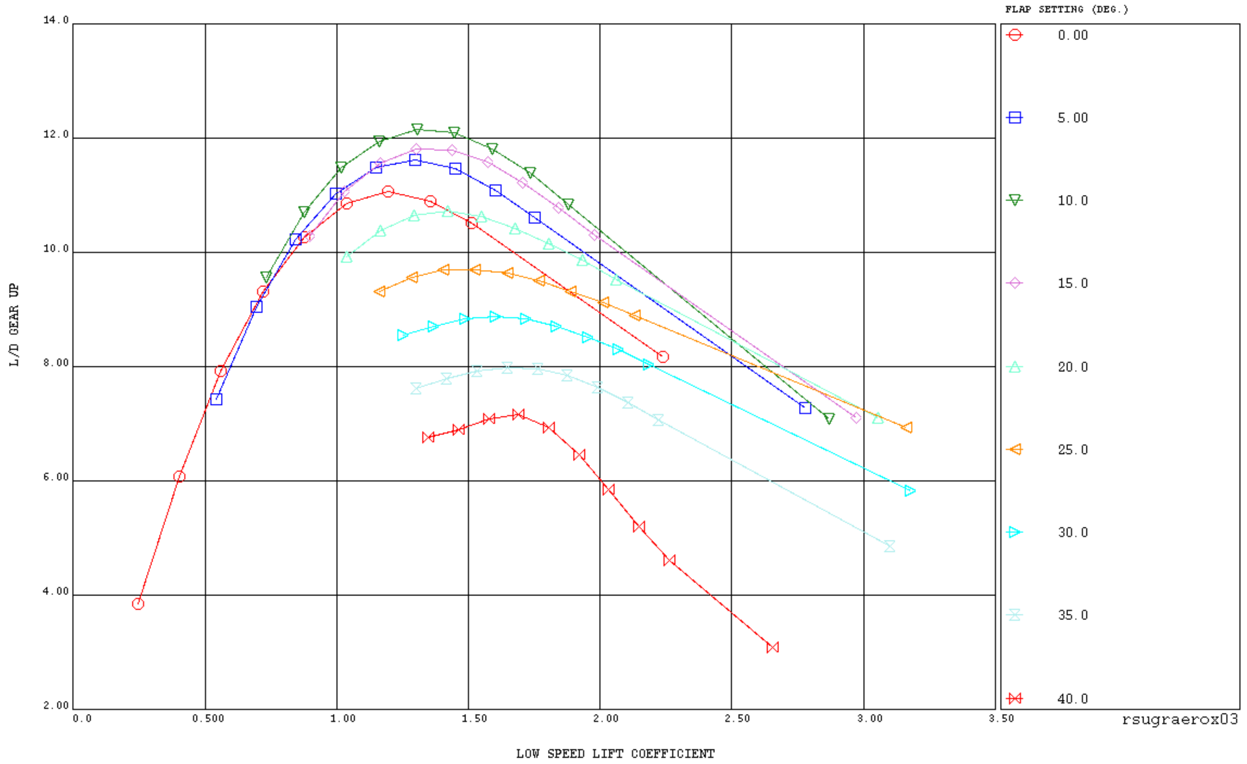


Figure 5.27 – 765-094 - Low Speed Lift / Drag; Free Air

5.4.3 – Mass Properties

The Refined SUGAR configuration was estimated by applying the N+3 weight reduction factors to SUGAR Free. Table 5.12 shows the resulting group weight statement which includes each group's percentage of TOGW. This information is presented graphically in Figure 5.28.

Table 5.12 – 765-094 Group Weight Statement

GROUP	WEIGHT (LB)	% TOGW
WING	**13,695**	**10.0**
BENDING MATERIAL	5,881	4.3
SPAR WEBS	1,016	0.7
RIBS AND BULKHEADS	1,036	0.8
AERODYNAMIC SURFACES	2,850	2.1
SECONDARY STRUCTURE	2,911	2.1
TAIL	**2,671**	**2.0**
FUSELAGE	**14,991**	**11.0**
LANDING GEAR	**5,052**	**3.7**
PYLON	**4,412**	**3.2**
PROPULSION	**9,027**	**6.6**
ENGINE	8,410	6.2
FUEL SYSTEM	617	0.5
FLIGHT CONTROLS	**2,900**	**2.1**
COCKPIT CONTROLS	252	0.2
SYSTEM CONTROLS	2,648	1.9
POWER SYSTEMS	**4,146**	**3.0**
AUXILIARY POWER PLANT	1,014	0.7
HYDRAULICS	836	0.6
ELECTRICAL	2,297	1.7
INSTRUMENTS	**773**	**0.6**
AVIONICS & AUTOPILOT	**1,504**	**1.1**
FURNISHINGS & EQUIPMENT	**9,115**	**6.7**
AIR CONDITIONING	**1,441**	**1.1**
ANTI-ICING	**108**	**0.1**
MANUFACTURER'S EMPTY WEIGHT (MEW)	**69,835**	**51.2**
OPERATIONAL ITEMS	7,207	5.3
OPERATING EMPTY WEIGHT (OEW)	**77,042**	**56.5**
USEABLE FUEL	23,180	17.0
PAYLOAD	36,190	26.5
TAKEOFF GROSS WEIGHT (TOGW)	**136,412**	**100.0**

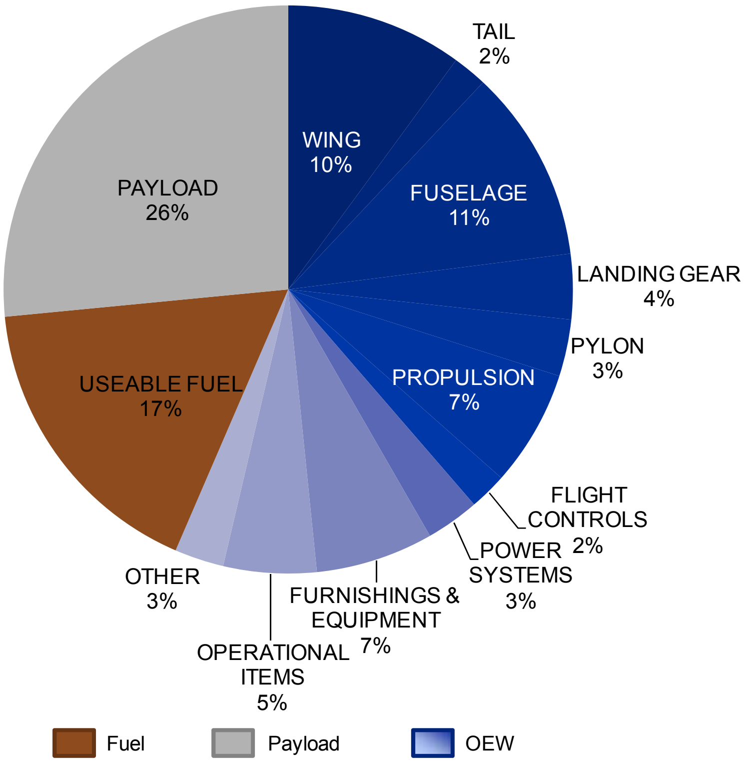


Figure 5.28 – 765-094 Weight Summary

5.4.4 – Engine Data – "gFan"

The engine designed for the refined SUGAR vehicle is a boosted 2-spool separate flow turbofan configuration informally designated "gFan". This engine is shown in Figure 5.29 and features a 66 OPR, 9.2 BPR, and relatively low hot section temperatures. The high OPR in conjunction with advanced component aerodynamic and materials technologies gives this engine very good thermal efficiency. The modest hot section temperatures in conjunction with advanced TAPS combustor technology make this engine very compatible with the aggressive N+3 emissions goals. This engine features an advanced shrouded fan/nacelle arrangement that yield good noise characteristics. This engine makes extensive use of CMCs in the hot section both for weight reduction and performance improvement. Key geometry, performance and weight information for this engine is provided in Table 5.13. This table also provides an overview of the various component technologies employed in this engine.

The combustor selected for this engine is a generation beyond the advanced TAPS combustors presently being planned for future products. This "GEN++ TAPS" combustor is of generally similar design to today's TAPS system but with improved mixing and improved operability features. This, in conjunction with significantly reduced cruise T4 levels relative to today's narrowbody engines, enables drastic reductions in NOx emissions. It is anticipated that this combustor design will yield significant reductions in particulate emissions levels. The impact on contrail formation is a topic for future research and will be better defined as the combustor design progresses in the future.

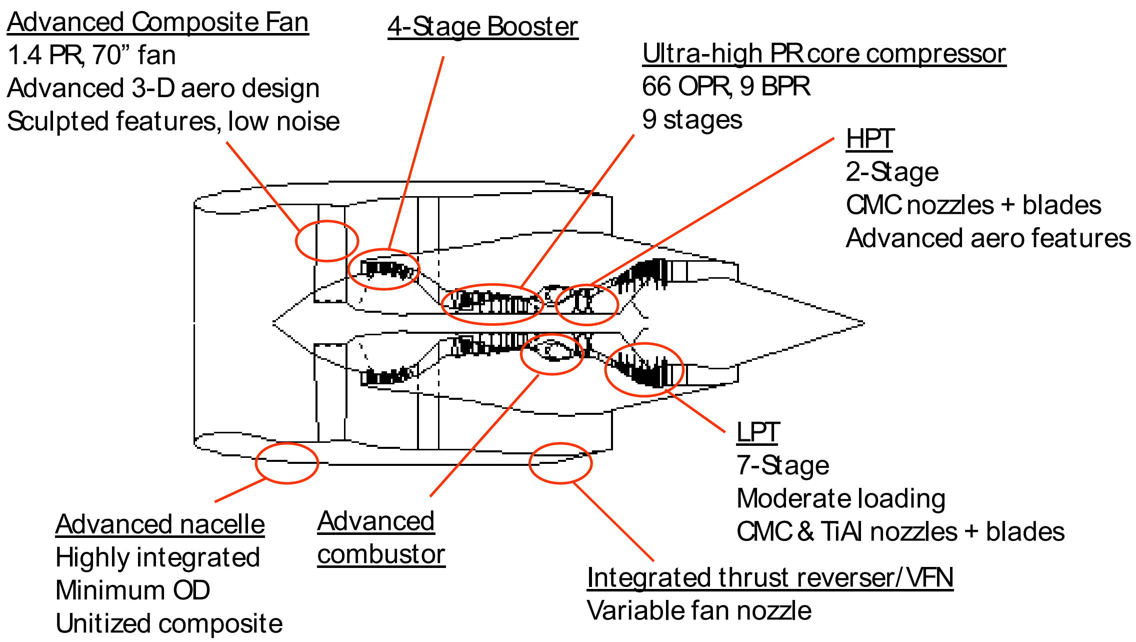


Figure 5.29 – "gFan" Engine Walk Around

Table 5.13 – gFan Engine Description

Propulsion system wt	6411	lbm
Fan diameter	70	in
Length	122	in, spinner to TRF
Performance	**Thrust, lbf**	**SFC, lbm/lbf-hr**
SLS	18,900	0.256
Rolling takeoff	14303	0.344
Top-of-climb	4229	0.534
Cruise	4025	0.528
Emissions	-58%	relative to CAEP/6

Projected Technologies
Advanced 3-D aero composite fan
Ultra-high PR compressor
Advanced low-emissions combustor
Integrated thrust reverser/variable fan nozzle
CMC turbine blades/vanes
Next-gen component aero technology
Next-gen nacelle technology
Improved shaft material
Acoustics technology suite
High DN bearings, high speed/temperature seals
TiAl materials & process technology

5.5 – 765-095 – SUGAR High (2030 Advanced Strut Braced High Span)

The SUGAR High configuration is a high span strut-braced wing concept that is tailored toward reducing fuel burn and noise via the aerodynamic benefits of high span.

5.5.1 – Configuration Layout

The 765-095 configuration is a high wing airplane with turbofan engines mounted on pylons below the wing and a T-tail layout. The very high aspect ratio wing is braced by a strut which joins the fuselage at the location of the body-mounted main landing gear in order to maximize load sharing. The main landing gear stows compactly in a fairing on the underside of the fuselage. The kinematics of the gear are similar to that of the BAe 146.

A three view drawing of the configuration is shown in Figure 5.30.

The fuselage is nominally circular in cross section and is sized to provide a seating arrangement of 6 abreast in economy class. The cabin length is sized to provide an airplane seating capacity in a dual class configuration of 154 passengers. The lower lobe accommodates bulk baggage only. A Layout of Passenger Accommodations (LOPA) is shown in Figure 5.13 and is the same as the SUGAR Free (765-093).

	WING Wimpress	V-TAIL Trap	H-TAIL Trap
Area*	1767.20	270.30	314.35
Aspect Ratio*	23.087	1.15	4.48
Taper Ratio	0.173	0.70	0.25
MAC Inches	115.90	185.88	112.46
Dihedral (Deg.)	0.0	-	0.00
1/4 Chord Sweep (Deg.)*	8.02	33.20	30.00
Root Chord (Inches)	194.30	216.44	160.64
Tip Chord (Inches)	33.70	151.50	40.23
Span (W/O Winglet)*	2423.90	211.56	450.68

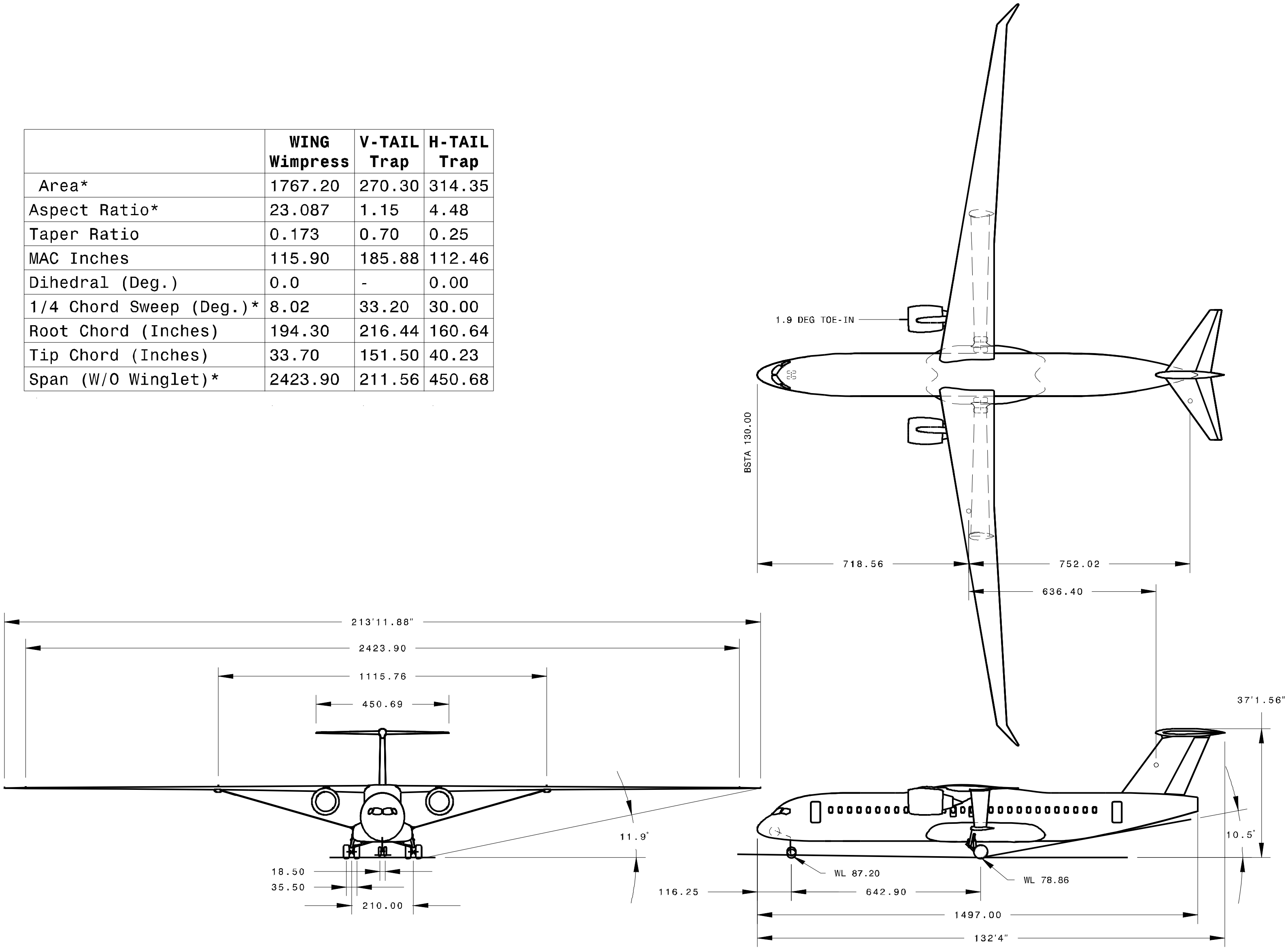


Figure 5.30 – 765-095 3-View Drawing

5.5.2 – Aerodynamic Buildup

High Speed:

The high-speed drag buildup for Sugar HIGH is shown in Table 5.14, and is summarized in Figure 5.31. CASES database is extrapolated for the high span configuration.

Table 5.14 – 765-095 High Speed Buildup

Configuration	765-095 Turbofan	765-095 Open Fan
SWEEP (DEG)	8°	8°
T/C-AVE	0.1119	0.1119
AIRFOIL TYPE	SUPERCRITICAL	SUPERCRITICAL
	F BUILD-UP (FT^2)	
FUSELAGE	8.8661	8.8661
WING	12.1223	12.1223
WINGLET	2.6111	2.6111
HORIZONTAL	1.8454	1.8454
VERTICAL	1.6581	1.6581
N&P	3.1500	1.7900
CANOPY	0.0405	0.0405
GEAR PODS	4.0542	4.0542
ETC BEFORE SUB	-6.6897	-5.8090
EXCRESCENCE	1.9001	1.8835
INTERFERENCE	0.0000	0.0000
UPSWEEP	0.6012	0.6012
WING TWIST	0.5219	0.5219
STRAKES	0.0000	0.0000
ETC AFTER SUB	-2.5913	-2.5603
FUSELAGE BUMP	1.0350	1.0350
F-TOTAL (FT^2)	**29.1249**	**28.6600**
E-VISC	0.824	0.824
	CRUISE CD BUILD-UP	
M-CRUISE	0.74	0.74
CL-CRUISE	0.75	0.75
CRUISE ALTITUDE	44000	44000
CD0	0.01713	0.01686
CDI	0.00905	0.00905
CDC	0.00212	0.00212
CDTRIM	0.00058	0.00057
CDTOT	0.02888	0.0286
L/D	**25.970**	**26.224**
ML/D	**19.217**	**19.406**

The ETC BEFORE SUB category includes technology projections for natural laminar flow over a portion of the wing, strut, and vertical tail as well as riblets applied to the turbulent portion of the wing and the fuselage, as illustrated in Figure 5.32. ETC AFTER SUB includes a technology projection for advanced supercritical airfoils with divergent trailing edge. In addition, technologies for low interference nacelles and strut/brace were included in the parasite buildup. Future work is needed to address airfoils and wings with extreme spans and high lift coefficients.

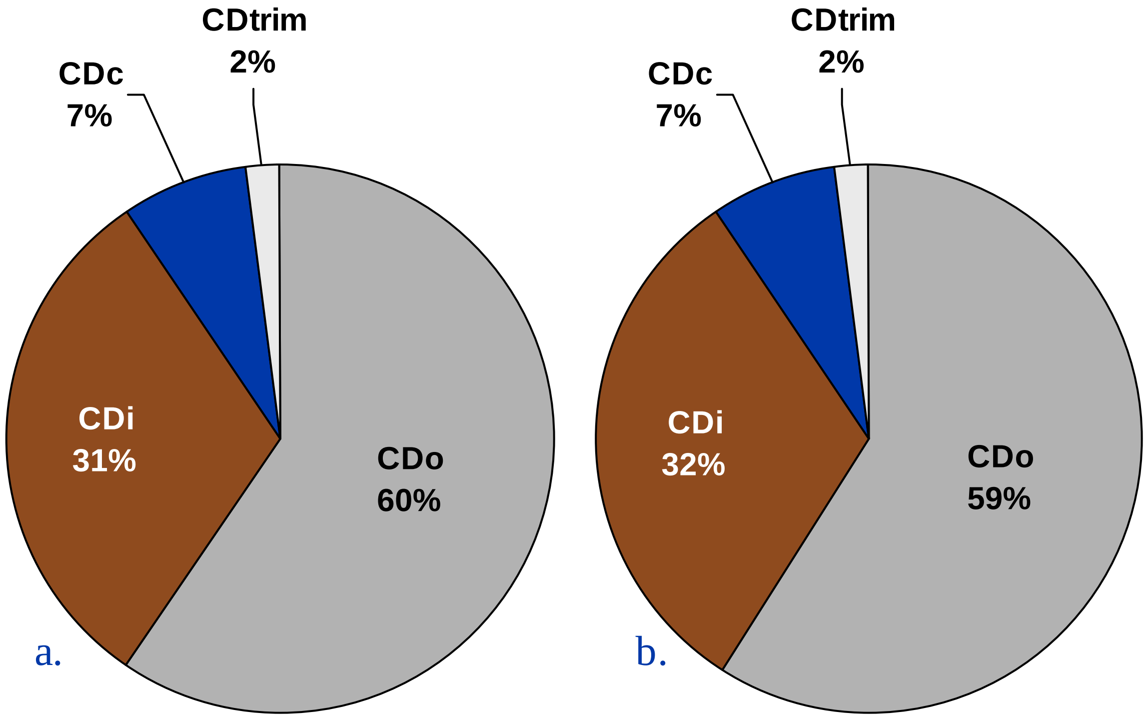


Figure 5.31 – 765-095 High Speed Buildup a) Turbofan b) Open Fan

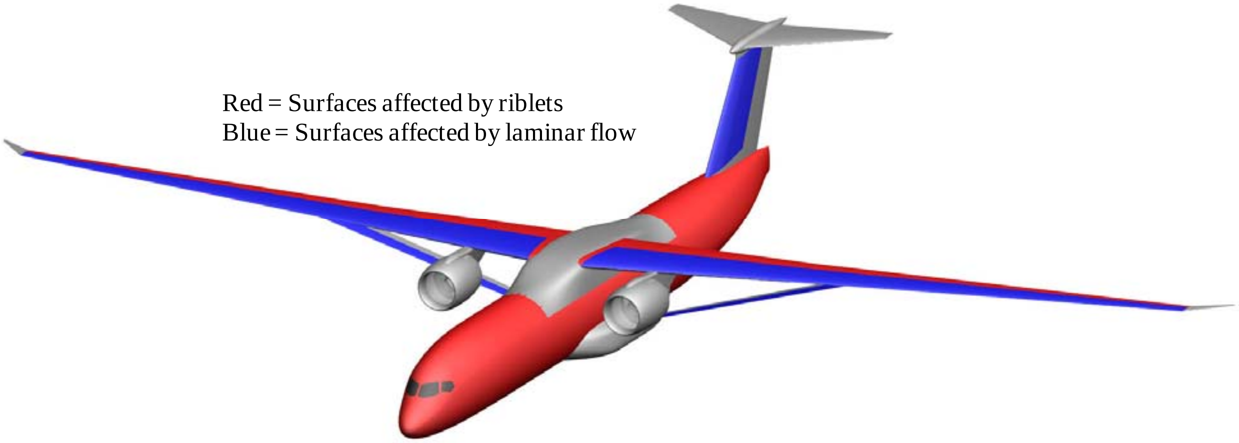


Figure 5.32 – 765-095 – Aerodynamic Technologies Application

The resulting high speed data is shown in Figure 5.24. The figure illustrates the maximum aerodynamic efficiency (M*L/D) occurring at a cruise Mach of 0.74 and a CL of 0.75. This is slightly higher than the efficiency at the Mach 0.7 and CL of 0.828 cruise point.

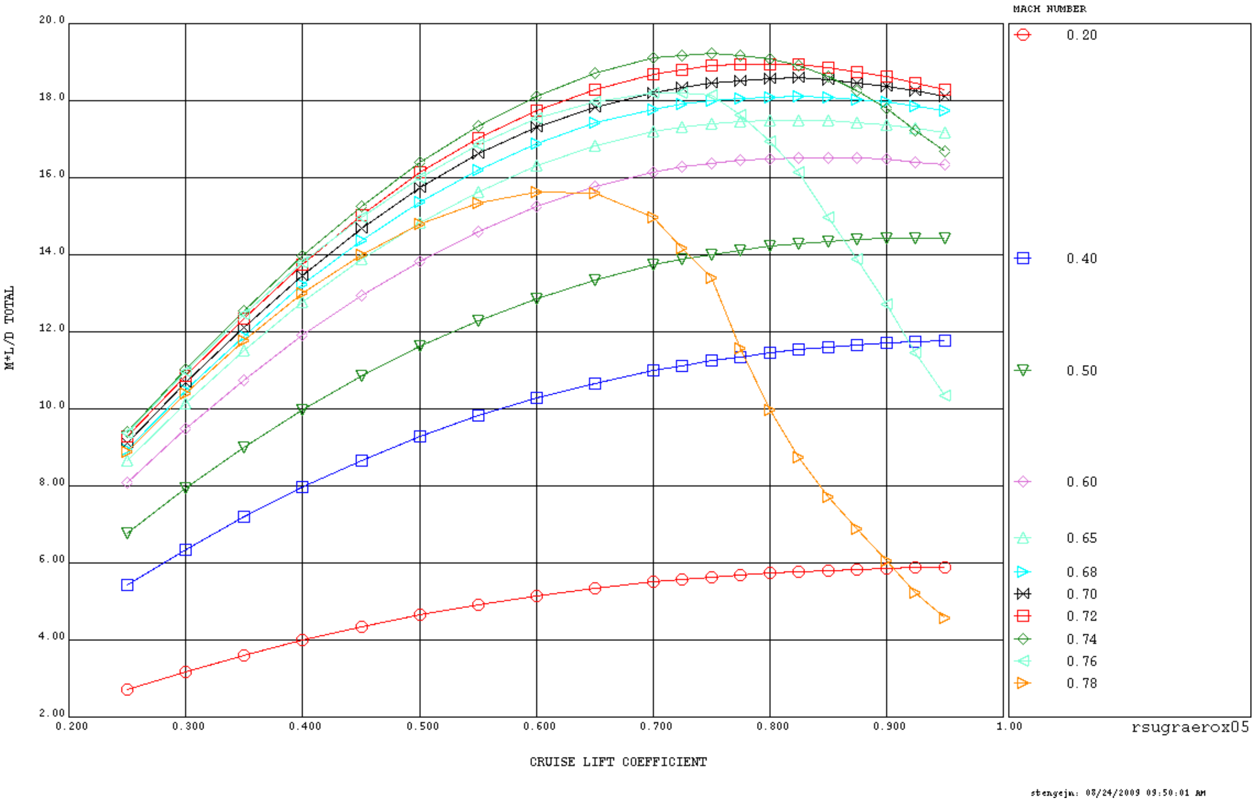


Figure 5.33 – 765-095 - M * L / D Total

Low Speed:

Figure 5.34 through Figure 5.36 show the turbofan low speed characteristics for SUGAR High. Low speed data are trimmed as a function of angle of attack, lift coefficient, and drag coefficient at each flap detent. Low speed high lift devices on wing leading and trailing edges are deployed.

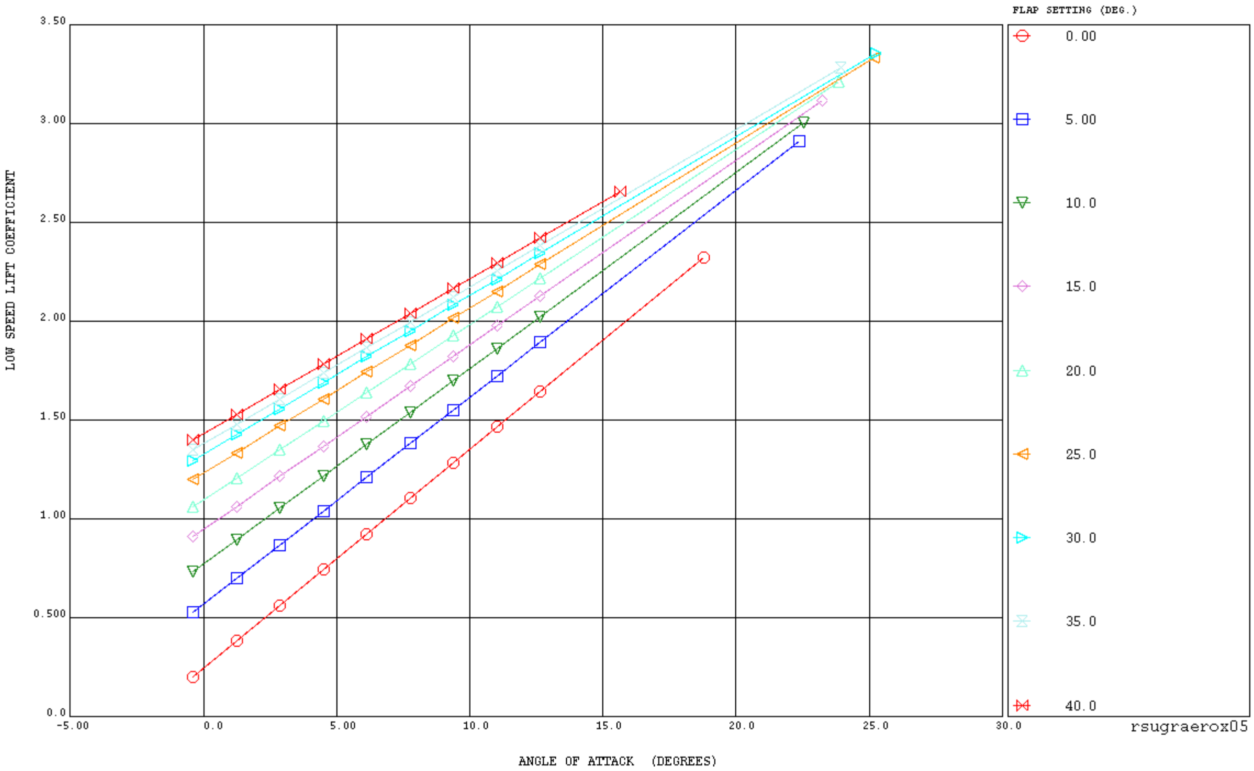


Figure 5.34 – 765-095 - Low Speed Lift Curve; Free Air

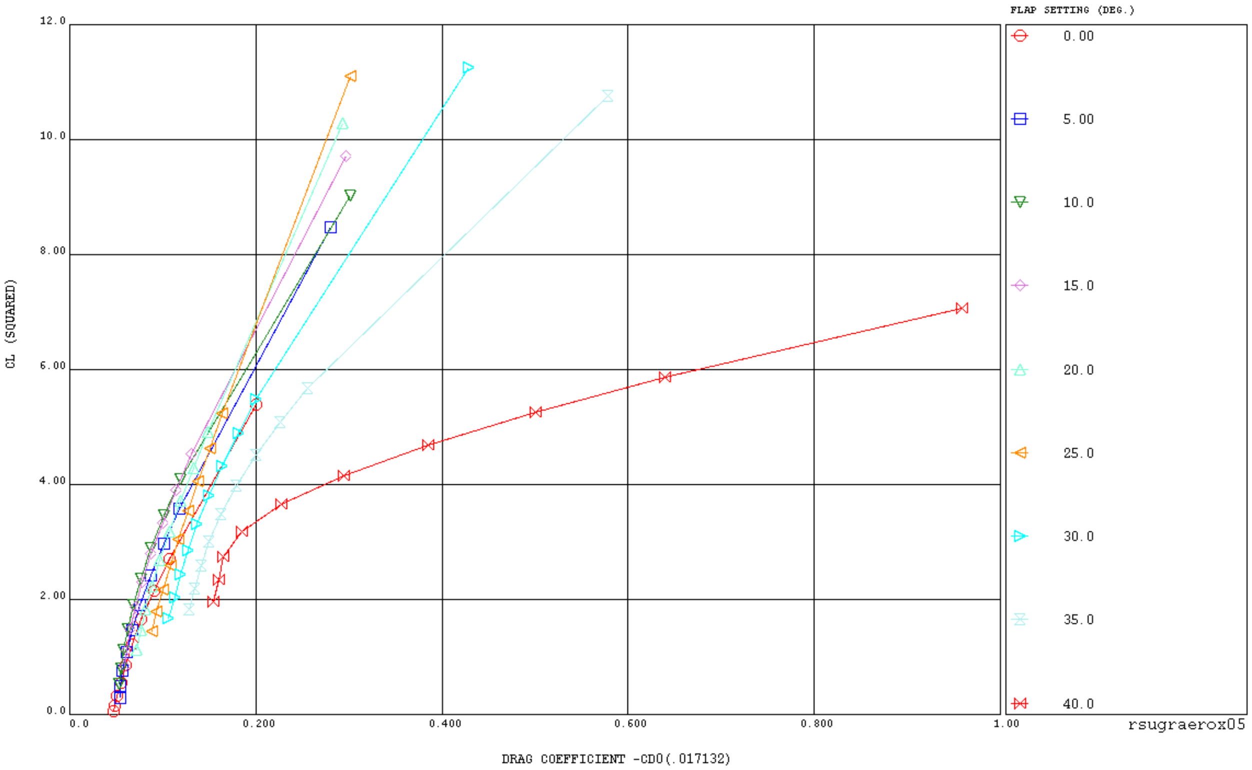


Figure 5.35 – 765-095 - Low Speed Polar; Free Air

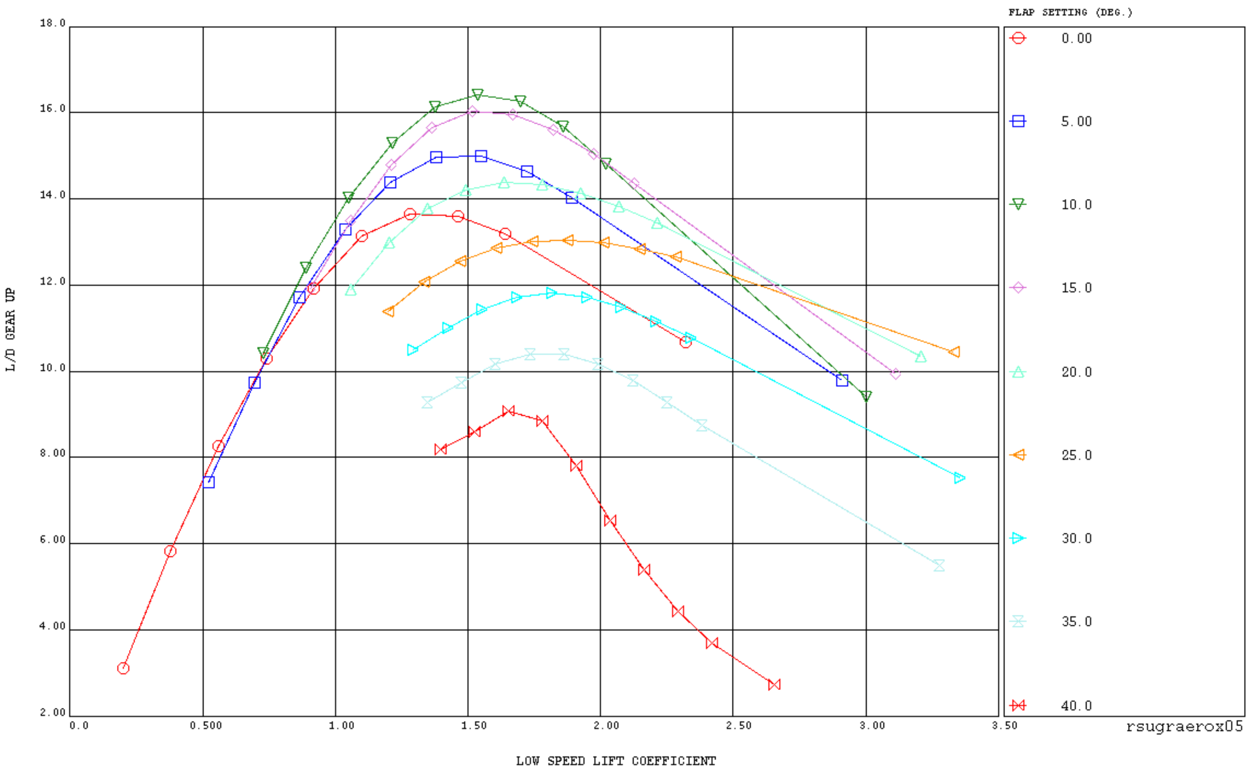


Figure 5.36 – 765-095 - Low Speed Lift / Drag; Free Air

5.5.3 – Mass Properties

The weight for the SUGAR High configuration was estimated by applying the N+3 weight reduction factors to a calibrated model which included factors for the high aspect ratio wing. Table 5.15 and Figure 5.37 show the subsystem weights and their percentages of TOGW for the as-drawn analyzed weight.

To derive the factors for the SUGAR High wing, additional analysis was needed to account for its high aspect ratio strut-braced wing. The wing was analyzed using station based analyses where the bending material was sized using empirical data, assuming that the strut reacted all outboard shear. Due to the inherent low bending and torsional resistance properties of this wing, an analysis was performed to account for aeroelastic effects. As a surrogate to more rigorous and costly analyses, a tip rotation constraint was imposed to assess the torsional penalty incurred by the bending material. The high weight of this wing is primarily due to the bending material thickness relative to the available box depth, even after including advanced aeroelastic load relief. The standard methods used to estimate the wing weight are not considered adequate to account for all of the advanced technologies. Therefore, there is high wing weight uncertainty and significant, although unproven, potential for weight reduction.

Further analysis using simple spreadsheet methods was done to explore potential weight reductions, as summarized in Figure 5.38. A non-optimized planform and the need for increased torsional rigidity were major contributors to the high wing weight of the point design configuration. With the goal of reducing this, parametric variations were made to the simple analysis model. Provisions were made to preserve the same stiffness while reducing structural material. The thickness of the wing was increased slightly; resulting in greater stiffness over the entire wing. The planform was modified to reduce taper inboard of the strut, which increased the chord at the strut-to-wing intersection. This allowed the strut to have greater leverage in resisting twist at the strut-to-wing intersection. These changes might allow the wing cover panels to be sized almost entirely by bending loads alone, with just a small increment added to meet the torsion requirement. The reduced stresses, which would result in lower skin thicknesses, would allow the N+3 weight reduction factors to be applied. The total benefit of these changes, when incorporated, could result in up to 20,000 lbs of weight savings (Figure 5.38). Additional work is needed to determine if this reduction is achievable.

Table 5.15 – 765-095 Group Weight Statement

GROUP	WEIGHT (LB)	% TOGW
WING	**36,798**	**22.5**
BENDING MATERIAL	20,602	12.6
SPAR WEBS	3,434	2.1
RIBS AND BULKHEADS	3,434	2.1
AERODYNAMIC SURFACES	4,925	3.0
SECONDARY STRUCTURE	4,403	2.7
STRUT	**2,800**	**1.7**
TAIL	**3,157**	**1.9**
FUSELAGE	**16,327**	**10.0**
LANDING GEAR	**5,595**	**3.4**
PYLON	**5,036**	**3.1**
PROPULSION	**9,984**	**6.1**
ENGINE	9,156	5.6
FUEL SYSTEM	828	0.5
FLIGHT CONTROLS	**2,873**	**1.8**
COCKPIT CONTROLS	252	0.2
SYSTEM CONTROLS	2,621	1.6
POWER SYSTEMS	**4,138**	**2.5**
AUXILIARY POWER PLANT	1,014	0.6
HYDRAULICS	827	0.5
ELECTRICAL	2,297	1.4
INSTRUMENTS	**773**	**0.5**
AVIONICS & AUTOPILOT	**1,504**	**0.9**
FURNISHINGS & EQUIPMENT	**9,115**	**5.6**
AIR CONDITIONING	**1,441**	**0.9**
ANTI-ICING	**141**	**0.1**
MANUFACTURER’S EMPTY WEIGHT (MEW)	**99,682**	**60.8**
OPERATIONAL ITEMS	7,207	4.4
OPERATING EMPTY WEIGHT (OEW)	**106,889**	**65.2**
USEABLE FUEL	20,774	12.7
PAYLOAD	36,190	22.1
TAKEOFF GROSS WEIGHT (TOGW)	**163,853**	**100.0**

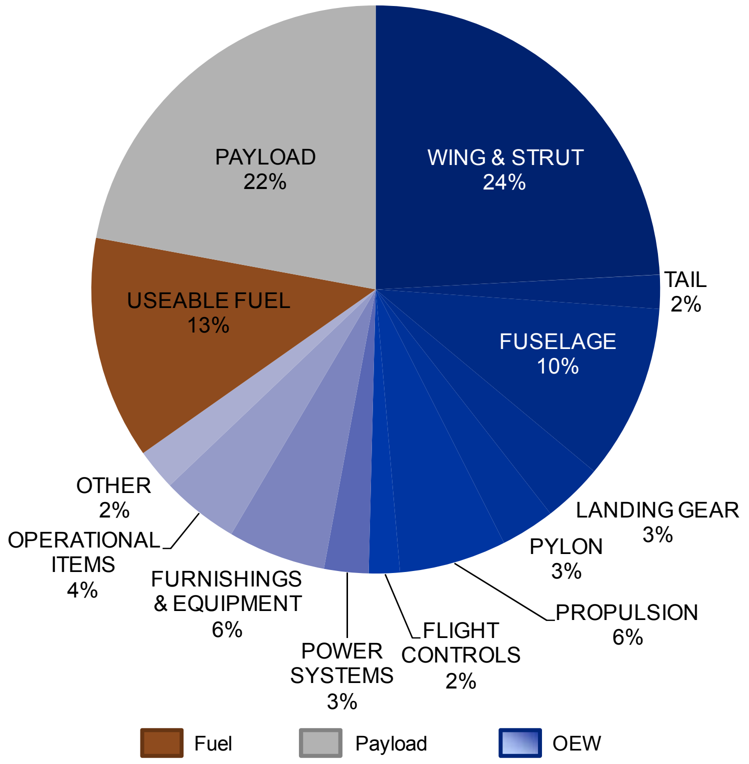


Figure 5.37 – 765-095 Weight Summary

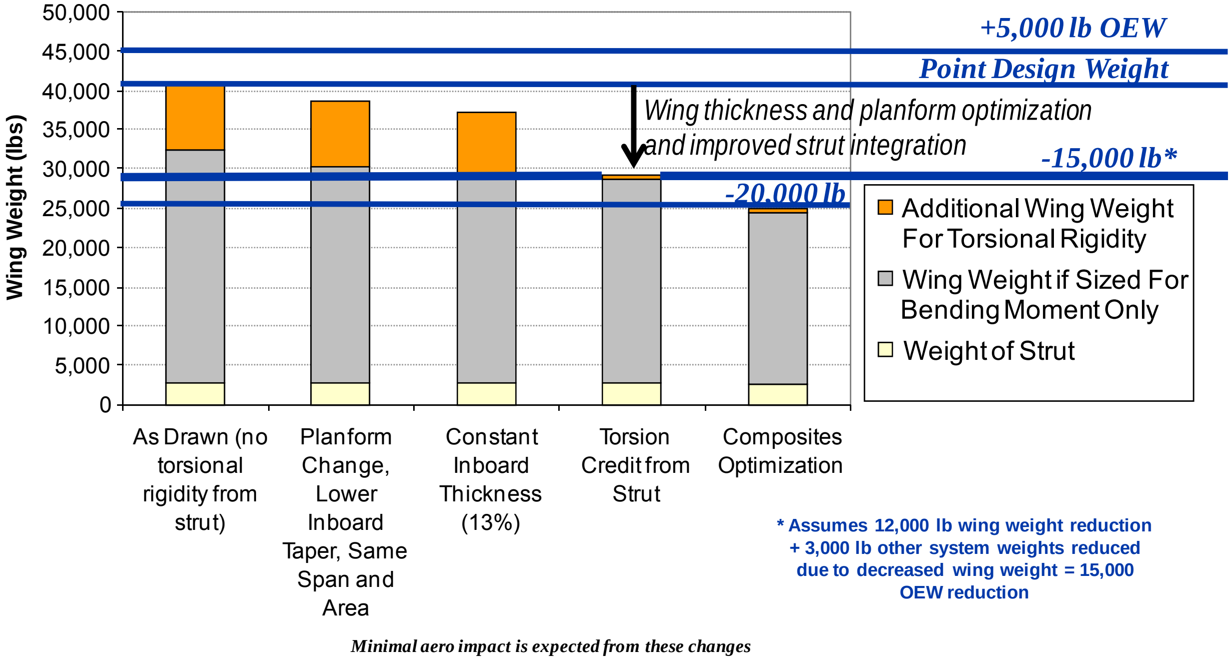


Figure 5.38 – 765-095 Weight Opportunities

5.5.4 – Engine Data – “gFan+”

The engine designed for the SUGAR High vehicle was given the informal designation “gFan+” and is shown in Figure 5.39. The overall engine design very similar to the gFan reference engine, but incorporates a variety of advanced technologies above and beyond those in the gFan design. Thus, the architectural concept is again a 2-spool separate flow turbofan but with a 59 OPR and 13 BPR (at top of climb). The difference in OPR between the gFan and gFan+ is primarily due to the lower FPR employed on the gFan+, which in turn leads to a slightly lower OPR for the same basic booster and compressor design. The difference in OPR is more than made up for in the improved propulsive efficiency and higher bypass ratio that ensue with the lower FPR. This engine also features relatively low hot section temperatures and makes extensive use of advanced CMCs.

Like the gFan, this engine design is compatible with the aggressive emissions goals by virtue of the relatively low hot section temperatures and an advanced low emissions combustor design. The combustor is a “NGEN+ TAPS” design that is similar to the gFan engine but with additional mixing effectiveness improvements and other features to improve NOx and particulate emissions levels. This engine is also more compatible with the very aggressive noise goals in that it features a conventional shrouded fan/nacelle that provides good inherent shielding and also has a suite of advanced acoustics technologies for lowest possible noise. Finally, this engine design features an advanced nacelle design to minimize nacelle drag associated with low FPRs and larger fan diameters. General geometry, weight, and performance information is shown in Table 5.16.

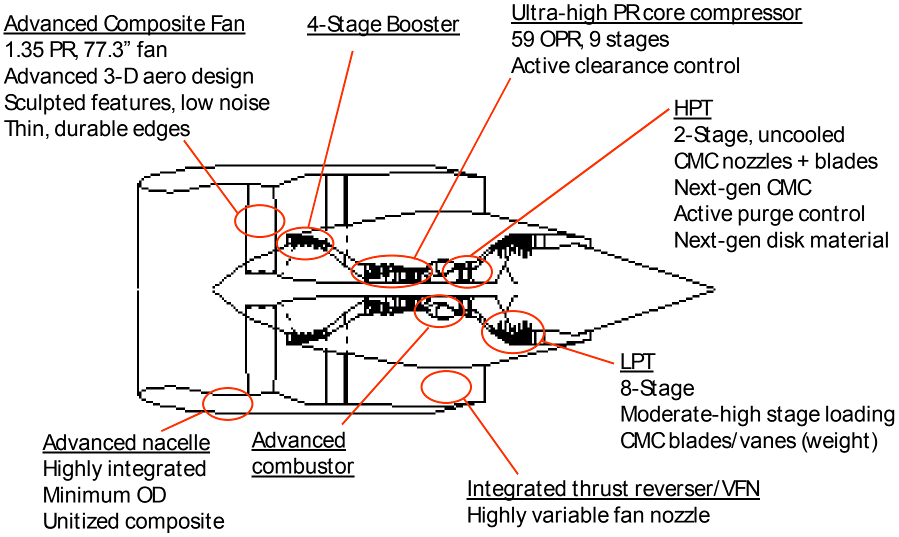


Figure 5.39 – "gFan+" Engine Walk Around

Table 5.16 – gFan+ Key Weight, Geometry, Performance, and Technologies

Propulsion system wt	7096	lbm
Fan diameter	77	in
Length	122	in, spinner to TRF
Performance	**Thrust, lbf**	**SFC, lbm/lbf-hr**
SLS	18800	0.211
Rolling takeoff	13385	0.301
Top-of-climb	3145	0.475
Cruise	3028	0.470
Emissions	-72%	relative to CAEP/6

Projected Technologies
Advanced 3-D aero composite fan
Ultra-high PR compressor
Advanced low-emissions combustor
Integrated thrust reverser/variable fan nozzle
Next-gen CMC HPT vanes, blades, and shrouds
Next-gen component aero technology
Next-gen nacelle technology
Improved shaft material
Acoustics technology suite
High DN bearings, high speed/temperature seals
TiAl materials & process technology
Advanced hot section disk material
Active purge control
Advanced CMC blade and vane features
Closed-loop, fast-response turbine ACC

5.6 – 765-096 - SUGAR Volt (2030 Advanced Electric)

The SUGAR Volt is a derivative of the SUGAR High configuration that has been resized to accommodate modular battery packages and a hybrid gas turbine electric propulsion system.

5.6.1 – Configuration Layout

The 765-096 configuration is a high wing airplane with hybrid gas turbine-electric engines mounted on pylons below the wing and a T-tail layout.

The configuration is identical in concept to the 765-095 SUGAR High configuration with the exception of the propulsion system and accommodating changes. In addition to the engine package itself the airplane has modular batteries fitted beneath the fuselage on centerline. The configuration also permits batteries to be mounted in wing pods instead of the body. The fuselage mount accommodates the battery volume and hard point structure better while the wing while pod mounts may benefit from flutter relief, spanload, and ground servicing. The mounting arrangements have not been traded. A three view drawing of the configuration is shown in Figure 5.40.

The fuselage and LOPA are nominally the same as that of the 765-093 configuration (SUGAR Free). The LOPA can be seen in Figure 5.13.

	WING Wimpress	V-TAIL Trap	H-TAIL Trap
Area*	1767.20	270.30	314.35
Aspect Ratio*	23.087	1.15	4.48
Taper Ratio	0.173	0.70	0.25
MAC Inches	115.90	185.88	112.46
Dihedral (Deg.)	0.0	-	0.00
1/4 Chord Sweep (Deg.)*	8.02	33.20	30.00
Root Chord (Inches)	194.30	216.44	160.64
Tip Chord (Inches)	33.70	151.50	40.23
Span (W/O Winglet)*	2423.90	211.56	450.68

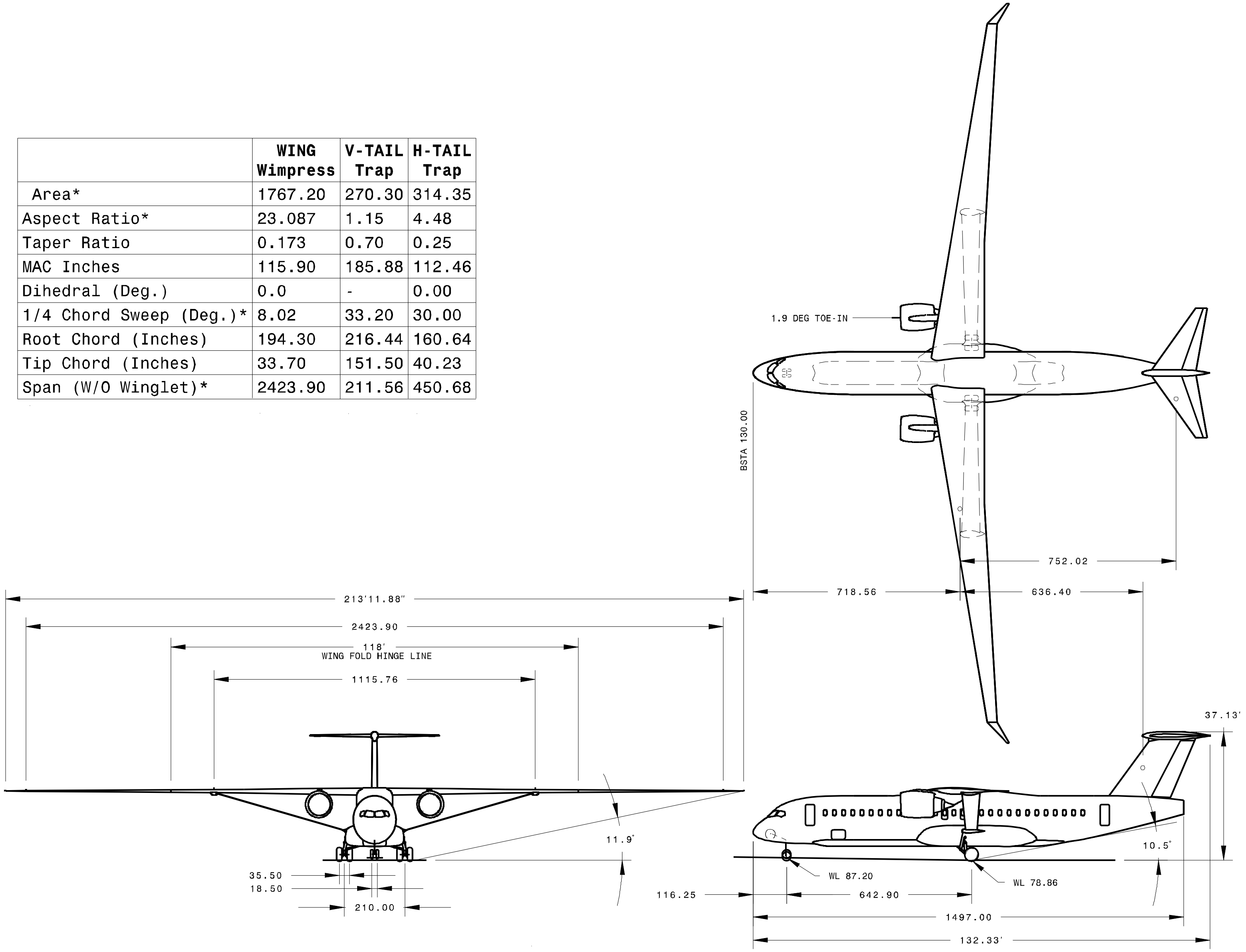


Figure 5.40 – 765-096 3-View Drawing

5.6.2 – Aerodynamic Buildup

The 765-096 aerodynamic buildup is the same as SUGAR High (765-095) (Section 1.1.1) with a 2.5 count parasite drag increase (applied with the performance tools) to account for the battery fairing. Only the battery fairing is different from the SUGAR High's outer mold line (OML). No new polars were generated for this configuration. The drag increase reduces the maximum M * L/D from 19.22 to 19.05 for the turbofan installation.

5.6.3 – Mass Properties

The group weights statements for SUGAR Volt were the same as SUGAR High with a few exceptions. The engine weight was increased 9,522 pounds to account for the difference between the gFan+ and hFan. Battery weight was added dependent on the sizing outputs. The capability to carry batteries was accompanied by an estimated 6,000 pound weight increase for mounting and wiring. The data represented for the SUGAR Volt include a lightweight wing consistent with a 15,000 pound weight reduction applied as a fixed increment during sizing. This weight reduction was applied with the assumption that three quarters of the total opportunity will be attainable from SUGAR High (765-095) discussed in Section 5.5.3.

It should be noted that the SUGAR Volt propulsion system could also be integrated on the Refined SUGAR or SUGAR Ray. Most of the benefit obtained by the SUGAR Volt concept would be available on the other concepts in the event the wing weight reduction goals are not met. It is recommended the installation be studied on other platforms since configurations with lower L/D will have larger performance decrements due to the increased propulsion system and battery weights.

5.6.4 – Engine Data – "e-f-hFan" Engines

Several engine designs were developed for consideration on the SUGAR Volt vehicle platform. These were given the informal designations "eFan", "fFan", and "hFan". The eFan is an all-electric propulsor basically consisting of an electric motor coupled to a fan via a gearbox. The fFan is a gas turbine-fuel cell hybrid engine concept utilizing the gas turbine core to produce the power required for takeoff and climb, but relying mainly on the fuel cell system to provide cruise electric power to a motor/gearbox attached to the LP spool. The hFan is a gas turbine-electric hybrid that has both a gas turbine and an electric motor attached to the LP spool such that it can run on a combination of jet fuel and battery power. This section describes each of these concepts in further detail.

"eFan" Propulsor:

The "eFan" propulsion system is effectively an advanced fan coupled to a lightweight, high power motor via a gearbox. The electric power required to drive the motor is assumed to come from an external source (batteries). The propulsion system is contained in a nacelle and lends itself to a variety of configurations, including distributed propulsion. The engine as sized for this application is intended to be one of two engines mounted on the vehicle but the basic design could easily be scaled down to a size appropriate for a plurality of distributed propulsors.

Key dimensions, weight and performance figures for the eFan propulsor are provided in Table 5.17. This propulsion system is surprisingly lightweight for its size, and this is aided by the fact that large portions of the nacelle and structure can be fabricated from composites. It should be noted, however, that the eFan geometry is not designed to the same level of fidelity as the gas turbine-based counterparts, simply because the database and tool set is much more limited for this type of engine. The weight estimate must therefore be recognized as having significantly wider error bands than the comparable gas turbine concept. Also, note that the engine is designed for a much higher thrust than the competing gas turbine concepts due to the mass of the battery required for an all-electric airplane to make the required mission range. This in turn makes the absolute weight of the eFan propulsor higher than the competing gas turbine concept.

Table 5.17 – eFan Key Weight, Dimensions, Performance, and Technologies

Propulsion system wt	~7000	lbm
Fan diameter	90	in
Length	~105	in, spinner to TRF
Performance	**Thrust, lbf**	**Elec. Power In, HP**
SLS	25500	15417
Rolling takeoff	18258	15926
Top-of-climb	4732	8667
Cruise	3333	5645
Emissions	-100%	relative to CAEP/6

Projected Technologies
Advanced 3-D aero composite fan
Integrated thrust reverser/variable fan nozzle
Next-gen nacelle technology
Acoustics technology suite
Advanced high efficiency gearbox
High-efficiency lightweight motor controller
Advanced lightweight high efficiency motor
Advanced battery technology (booked w/ airframe techs)
Lightweight, low loss radiators and surface coolers

“fFan” Propulsor:

The “fFan” engine concept is a hybrid fuel cell-gas turbine engine wherein the power required to drive the fan comes primarily from the gas turbine at takeoff and climb conditions, and primarily from the fuel cell system during cruise. This is intended to take advantage of the strengths of each subsystem while mitigating the weaknesses. Specifically, use of the gas turbine to produce the high horsepower requirements at takeoff and climb takes advantage of the inherently high power/weight of gas turbines while use of the fuel cell-electric subsystem for cruise takes advantage of the high theoretical thermal efficiency of the fuel cell system while minimizing the physical size and weight of the fuel cell.

The general arrangement of the fFan propulsion system is shown in Figure 5.41. The nacelle contains the gas turbine propulsor, an electric motor, gearbox, and the fan. The gas turbine portion of the propulsor consists of a single spool unit connected to the main fan via a gearbox. This gas turbine core is designed to be compatible with the RPM requirement needed for an efficient, lightweight electric motor. The single spool arrangement provides relative simplicity and the modest pressure ratio and temperatures employed in the gas turbine portion of the unit are conducive to low cost and very good emissions characteristics. The principal disadvantage of this arrangement is the need for a high power gearbox to connect the fan and core shafts. Alternate 2-spool arrangements are possible, but the electric motor will still require a gearbox in order to minimize motor size and weight.

The fuel cell itself consists of a solid oxide fuel cell (SOFC) stack fed by pressurized air bled from the gas turbine subsystem when in cruising flight. The solid oxide fuel cell was chosen primarily because it offers the possibility of on-cell fuel reform of Jet-A type fuels (a fundamental assumption of this study was that the propulsion system had to use Jet-A fuel). Further, the SOFC offers the possibility of a self-cooled system and its inlet/discharge temperatures are quite compatible with the gas turbine.

The relatively low power/weight of projected fuel cell systems as well as their physical bulk (volume/power) makes them too large to fit inside the propulsion nacelle for the configuration studied. Thus, the fuel cell itself is presumed to be located outside the propulsion nacelle (presumably in the fuselage). The air supplied to the fuel cell is taken from compressor discharge and is collected in a volute as shown in the figure. The effluent discharged from the fuel cell is passed back into the gas turbine through the combustor and subsequently through the turbine.

Note that the provision of a variable bleed system to supply the necessary cruise flow to the fuel cells while maintaining acceptable gas turbine performance is non-trivial and requires the use of innovative features in the gas turbine portion of the engine. Also, the reintroduction of the fuel cell effluent back into the combustor is a challenge, as the available pressure drop across the fuel cell system will be limited to something on the order of 5%. It is unclear at this point what impact the reintroduction of fuel cell effluent into the combustor would have on the emissions levels of the gas turbine portion of the system and this is an area that would require further study.

It became evident relatively early in the course of developing the fFan propulsion concept design that a fuel cell-based propulsion system would face numerous challenges relative to the incumbent gas turbine-based system. Further, the experience base and tools available to aid in the design are in a relatively primitive state in comparison to the gas turbine knowledge base. Thus, this design was not developed to the level of detail that the other engines were. Engine performance was only roughly estimated for cruise and takeoff, and no detailed performance model is yet available. Table 5.18 provides a general overview of fFan engine geometry, performance, weight and technologies as they were defined at the conclusion of the fuel cell portion of this study.

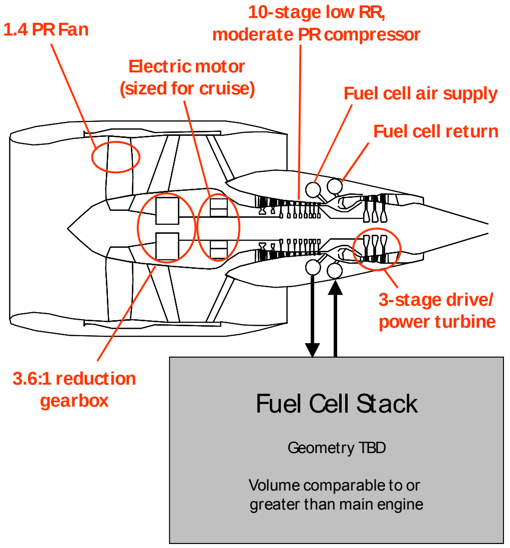


Figure 5.41 – "fFan" Propulsion System General Arrangement

Table 5.18 – fFan Key Weight Geometry, Performance, and Technologies

Propulsion system wt	~15K-20K	lbm
Fan diameter	89	in
Length	>120	in, spinner to TRF
Performance	**Thrust, lbf**	**SFC, lbm/lbf-hr**
SLS	TBD	TBD
Rolling takeoff	TBD	TBD
Top-of-climb	TBD	TBD
Cruise	TBD	TBD
Emissions	TBD	relative to CAEP/6

Projected Technologies

Advanced lightweight prime-reliable Solid Oxide FC
On-cell fuel reform technology
Advanced 3-D aero composite fan
Next-gen nacelle technology
Acoustics technology suite
Advanced high efficiency gearbox
High-efficiency lightweight motor controller
Advanced lightweight high efficiency motor
Lightweight, low loss radiators and surface coolers
Advanced low-emissions combustor
Next-gen component aero technology

“hFan” Propulsor:

The overall engine design of the “hFan” engine is very similar to “gFan+” propulsion system in that the architectural concept is a boosted 2-spool separate flow turbofan having a 59 OPR at top of climb, but with an 18 BPR. The hFan also features a conventional fan and nacelle arrangement for lowest possible noise, as shown in Figure 5.42. The hFan and gFan+ engines share a common core design with only minor differences between the two cores. However, the LP spools are considerably different. Specifically, the hFan engine is designed to the same FPR as the gFan+ but with a higher thrust level (required to cope with the added weight of the batteries needed to power the electric subsystem). The additional power required to drive the larger hFan fan is derived from the electric subsystem, which consists of an electric motor mounted inside the core exhaust nozzle and attached to the LP spool via a gearbox.

The hybrid electric system offers considerable flexibility to utilize gas turbine versus battery for various missions. In general, the gas turbine is used for long range cruise while the electric motor is used for short range cruise. This enables dramatic reductions in mission fuel burn for short range missions. The electric motor and gearbox are sized to 5500 HP output. This is sufficient to make adequate top-of-climb thrust in electric mode but is not adequate to make full thrust at takeoff and climb (the fan power input requirement at takeoff is on the order of 20,000 HP). Thus, the gas turbine is always needed for the low altitude portions of the mission.

A further consideration in the design of this engine is the attainment of top-of-climb thrust. The original requirements for this engine design specified that the engine should be able to make full top-of-climb thrust in either electric or gas turbine modes. However, when in electric mode, the loss of the thrust from the core nozzle implies that some other means would be required to make up the difference (such as increased electric power to the fan or oversizing the fan to regain the additional thrust). However, this may be a heavier solution because it increases the electric horsepower requirement and may compromise the design of the fan. Therefore, the thrust requirements were modified such that the top-of-climb thrust available in electric mode is somewhat less than that available in combined mode. As a result, the full top-of-climb thrust can only be made in combined mode using both the gas turbine and the electric subsystems. Specifically, if the gas turbine core is operating at full power output at the top-of-climb condition, an additional 1275 HP motor power input to the LP spool is required to reach full thrust. This translates into an electrical power input of 1363 HP (1.01 MW).

This arrangement yields a good compromise between providing maximum capability to provide mission thrust via the electric subsystem while minimizing the required motor size and power output. General weight, dimension and performance characteristics for the hFan engine are shown in Table 5.19. This table also shows the suite of technologies envisioned for this engine. These technologies include all those applicable to the gFan+ propulsion system as well as many of the eFan electric power technologies. A final technology unique to this engine is the use of a variable core nozzle that is independent from the variable fan nozzle. This is needed to compensate to the speed-speed shift and accompanying booster operating line migration induced by modulation of the electric motor power input to the LP spool during the operating mode shifts between gas turbine, hybrid, and electric modes.

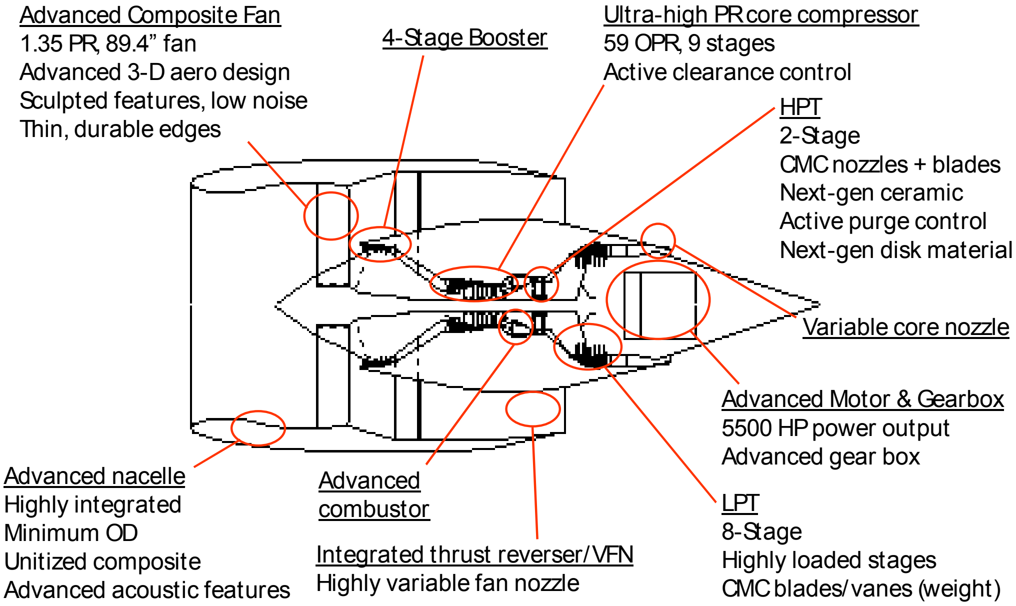


Figure 5.42 – “hFan” Engine Walk Around

Table 5.19 – hFan Key Weight, Geometry, Performance, and Technologies

Propulsion system wt	10475	lbm
Fan diameter	89	in
Length	156	in, spinner to motor
Performance	**Thrust, lbf**	**SFC, lbm/lbf-hr**
SLS (GT mode)	18800	0.211
Rolling tkoff (GT mode)	13385	0.301
Top-of-clmb (hybrid md)	4364	0.372 + 1363 HP in
Cruise (typ. hybrid mode)	3344	0.341 + 1363 HP in
Emissions	-72% to -100% relative to CAEP/6	

Projected Technologies
Advanced 3-D aero composite fan
Ultra-high PR compressor
Advanced low-emissions combustor
Integrated thrust reverser/variable fan nozzle
Next-gen CMC HPT vanes, blades, and shrouds
Next-gen component aero technology
Next-gen nacelle technology
Improved shaft material
Acoustics technology suite
High DN bearings, high speed/temperature seals
TiAl materials & process technology
Advanced hot section disk material
Active purge control
Advanced CMC blade and vane features
Closed-loop, fast-response turbine ACC
Advanced high efficiency gearbox
High-efficiency lightweight motor controller
Advanced lightweight high efficiency motor
Advanced battery technology (booked w/ airframe techs)
Lightweight, low loss radiators and surface coolers

5.7– 765-097 - SUGAR Ray (2030 Advanced Low Noise Hybrid Wing Body)

The SUGAR Ray configuration is an advanced HWB concept with a technology suite similar to the SUGAR High.

5.7.1 – Configuration Layout

The 765-097 configuration is a semi-high wing blended body consisting of a center body, a transition region and an outboard wing. The transition region between the center body and outboard wing provides for main landing gear (forward) retraction and the bulk of the fuel. The advanced turbofan engines are mounted on pylons above the center body which provides noise shielding downward for both the inlet (fan) and the exhaust nozzle. The vertical tail surfaces are mounted at the outboard boundary of the center body and provide lateral stability and control, and sideline noise shielding for the engine core and fan nozzles. A three view drawing of the configuration is shown in Figure 5.43. The outboard wing provides additional fuel, control surfaces, and accommodates folding at BL = 702 as no fuel is carried outboard of this location.

The center body provides accommodations for 155 passengers in two classes together with bulk cargo provisions, crew accommodations, flight deck and control surfaces. The LOPA is shown in Figure 5.44

	WING	V-TAIL	H-TAIL
Area (gross)	4,136.0	90.8	N/A
Aspect Ratio (gross)	6.865	1.705	
Taper Ratio (trap)	0.228	0.366	
MAC Inches (gross)	489.7	101.3	
Dihedral (Deg.)	3.0	62.0	
1/4 Chord Sweep (Deg.)	27.7	39.2	
Root Chord (Inches) (trap)	322.6	129.23	
Tip Chord (Inches) (trap)	73.6	44.90	
Span (W/O Winglet)	1,936.8		

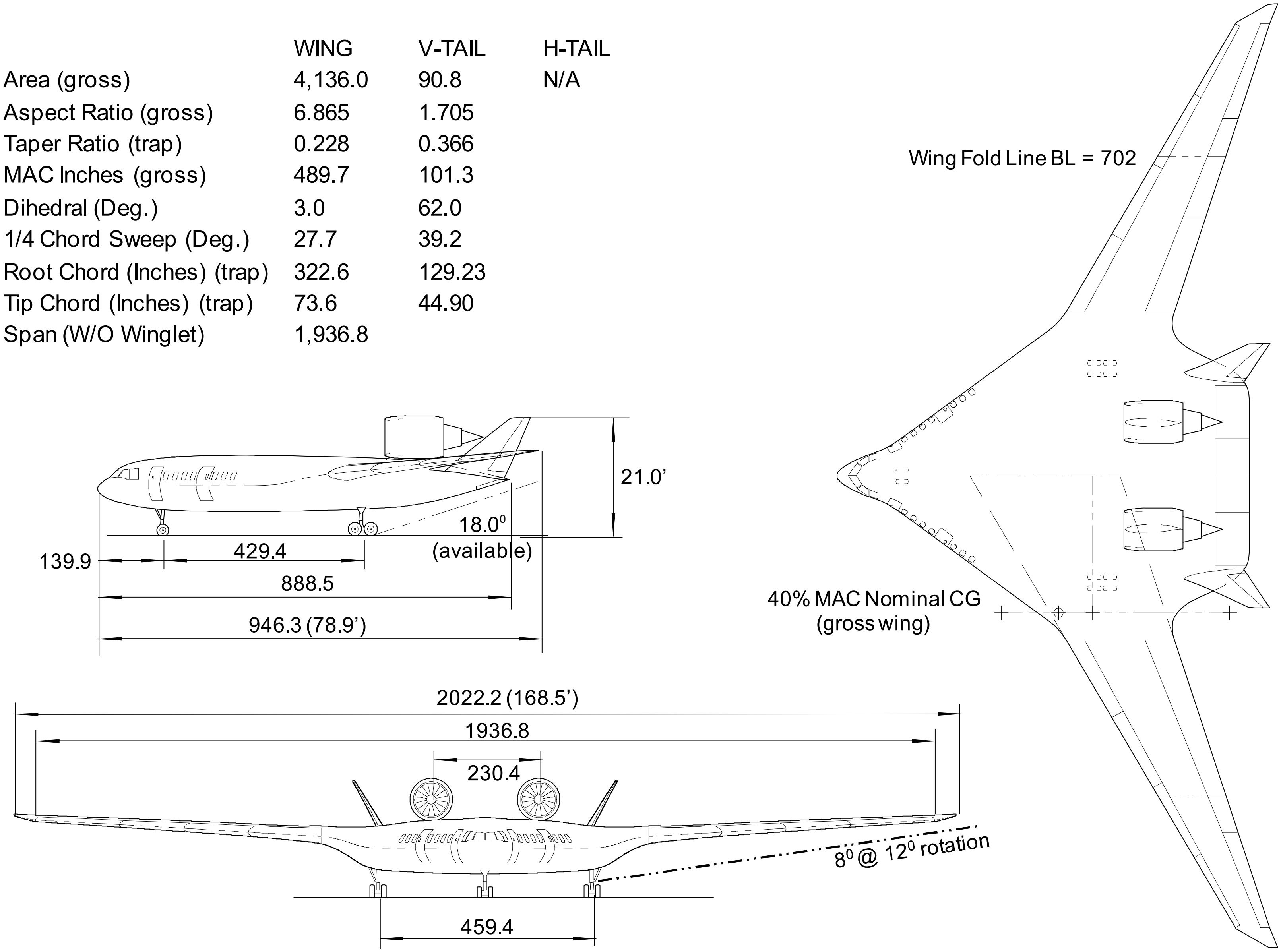
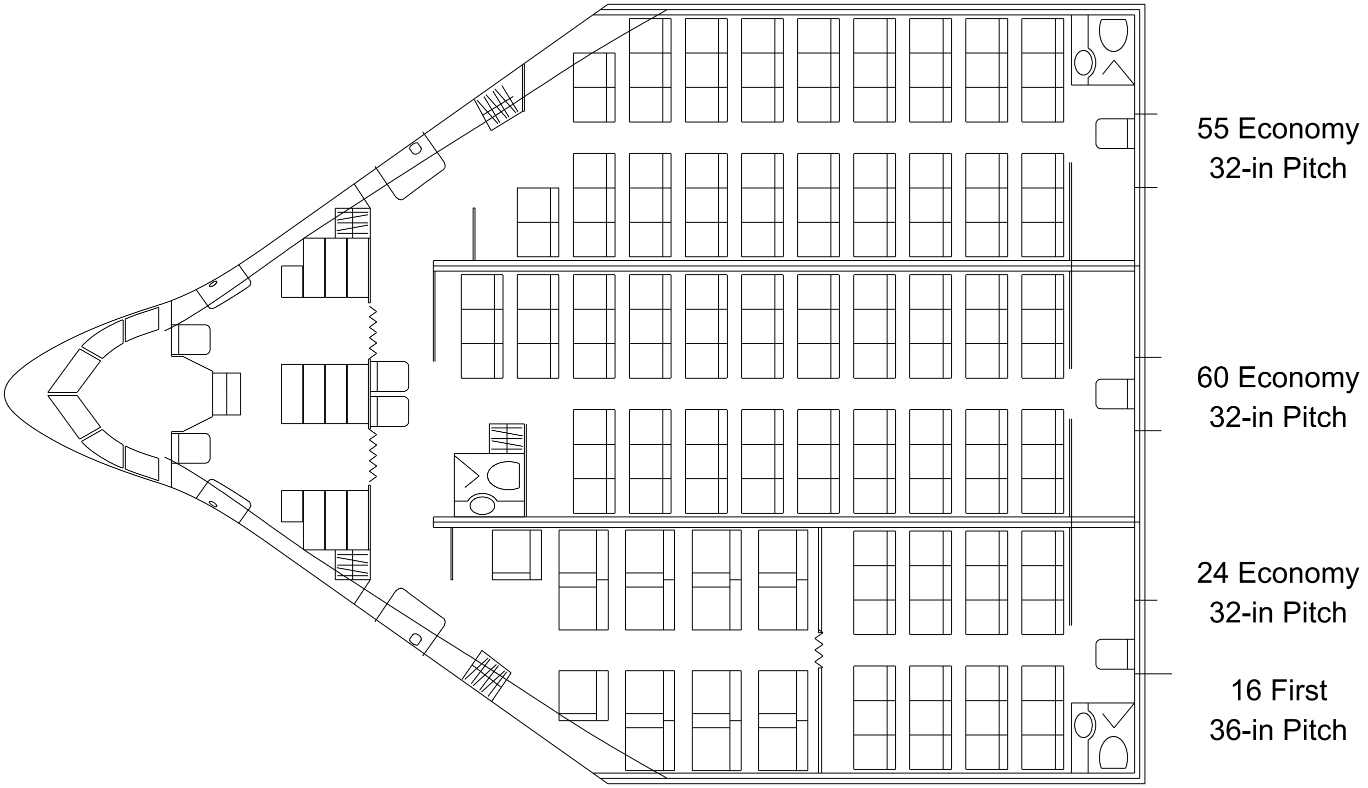


Figure 5.43 – 765-097 Configuration Layout

Interior Arrangement

IAC Short / Medium Range – Dual Class



	Class (%)	Carts (qty)	Cart Ratio (Carts/Pax)	Lavatory Ratio (Pax/Lav)	Closet Ratio (Rod-in/Pax)
First	10.32	4.0	0.250	16	3.75
Economy	89.68	7.0	0.050	70	0.27
Total	100.00	11.0	0.071	–	–

Figure 5.44 – 765-097 LOPA

5.7.2 – Aerodynamic Buildup

High Speed:

The high-speed buildup for SUGAR Ray is shown in Table 5.20, and is summarized in Figure 5.45. This configuration uses gross wing reference wing area. Trim drag is zero since the wing, at the cruise design point, has zero pitching moment.

Table 5.20 – 765-097 High Speed Buildup

Configuration	765-097
SWEEP (DEG)	27.7
T/C-AVE	0.1312
AIRFOIL TYPE	CONVENTIONAL
F BUILD-UP (FT^2)	
FUSELAGE	0.0000
WING	29.2743
WINGLET	0.2365
HORIZONTAL	0.4800
VERTICAL	0.9025
N&P	2.9900
CANOPY	0.0000
GEAR PODS	0.0000
ETC BEFORE SUB	-5.7256
EXCRESCENCE	2.2808
INTERFERENCE	0.0000
UPSWEEP	0.0000
WING TWIST	0.0000
STRAKES	0.0000
ETC AFTER SUB	0.0000
FUSELAGE BUMP	0.0000
F-TOTAL (FT^2)	**30.4384**
E-VISC	0.965
CRUISE CD BUILD-UP	
M-CRUISE	0.74
CL-CRUISE	0.3
CRUISE ALTITUDE	35000
CD0	0.00596
CDI	0.00468
CDC	0.00063
CDTRIM	0.00000
CDTOT	0.01127
L/D	**26.611**
ML/D	**19.692**

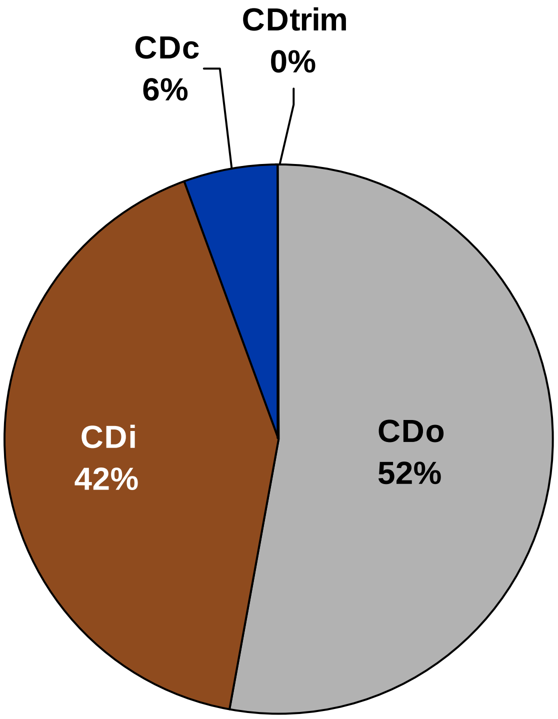


Figure 5.45 – 765-097 High Speed Buildup

The ETC BEFORE SUB category includes technology projections of natural laminar flow over a portion of the wing and verticals as well as riblets applied to the turbulent portion of the wing and body, as illustrated in Figure 5.46. ETC AFTER SUB is not used in this case because the configuration does not need advanced supercritical airfoils like the other advanced concepts. The M * L / D for the configuration is shown in Figure 5.47.

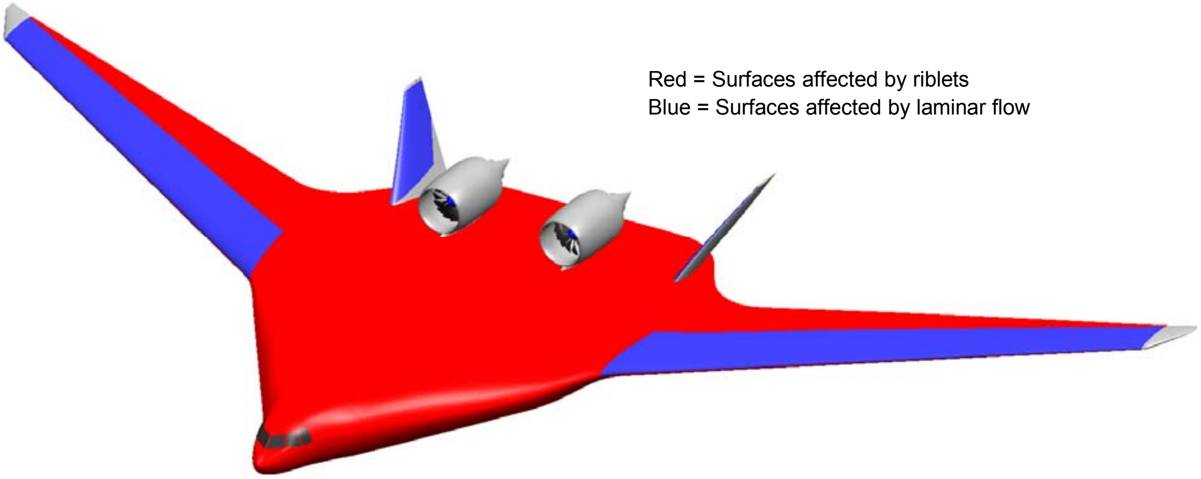


Figure 5.46 – 765-097 - Aerodynamic Technologies Application

The resulting high speed data is shown in Figure 5.47. The figure illustrates the maximum aerodynamic efficiency (M*L/D) occurring at a cruise Mach of 0.74 and a CL of 0.30 which is very close to the Mach 0.7 cruise point.

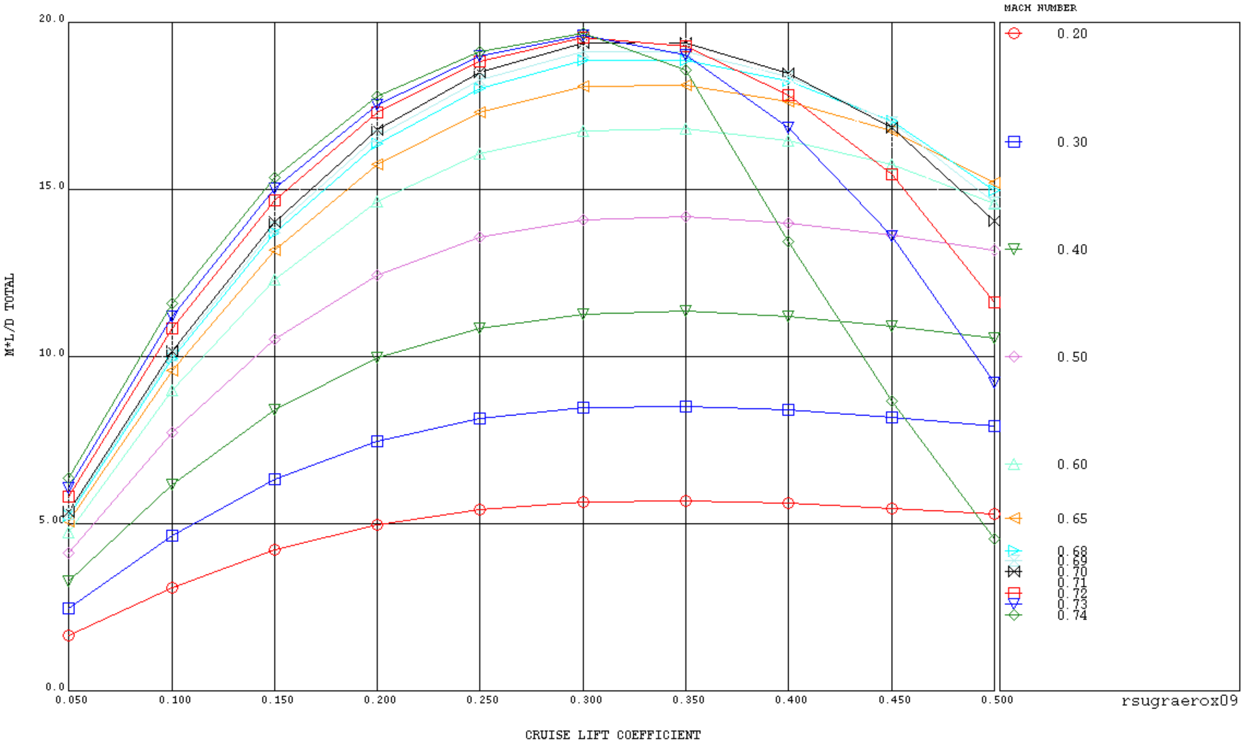


Figure 5.47 – 765-097 - M * L / D Total

Low Speed:

Figure 5.48 through Figure 5.50 show the low speed characteristics for SUGAR Ray. Low speed data are trimmed as a function of angle of attack, lift coefficient, and drag coefficient at near zero elevon deflections. Low speed high lift devices on wing leading and trailing edges are deployed.

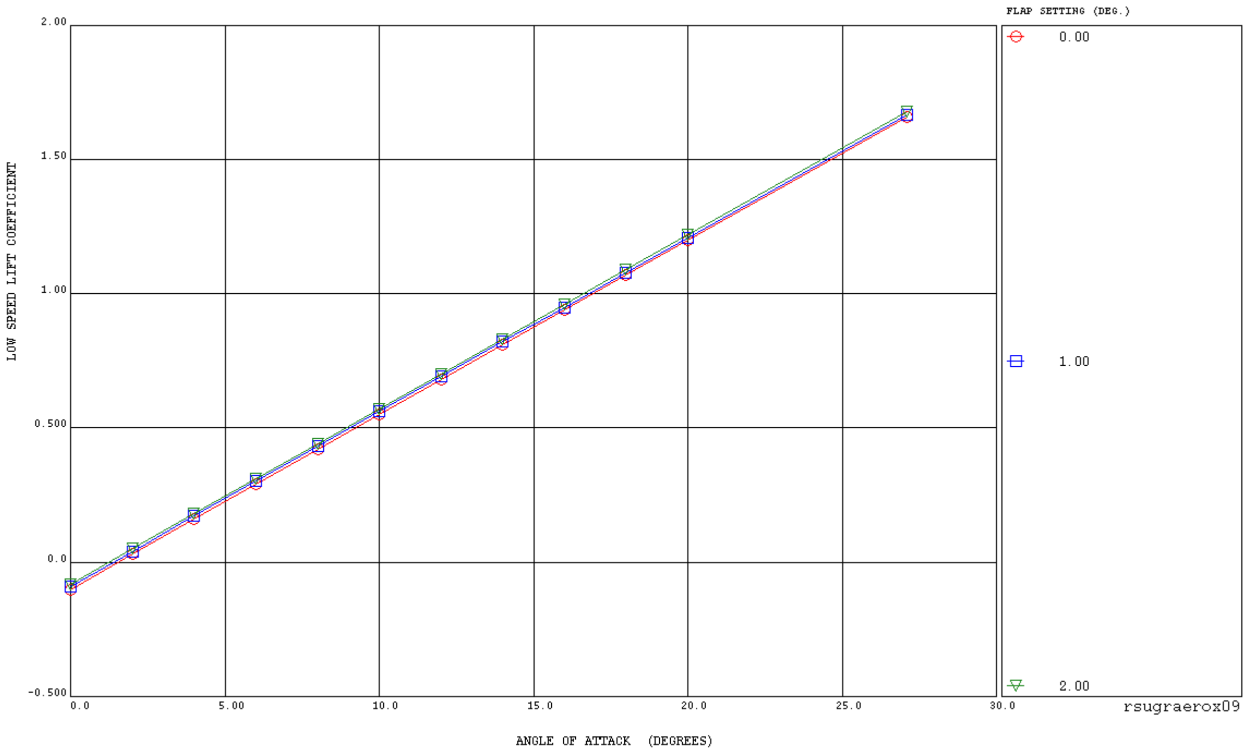


Figure 5.48 – 765-097 - Low Speed Lift Curve; Free Air

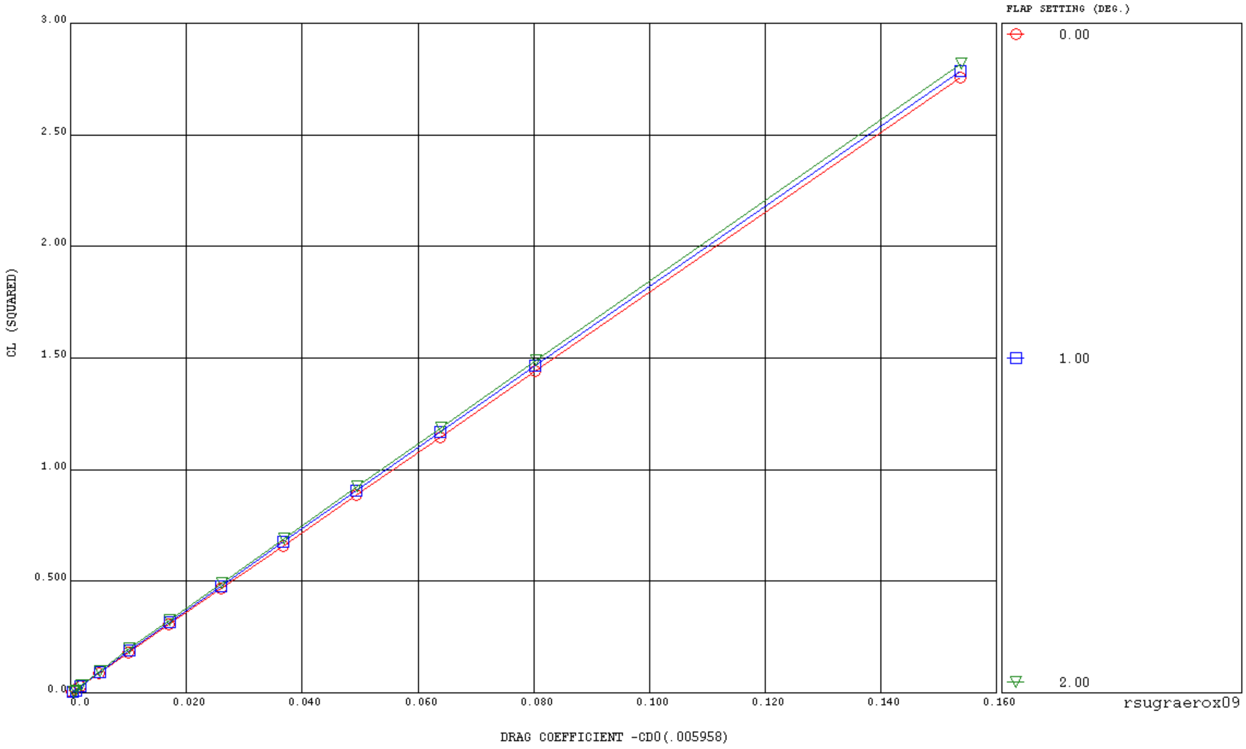


Figure 5.49 – 765-097 - Low Speed Polar; Free Air

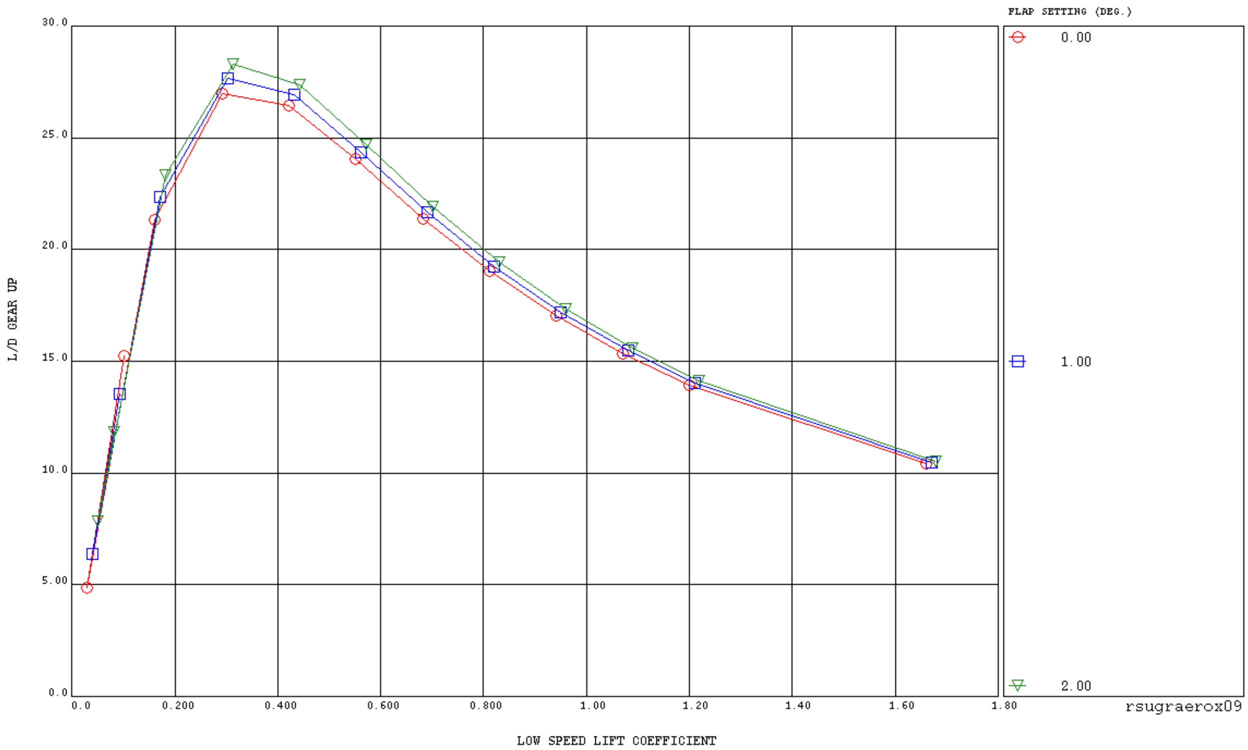


Figure 5.50 – 765-097 - Low Speed Lift / Drag; Free Air

5.7.3 – Mass Properties

The SUGAR Ray configuration was estimated by applying the N+3 weight reduction factors to a calibrated BWB model. Table 5.21 and Figure 5.51 show the group weights and their percentages of TOGW.

Table 5.21 – 765-097 Group Weight Statement

GROUP	WEIGHT (LB)	% TOGW
WING	**12,500**	**6.8**
TAIL	**904**	**0.5**
BODY	**41,137**	**22.5**
LANDING GEAR	**7,198**	**3.9**
PROPULSION	**15,918**	**8.7**
ENGINE, NACELLE, PYLON	14,192	7.8
ENGINE SYSTEM	400	0.2
FUEL SYSTEM	1,326	0.7
FLIGHT CONTROLS	**6,015**	**3.3**
ELECTRICAL	**3,346**	**1.8**
INSTRUMENTS	**1,079**	**0.6**
AVIONICS & AUTOPILOT	**3,225**	**1.8**
FURNISHINGS & EQUIPMENT	**9,080**	**5.0**
PNEUMATICS, AIR CONDITIONING, APU	**3,553**	**1.9**
ANTI-ICING	**186**	**0.1**
MANUFACTURER'S EMPTY WEIGHT (MEW)	**104,142**	**57.1**
OPERATIONAL ITEMS	6,350	3.5
OPERATING EMPTY WEIGHT (OEW)	**110,493**	**60.5**
USEABLE FUEL	35,582	19.5
PAYLOAD	36,425	20.0
TAKEOFF GROSS WEIGHT (TOGW)	**182,500**	**100.0**

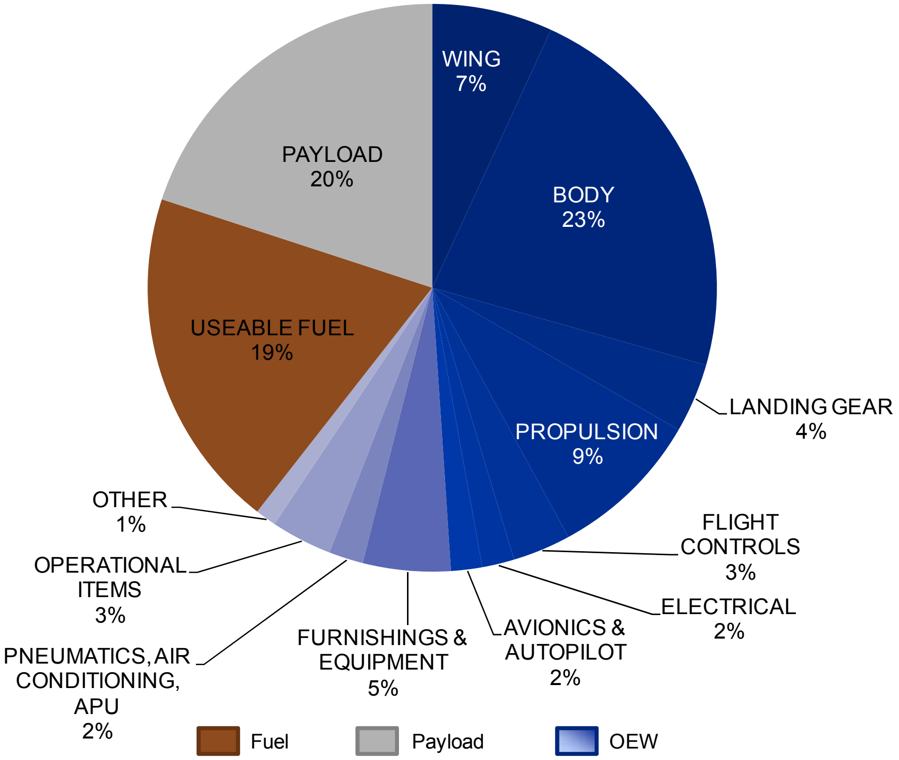


Figure 5.51 – 765-097 Weight Summary

5.7.4 – Engine Data – “gFan+”

The HWB configuration uses the same “gFan+” engine as SUGAR High which is discussed in Section 5.5.4.

6.0 – Vehicle Performance and Environmental Impact

6.1 – Performance and Noise Analysis Methods and Ground Rules

The performance analysis methods and ground rules are discussed in the subsections below. For a definition of the payload-range requirements please reference Table 2.2 and Figure 5.1.

6.1.1 – Performance Analysis Tools

The Boeing Mission Analysis Program (BMAP) is the principal tool used by Boeing Commercial Airplanes (BCA) to calculate mission performance such as payload, range, or fuel burn. It can analyze missions of varying complexity and has been validated to actual airplane performance. It has the capability to model complex tracks with enroute and alternate waypoints and complex profiles with multiple cruise segments including step and cruise climbs. It will calculate airplane performance including redispatch, through-stop, radius, and extended-range twin-engine operations (ETOPS) capability.

Use of the Low Speed Performance System (LSPS) provides field length analysis. LSPS can calculate takeoff performance at any specified atmospheric condition (altitude and temperature within its atmospheric model) and includes One Engine Inoperative (OEI) in its calculations. Like BMAP, it is calibrated to existing commercial airplanes.

Vehicle performance and sizing is performed with Boeing's Aircraft Design Navigator (ADNav) which encapsulates both mission performance (BMAP) and airfield performance calculations (LSPS). It provides the capability to scale engine thrust and wing area and provides the ability to size airplanes to their optimum sizes given a set of constraints (such as TOFL, ICAC, time and distance to climb, etc). It also provides some data visualization tools.

The sizing process is illustrated in Figure 6.1

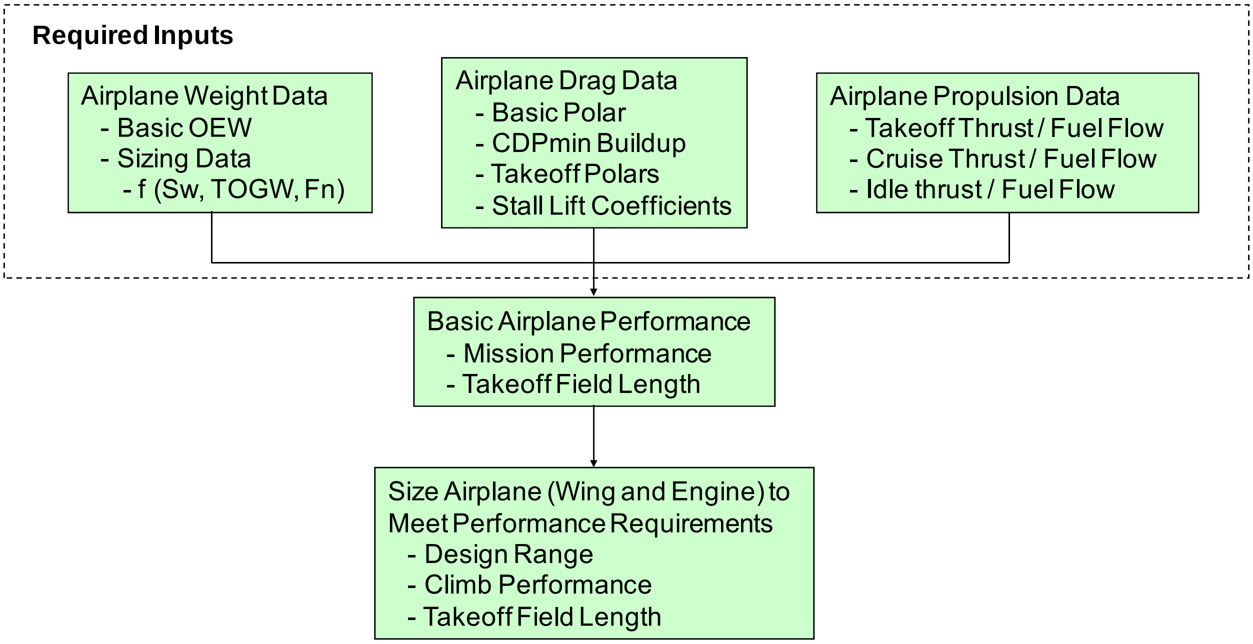


Figure 6.1 – Airplane Sizing Using ADNav

It should be noted that BCA uses reference Wimpress area as the reference area for non-dimensional quantities.

6.1.2 – Mission Profiles

The future scenario (discussed in Section 2.0) was used to generate the desired vehicle characteristics (Table 2.2). These characteristics, along with the payload range requirements (discussed in Section 5.1) and the mission profiles outlined in this section, are used for vehicle sizing.

Future Ground and Air Traffic Management systems will allow for reduced mission fuel burn, emissions, and noise. The current environment introduces delays and mission inefficiencies into the system, which in the future can be eliminated. In addition, future predictive technologies and real-time mission optimization will allow for a higher confidence level in completing the mission as planned.

Mission Profiles have been developed to approximate the difference between an airplane operating in the current environment, versus an airplane operating in the future environment. Differences between the two profiles are shown in Table 6.1.

A schematic of the 2008 Reference Mission Profile is shown in Figure 6.2, and a schematic of the 2030 Mission Profile is shown in Figure 6.3. The sizing payload is the low density seats (dual class) at 200 pounds per passenger at the maximum range specified in Table 2.2 and Figure 5.1. The still air range of Figure 6.2 is five percent longer than the maximum range shown in Table 2.2 while in Figure 6.3 they are the same.

Table 6.1 – Mission Changes due to NextGen ATM

	2008 Mission Profile Figure 6.2	**2030 Mission Profile** Figure 6.3
Mission		
Taxi Out	Airport congestion and queues at runways increase airplane idle time while waiting to takeoff	Better Ground Traffic Management allows airplane to taxi directly from gate to runway
Climb	Air Traffic Management requires airplane to climb at or below 250 kts below 10,000 ft altitude. Traditional time and distance to climb requirements.	Airplane is allowed to climb at optimum fuel burn speed below 10,000 ft altitude. No time and distance to climb requirements.
Cruise	Air Traffic Management requires an airplane to fly specific altitudes and tracks which may not be optimum, this increases fuel burn and flight distance to destination. 5% increase in range is assumed.	Free Flight allows airplane to real-time optimize airplane altitude and speed in 4D to minimize track distance and fuel burn while maintaining safe separation distances
Descent	Air Traffic Management may require an airplane to descend in a non-optimum flight path, potentially leveling off at different altitudes and having to increase thrust. This is modeled with an additional 12 minute loiter. Air Traffic Management requires airplane to descend at or below 250 kts below 10,000 ft altitude	Tailored Arrivals allow for continuous idle descent approaches optimized for fuel burn in a 4D environment
Taxi In	Airport congestion and waiting for gates to clear increase time airplane idles while waiting to unload	Better Ground Traffic Management allows airplane to taxi directly from runway to gate
Reserves		
Flight Fuel Allowance	Assumed 5% flight fuel allowance for contingencies	Better enroute weather and track predictions, along with 4D flight optimization, allow airline to decrease contingency fuel to 3%
Climb	Air Traffic Management requires airplane to climb at or below 250 kts below 10,000 ft altitude	Airplane is allowed to climb at optimum fuel burn speed below 10,000 ft altitude
Descent	Air Traffic Management requires airplane to descend at or below 250 kts below 10,000 ft altitude	Airplane is allowed to descend at optimum fuel burn speed below 10,000 ft altitude
Hold	Assumed 30 minute hold time allowance at alternate for contingencies	Better weather and track predictions allow airline to decrease hold time allowance at alternate to 10 minutes
Note: Segments not listed indicate no change between profiles.		

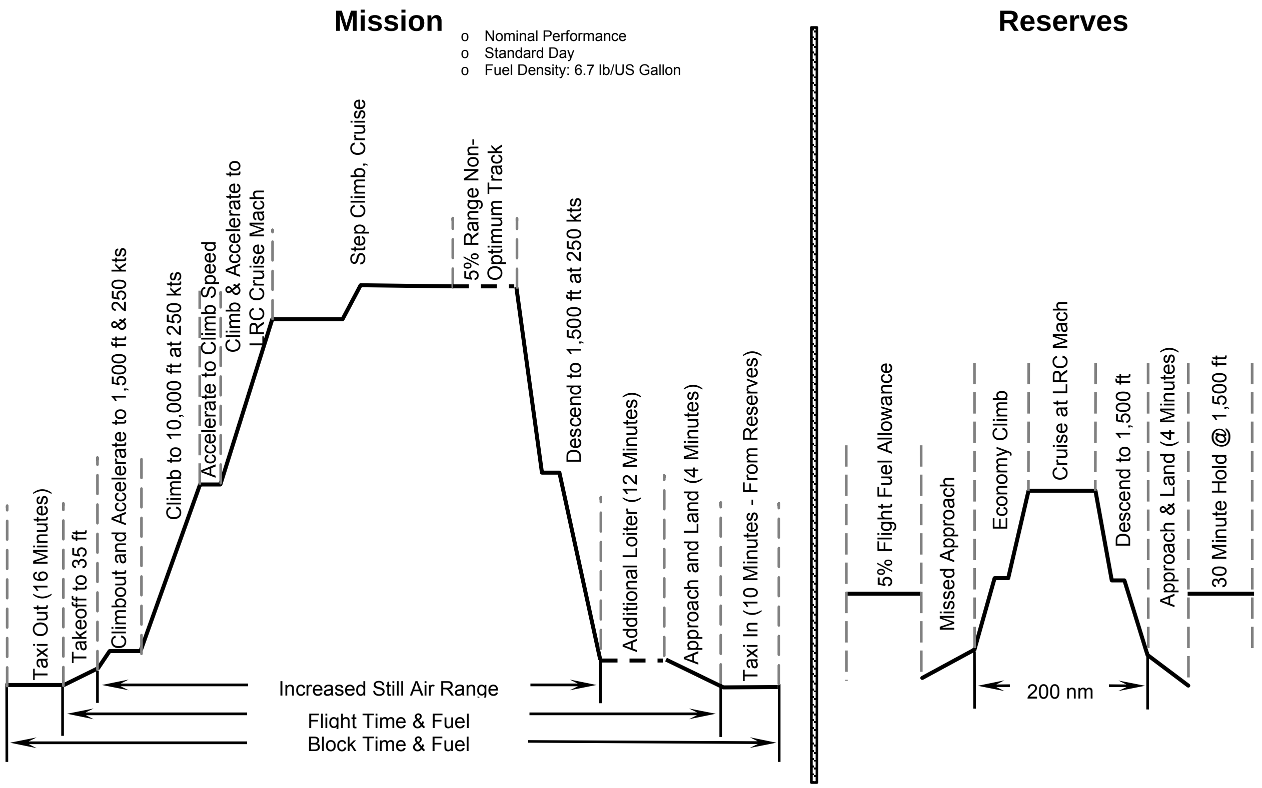


Figure 6.2 – 2008 Reference Mission Profile

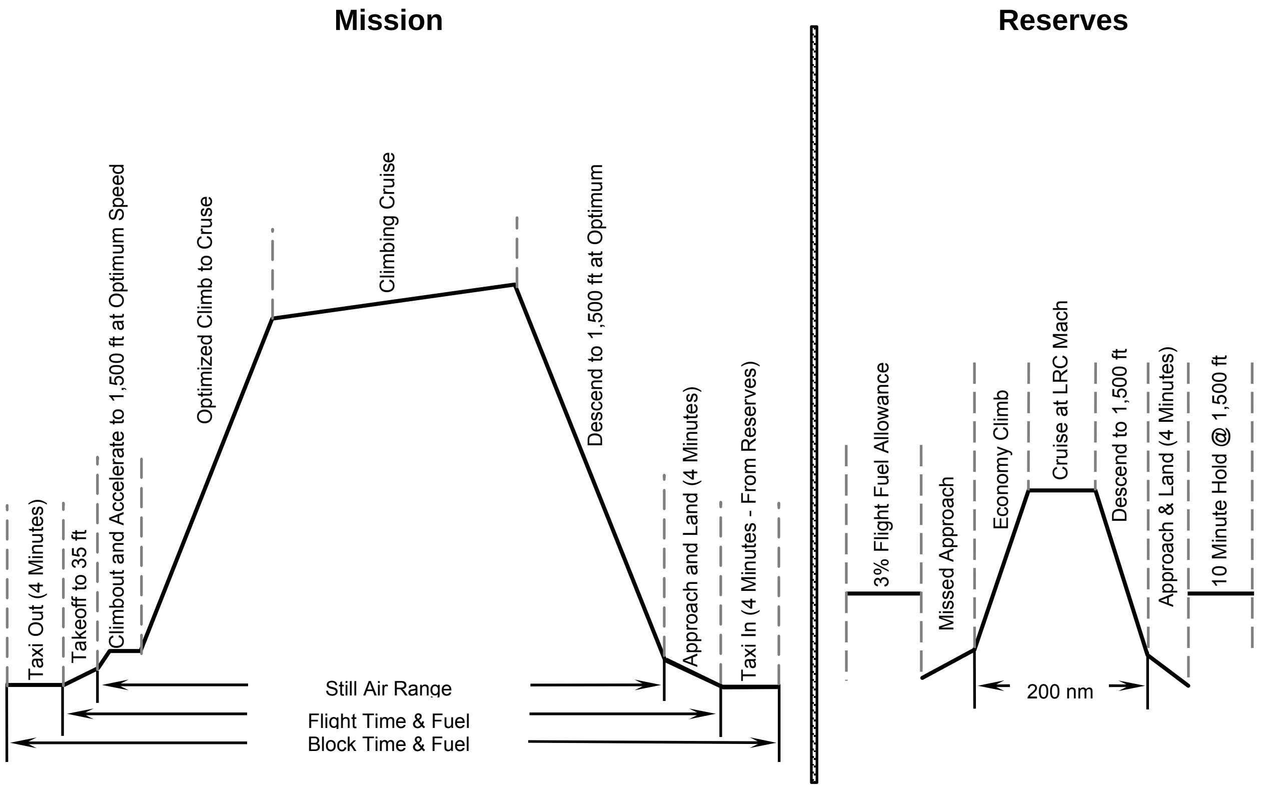


Figure 6.3 – 2030 Mission Profile with NextGen Air Traffic Management

6.1.3 – DNL Contour Methods

The process for developing DNL contours for the concept aircraft has been established. A generic airport, similar to Cleveland Hopkins International Airport, was selected. This enables model calibration to actual Cleveland airport noise data, but allows additional flexibility in establishing the airport boundaries and defining the airport scenarios. Cleveland is an airport that has a recent Noise Exposure Map (NEM) approved by FAA and this airport has an appropriate fleet mix that contains a significant number of medium sized aircraft that are being evaluated in the SUGAR study. The future scenario supplies the fleet mix and generation mix for today, 2030, and in the future when N+3 aircraft will be present in large numbers.

Noise Power Distance (NPD) information for the current aircraft in the fleet mix, the expected fleet mix in 2030, 2055, and an all N+3 technology aircraft fleet was generated. An Integrated Noise Model (INM) was then used to generate 55, 60, and 65 DNL contours and compare the contours for the different fleet scenarios. Sensitivities to fleet size and N+3 fleet replacement percentage were also generated.

Initial calculations were made using 2008 Cleveland noise data, and the model has been calibrated to match these results (Figure 6.4). The noise performance of all five concept aircraft was estimated to allow a comparison between the concepts. The noise signature for the SUGAR Ray low noise configuration, and how it performs relative to the NASA noise goals was studied in detail.

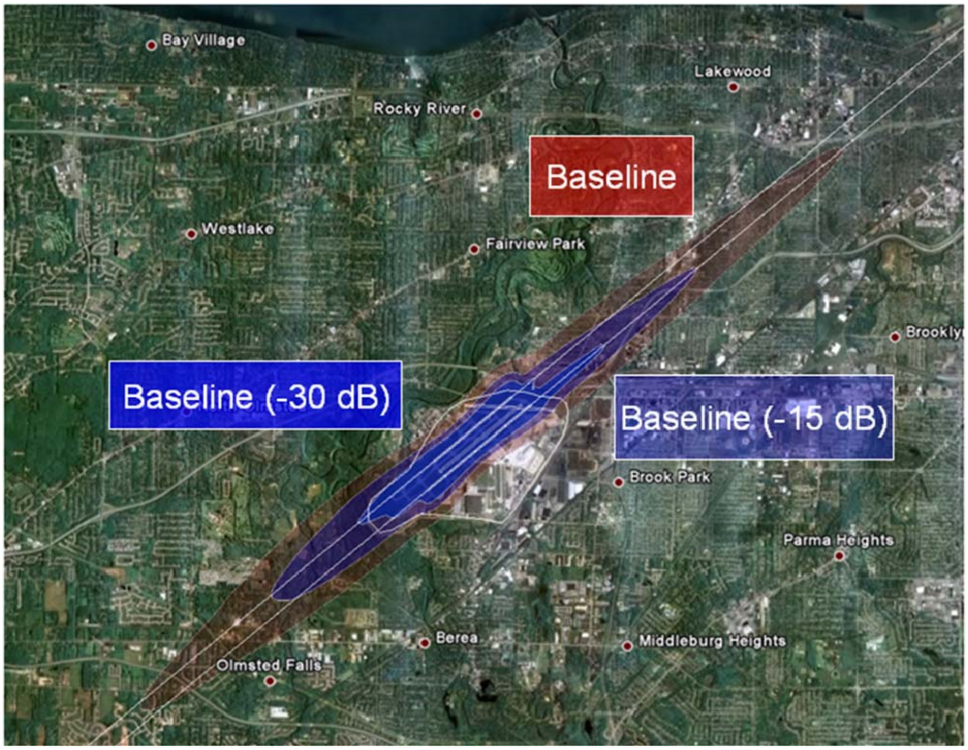


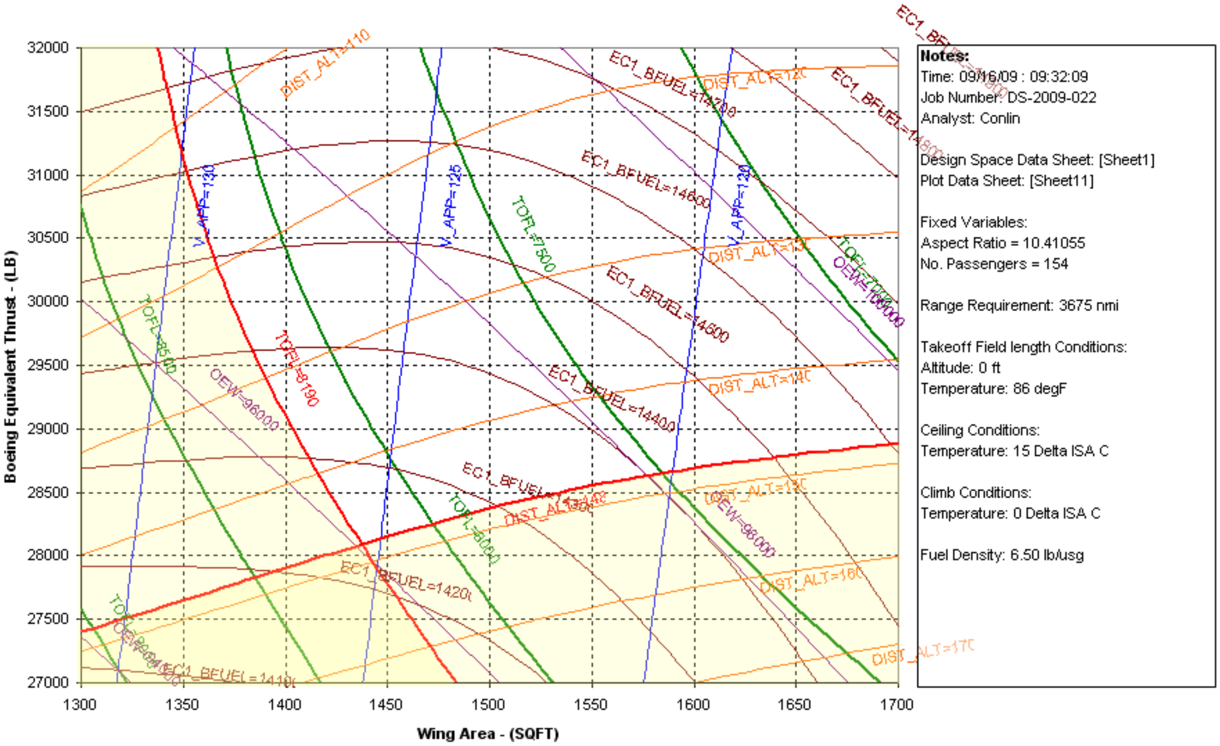
Figure 6.4 – Noise Methods Calibrated to Airport Data

6.2 – Vehicle Performance and Sizing

765-093 – SUGAR Free:

The reference 2008 performance level airplane is known as “SUGAR Free”. SUGAR Free was sized to provide a 3,500 nmi range with 154 passengers @ 200 lb / passenger dual-class payload (design range). SUGAR Free performance is quoted using the 2008 Reference Mission Profile.

The SUGAR Free sizing chart is shown in Figure 6.5. The chart represents a matrix of airplane performance variation as airplane wing area and engine scale vary, while design range is held constant. The x-axis is wing area variation, and the y-axis is engine scale variation. Plotted on the chart are contour lines of constant takeoff field length, distance to altitude, approach speed, Operational Empty Weight (OEW), and block fuel / seat on a 500 nmi mission. Constraint lines of takeoff field length ~ 8,200 ft at Maximum Takeoff Weight (MTOW), at Sea Level, on an 86° day, and a distance to climb to 35,000 ft after a takeoff at Maximum Takeoff Weight (MTOW) on a Standard Day are also plotted in red. These two constraints were chosen as representative of the performance level of airplanes in service today, and the intersection of those two constraints was used as the wing and thrust sizing point for SUGAR Free. All other performance levels, as shown in Table 6.2, were a fallout from these two constraints.



Notes:
Time: 09/16/09 : 09:32:09
Job Number: DS-2009-022
Analyst: Conlin

Design Space Data Sheet: [Sheet1]
Plot Data Sheet: [Sheet11]

Fixed Variables:
Aspect Ratio = 10.41055
No. Passengers = 154

Range Requirement: 3675 nmi

Takeoff Field length Conditions:
Altitude: 0 ft
Temperature: 86 degF

Ceiling Conditions:
Temperature: 15 Delta ISA C

Climb Conditions:
Temperature: 0 Delta ISA C

Fuel Density: 6.50 lb/usg

Figure 6.5 – 765-093 Sizing

Table 6.2 – 765-093 - SUGAR Baseline Sizing

MODEL Sizing Level		SUGAR Free
PASSENGERS / CLASS		154 / Dual
MAX TAKEOFF WEIGHT	LB	184,800
MAX LANDING WEIGHT	LB	151,000
MAX ZERO FUEL WEIGHT	LB	142,000
OPERATING EMPTY WEIGHT	LB	96,000
FUEL CAPACITY REQ	USG	9,710
ENGINE MODEL		Scaled CFM56-7B27
FAN DIAMETER	IN	62
BOEING EQUIVLENT THRUST (BET)	LB	28,200
WING AREA / SPAN	FT^2 / FT	1429 / 122
ASPECT RATIO (EFFECTIVE)		10.41
OPTIMUM CL		0.583
CRUISE L/D @ OPT CL		18.068
DESIGN MISSION RANGE	NMI	3,500
PERFORMANCE CRUISE MACH		0.785
LONG RANGE CRUISE MACH (LRC)		0.785
THRUST ICAC (MTOW, ISA)	FT	37,200
TIME / DIST (MTOW, 35k FT, ISA)	MIN / NMI	23 / 148
OPTIMUM ALTITUDE (MTOW, ISA)	FT	35,000
BUFFET ICAC (MTOW, ISA)	FT	36,200
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	8,190
APPROACH SPEED (MLW)	KT	126
BLOCK FUEL / SEAT (900 NMI)	LB	92.35

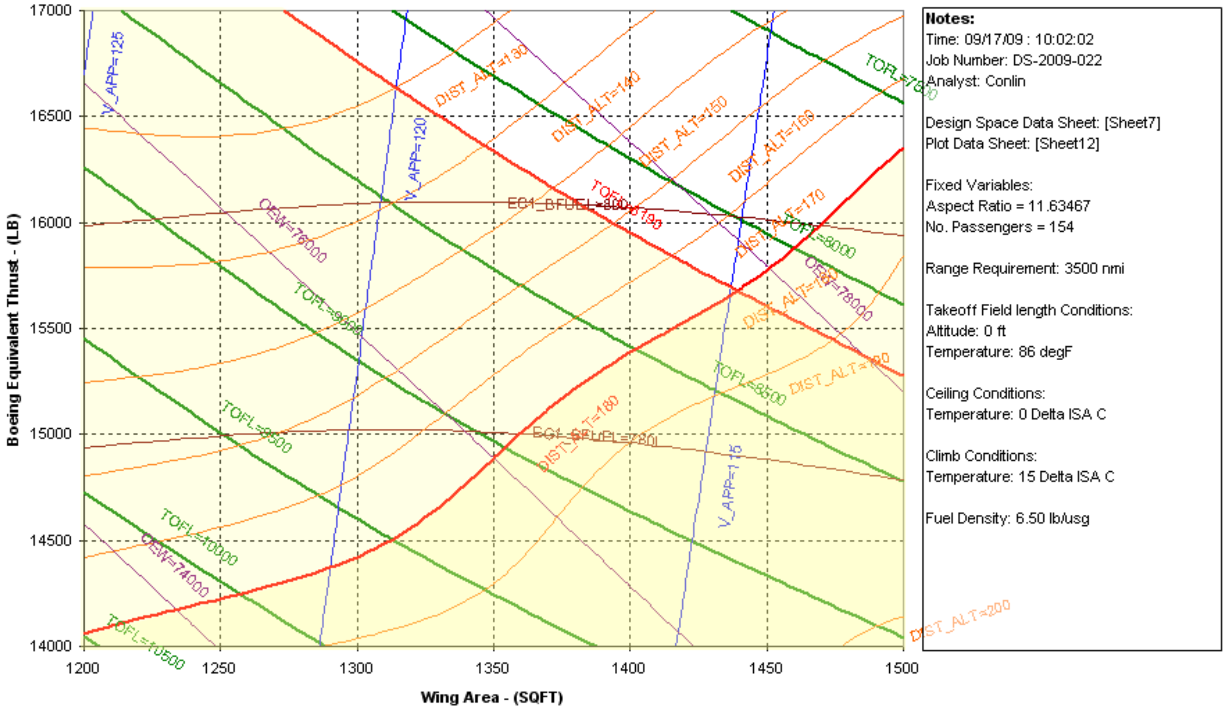
A trade was done to quantify the block fuel benefit of changing from the 2008 Reference Mission Profile to the 2030 Mission profile using SUGAR Free as the base airplane. The trade was done by changing the mission profile in BMAP, rerunning the performance, and resizing the airplane. The airplane wing and engine were sized using the same procedure and constraints as were used in sizing the base SUGAR Free. A comparison of the airplane using the 2008 Reference Mission Profile versus an airplane using the 2030 Mission Profile is shown in Table 6.3. Comparing the two airplane performance levels, one can see design range, distance to climb, and takeoff field length are constant between the two airplanes, while block fuel / seat is improved 17.5% using the 2030 Mission Rules, and the airplane is altogether smaller and lighter.

Table 6.3 – 765-093 – SUGAR Free Mission Profile Trade

MODEL Sizing Level		N Reference Mission	N+3 Reference Mission
PASSENGERS / CLASS		154 / Dual	154 / Dual
MAX TAKEOFF WEIGHT	LB	184,800	173,300
MAX LANDING WEIGHT	LB	151,000	147,500
MAX ZERO FUEL WEIGHT	LB	142,000	138,500
OPERATING EMPTY WEIGHT	LB	96,000	92,500
FUEL CAPACITY REQ	USG	9,710	8,414
ENGINE MODEL		Scaled CFM56-7B27	Scaled CFM56-7B27
FAN DIAMETER	IN	62	61
BOEING EQUIVLENT THRUST (BET)	LB	28,200	26,800
WING AREA / SPAN	FT^2 / FT	1429 / 122	1314 / 117
ASPECT RATIO (EFFECTIVE)		10.41	10.41
OPTIMUM CL		0.583	0.589
CRUISE L/D @ OPT CL		18.068	17.695
DESIGN MISSION RANGE	NMI	3,500	3,500
PERFORMANCE CRUISE MACH		0.785	0.785
LONG RANGE CRUISE MACH (LRC)		0.785	0.785
THRUST ICAC (MTOW, ISA)	FT	37,200	37,100
TIME / DIST (MTOW, 35k FT, ISA)	MIN / NMI	23 / 148	22 / 148
OPTIMUM ALTITUDE (MTOW, ISA)	FT	35,000	34,700
BUFFET ICAC (MTOW, ISA)	FT	36,200	35,700
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	8,190	8,190
APPROACH SPEED (MLW)	KT	126	130
BLOCK FUEL / SEAT (900 NMI)	LB	92.35 (Base)	76.14 (-17.5%)

765-094 – Refined SUGAR:

“Refined SUGAR” is a high technology version of the SUGAR Free configuration. A list of technologies included in Refined SUGAR is contained in Section 4.0. Refined SUGAR was sized using the same procedure as was used for SUGAR Free, the one change being the distance to climb constraint was relaxed to 182 nmi from 148 nmi, as will be the case for all the remaining airplanes. This change results in an airplane sized with a relatively larger wing area, but smaller engine, and an overall block fuel / seat benefit compared to an airplane that climbs faster. Figure 6.6 shows the sizing chart, and the resultant sizing point for the Refined SUGAR configuration. Table 6.4 details the performance characteristics of Refined SUGAR. The airplane, with increased airframe and engine technology, and using the 2030 mission profile shows a 44.2% block fuel / seat benefit relative to SUGAR free.



Notes:
Time: 09/17/09 : 10:02:02
Job Number: DS-2009-022
Analyst: Conlin

Design Space Data Sheet: [Sheet7]
Plot Data Sheet: [Sheet12]

Fixed Variables:
Aspect Ratio = 11.63467
No. Passengers = 154

Range Requirement: 3500 nmi

Takeoff Field length Conditions:
Altitude: 0 ft
Temperature: 86 degF

Ceiling Conditions:
Temperature: 0 Delta ISA C

Climb Conditions:
Temperature: 15 Delta ISA C

Fuel Density: 6.50 lb/usg

Figure 6.6 – 765-094 Sizing

Table 6.4 – 765-094 - Refined SUGAR Baseline Sizing

MODEL Sizing Level		Refined SUGAR
PASSENGERS / CLASS		154 / Dual
MAX TAKEOFF WEIGHT MAX LANDING WEIGHT MAX ZERO FUEL WEIGHT OPERATING EMPTY WEIGHT FUEL CAPACITY REQ	LB LB LB LB USG	139,700 131,800 123,800 77,800 5,512
ENGINE MODEL FAN DIAMETER BOEING EQUIVLENT THRUST (BET)	 IN LB	Scaled gFan 66 15,700
WING AREA / SPAN ASPECT RATIO (EFFECTIVE) OPTIMUM CL CRUISE L/D @ OPT CL	FT^2 / FT	1440 / 129 11.63 0.654 21.981
DESIGN MISSION RANGE PERFORMANCE CRUISE MACH LONG RANGE CRUISE MACH (LRC) THRUST ICAC (MTOW, ISA) TIME / DIST (MTOW, 35k FT, ISA) OPTIMUM ALTITUDE (MTOW, ISA) BUFFET ICAC (MTOW, ISA) TOFL (MTOW, SEA LEVEL, 86 DEG F) APPROACH SPEED (MLW)	NMI FT MIN / NMI FT FT FT KT	3,500 0.70 0.70 38,800 29 / 182 38,400 45,200 8,190 115
BLOCK FUEL / SEAT (900 NMI)	LB	51.53

Engine size is primarily due to takeoff field length and time and distance to climb constraints. Takeoff thrust required can be reduced with larger wing area, resulting in lower fuel burn, however using wing area to reduce thrust required will result in an airplane with increased time and distance to climb. This trend can be seen in the Table 6.5 sizing chart for Refined SUGAR.

One of the considerations which drives up thrust requirements for time and distance to climb, are Air Traffic Control (ATC) constraints which may restrict an airplane to lower than optimum altitude if the airplane does not climb to optimum altitude quickly enough. The future ATC environment should alleviate this consideration and allow engines to size down accordingly. This change in time and distance to climb requirements results in a 1.1% block fuel / seat benefit as shown in Table 6.5.

Table 6.5 – 765-094 – Refined SUGAR Time and Distance to Climb Trade

MODEL Sizing Level		Meet SUGAR Free Climb Performance	Relax Climb Requirement
PASSENGERS / CLASS		154 / Dual	154 / Dual
MAX TAKEOFF WEIGHT	LB	139,800	139,700
MAX LANDING WEIGHT	LB	131,500	131,800
MAX ZERO FUEL WEIGHT	LB	123,500	123,800
OPERATING EMPTY WEIGHT	LB	77,500	77,800
FUEL CAPACITY REQ	USG	5,582	5,512
ENGINE MODEL		Scaled gFan	Scaled gFan
FAN DIAMETER	IN	68	66
BOEING EQUIVLENT THRUST (BET)	LB	16,200	15,700
WING AREA / SPAN	FT^2 / FT	1367 / 126	1440 / 129
ASPECT RATIO (EFFECTIVE)		11.63	11.63
OPTIMUM CL		0.659	0.654
CRUISE L/D @ OPT CL		21.639	21.981
DESIGN MISSION RANGE	NMI	3,500	3,500
PERFORMANCE CRUISE MACH		0.70	0.70
LONG RANGE CRUISE MACH (LRC)		0.70	0.70
THRUST ICAC (MTOW, ISA)	FT	39,100	38,800
TIME / DIST (MTOW, 35k FT, ISA)	MIN / NMI	24 / 152	29 / 182
OPTIMUM ALTITUDE (MTOW, ISA)	FT	37,400	38,400
BUFFET ICAC (MTOW, ISA)	FT	44,100	45,200
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	8,190	8,190
APPROACH SPEED (MLW)	KT	118	115
BLOCK FUEL / SEAT (900 NMI)	LB	52.08 (Base)	51.53 (-1.1%)

General Electric (GE) provided data for several engines, the engine used on the Refined SUGAR was a high technology advanced turbofan labeled the gFan. Another version of the engine, the gFan+, was a higher technology advanced turbofan. Table 6.6 compares the Refined SUGAR airplane to an airplane sized using the higher technology gFan+. While the gFan+ has a larger diameter, i.e. higher drag, and a higher bare engine weight, the improved Specific Fuel Consumption (SFC) of the engine more than offsets these penalties, and the airplane sized with the gFan+ has a 6.2% block fuel / seat benefit compared to the airplane sized with the basic gFan.

Table 6.6 – 795-094 – Refined SUGAR Advanced Engine Trade

MODEL Sizing Level		Refined SUGAR	Refined SUGAR gFan+ Engine
PASSENGERS / CLASS		154 / Dual	154 / Dual
MAX TAKEOFF WEIGHT	LB	139,700	139,500
MAX LANDING WEIGHT	LB	131,800	133,600
MAX ZERO FUEL WEIGHT	LB	123,800	125,600
OPERATING EMPTY WEIGHT	LB	77,800	79,600
FUEL CAPACITY REQ	USG	5,512	5,208
ENGINE MODEL		Scaled gFan	Scaled gFan+
FAN DIAMETER	IN	66	76
BOEING EQUIVLENT THRUST (BET)	LB	15,700	15,300
WING AREA / SPAN	FT^2/ FT	1440 / 129	1407 / 128
ASPECT RATIO (EFFECTIVE)		11.63	11.63
OPTIMUM CL		0.654	0.708
CRUISE L/D @ OPT CL		21.981	21.428
DESIGN MISSION RANGE	NMI	3,500	3,500
PERFORMANCE CRUISE MACH		0.70	0.70
LONG RANGE CRUISE MACH (LRC)		0.70	0.70
THRUST ICAC (MTOW, ISA)	FT	38,800	40,100
TIME / DIST (MTOW, 35k FT, ISA)	MIN/ NMI	29 / 182	29 / 186
OPTIMUM ALTITUDE (MTOW, ISA)	FT	38,400	39,600
BUFFET ICAC (MTOW, ISA)	FT	45,200	44,800
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	8,190	8,190
APPROACH SPEED (MLW)	KT	115	117
BLOCK FUEL / SEAT (900 NMI)	LB	51.53 (Base)	48.31 (-6.2%)

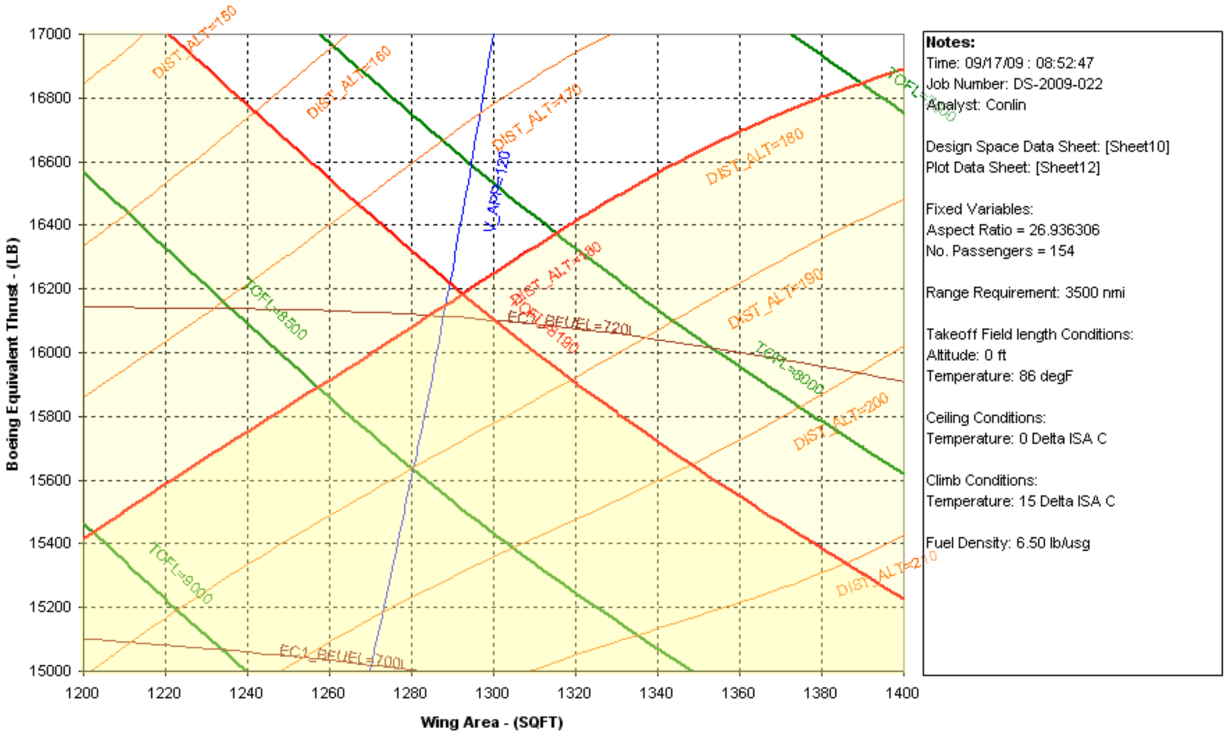
As stated previously, the airplane requirement for TOFL was ~ 8,200 ft at MTOW. Designing an airplane to be able to utilize smaller metroplex airports, i.e. ones with shorter field lengths, would result in an airplane which required more thrust and wing area, and hence pay a penalty in block fuel / seat. This penalty is quantified in Table 6.7. Operationally, an airplane can takeoff from smaller fields, as noted by quoting the 900 nmi takeoff weight mission takeoff field length without paying this penalty, but would need to reduce payload, or range, or both. Alternately, the high lift system can be made more powerful to reduce field lengths, with potentially less fuel burn penalty, but this option has not been explored in this study.

Table 6.7 – 795-094 – Refined SUGAR Takeoff Field Length Trade

MODEL Sizing Level		+500 ft	Base TOFL	-500 ft	-1,000 ft
PASSENGERS / CLASS		154 / Dual	154 / Dual	154 / Dual	154 / Dual
MAX TAKEOFF WEIGHT	LB	138,400	139,700	141,200	142,900
MAX LANDING WEIGHT	LB	130,800	131,800	132,900	134,300
MAX ZERO FUEL WEIGHT	LB	122,800	123,800	124,900	126,300
OPERATING EMPTY WEIGHT	LB	76,800	77,800	78,900	80,300
FUEL CAPACITY REQ	USG	5,457	5,512	5,571	5,615
ENGINE MODEL		Scaled gFan	Scaled gFan	Scaled gFan	Scaled gFan
FAN DIAMETER	IN	65	66	68	69
BOEING EQUIVLENT THRUST (BET)	LB	15,100	15,700	16,300	16,700
WING AREA / SPAN	FT^2/ FT	1400 / 128	1440 / 129	1490 / 132	1580 / 136
ASPECT RATIO (EFFECTIVE)		11.63	11.63	11.63	11.63
OPTIMUM CL		0.660	0.654	0.652	0.653
CRUISE L/D @ OPT CL		21.874	21.981	22.109	22.374
DESIGN MISSION RANGE	NMI	3,500	3,500	3,500	3,500
PERFORMANCE CRUISE MACH		0.70	0.70	0.70	0.70
LONG RANGE CRUISE MACH (LRC)		0.70	0.70	0.70	0.70
THRUST ICAC (MTOW, ISA)	FT	38,400	38,800	39,500	40,100
TIME / DIST (MTOW, 35k FT, ISA)	MIN/ NMI	30 / 189	29 / 182	28 / 177	29 / 168
OPTIMUM ALTITUDE (MTOW, ISA)	FT	38,400	38,400	38,800	39,900
BUFFET ICAC (MTOW, ISA)	FT	45,100	45,200	45,700	46,800
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	8,680	8,190	7,690	7,190
TOFL (900 NMI MISS, SEA LEVEL, 86 DEG F)	FT	5,790	5,510	5,240	4,940
APPROACH SPEED (MLW)	KT	116	115	113	111
BLOCK FUEL / SEAT (900 NMI)	LB	50.84 (-1.3%)	51.53 (Base)	52.29 (+1.5%)	52.97 (+2.8%)

765-095 – SUGAR High:

“SUGAR High”, is a strut-braced, large span, high wing airplane configuration utilizing the gFan+ engine, and increased technology beyond the Refined SUGAR as defined in Section 4.0. SUGAR High was sized using the same process, mission profile, and performance requirements, as Refined SUGAR. The SUGAR High sizing chart is shown in Figure 6.7 uses these assumptions, but this particular sizing chart includes an additional 15,000 lb OEW benefit which is not included in the base SUGAR high shown in Table 6.8. This OEW benefit is further explained in the SUGAR High OEW Trade in Section 5.5.3. While the base SUGAR High utilizes higher technology levels and engines than Refined SUGAR, the block fuel / seat benefit relative to the SUGAR Free airplane is only 38.9%, which is less than the Refined SUGAR value of 44.2%.



Notes:
Time: 09/17/09 : 08:52:47
Job Number: DS-2009-022
Analyst: Conlin

Design Space Data Sheet: [Sheet10]
Plot Data Sheet: [Sheet12]

Fixed Variables:
Aspect Ratio = 26.936306
No. Passengers = 154

Range Requirement: 3500 nmi

Takeoff Field length Conditions:
Altitude: 0 ft
Temperature: 86 degF

Ceiling Conditions:
Temperature: 0 Delta ISA C

Climb Conditions:
Temperature: 15 Delta ISA C

Fuel Density: 6.50 lb/usg

Figure 6.7 – 765-095 Sizing (assumes 15,000 pound weight reduction)

Table 6.8 – 765-095 Baseline Sizing

MODEL Sizing Level		SUGAR High
PASSENGERS / CLASS		154 / Dual
MAX TAKEOFF WEIGHT	LB	176,800
MAX LANDING WEIGHT	LB	167,300
MAX ZERO FUEL WEIGHT	LB	159,300
OPERATING EMPTY WEIGHT	LB	113,300
FUEL CAPACITY REQ	USG	5,754
ENGINE MODEL		Scaled gFan+
FAN DIAMETER	IN	86
BOEING EQUIVLENT THRUST (BET)	LB	19,600
WING AREA / SPAN	FT^2 / FT	1722 / 215
ASPECT RATIO (EFFECTIVE)		26.94
OPTIMUM CL		0.828
CRUISE L/D @ OPT CL		25.934
DESIGN MISSION RANGE	NMI	3,500
PERFORMANCE CRUISE MACH		0.70
LONG RANGE CRUISE MACH (LRC)		0.70
THRUST ICAC (MTOW, ISA)	FT	43,300
TIME / DIST (MTOW, 35k FT, ISA)	MIN / NMI	29 / 182
OPTIMUM ALTITUDE (MTOW, ISA)	FT	42,100
BUFFET ICAC (MTOW, ISA)	FT	44,000
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	8,190
APPROACH SPEED (MLW)	KT	115
BLOCK FUEL / SEAT (900 NMI)	LB	56.43

Much of the block fuel / seat penalty of SUGAR High relative to Refined SUGAR is due to the high wing weight of SUGAR High's large span wing. Currently, there is a lot of uncertainty as to the structural characteristics of this wing, which in turn results in a large uncertainty in the OEW of the airplane. Because of this large uncertainty in wing weight, a trade was done to quantify the spread in potential fuel burn uncertainty for this airplane. The results of this trade are shown in Table 6.9. For the remainder of the performance section, the airplane assumed to have a 15,000 lb weight reduction, as sized in Figure 6.7, will be used as the basis for trades.

Table 6.9 – 765-095 OEW Trade

MODEL Sizing Level		***+5,000 lb***	**Base**	**-5,000 lb**	**-10,000 lb**	**-15,000 lb**	**-20,000 lb**
PASSENGERS / CLASS		*154 / Dual*	154 / Dual	154 / Dual	154 / Dual	154 / Dual	154 / Dual
MAX TAKEOFF WEIGHT	LB	*189,200*	176,800	164,400	152,100	140,100	128,200
MAX LANDING WEIGHT	LB	*177,900*	167,300	156,700	146,200	136,000	125,800
MAX ZERO FUEL WEIGHT	LB	*169,900*	159,300	148,700	138,200	128,000	117,800
OPERATING EMPTY WEIGHT	LB	*123,900*	113,300	102,700	92,200	82,000	71,800
FUEL CAPACITY REQ	USG	*6,038*	5,754	5,470	5,184	4,928	4,658
ENGINE MODEL		*Scaled gFan+*	Scaled gFan+	Scaled gFan+	Scaled gFan+	Scaled gFan+	Scaled gFan+
FAN DIAMETER	IN	*89*	86	83	80	78	75
BOEING EQUIVLENT THRUST (BET)	LB	*20,800*	19,600	18,400	17,200	16,200	15,000
WING AREA / SPAN	FT^2 / FT	*1866 / 224*	1722 / 215	1578 / 206	1441 / 197	1292 / 187	1153 / 176
ASPECT RATIO (EFFECTIVE)		*26.94*	26.94	26.94	26.94	26.94	26.94
OPTIMUM CL		*0.825*	0.828	0.831	0.836	0.865	0.877
CRUISE L/D @ OPT CL		*26.426*	25.934	25.442	24.909	24.161	23.45
DESIGN MISSION RANGE	NMI	*3,500*	3,500	3,500	3,500	3,500	3,500
PERFORMANCE CRUISE MACH		*0.70*	0.70	0.70	0.70	0.70	0.70
LONG RANGE CRUISE MACH (LRC)		*0.70*	0.70	0.70	0.70	0.70	0.70
THRUST ICAC (MTOW, ISA)	FT	*43,500*	43,300	43,100	43,000	42,900	42,600
TIME / DIST (MTOW, 35k FT, ISA)	MIN / NMI	*29 / 184*	29 / 182	28 / 180	28 / 180	28 / 181	28 / 180
OPTIMUM ALTITUDE (MTOW, ISA)	FT	*42,300*	42,100	41,900	41,700	41,900	41,600
BUFFET ICAC (MTOW, ISA)	FT	*44,300*	44,000	43,700	43,500	42,900	42,400
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	*8,190*	8,190	8,180	8,180	8,150	8,230
APPROACH SPEED (MLW)	KT	*114*	115	116	118	120	122
BLOCK FUEL / SEAT (900 NMI)	LB	*59.72 (+5.8%)*	56.43 (Base)	53.14 (-5.8%)	49.84 (-11.7%)	46.78 (-17.1%)	43.55 (-22.8%)

The high wing configuration of SUGAR High lends itself to having an open fan puller engine installed on the wing. The Open Fan engine, while heavier because of bare engine weight and increased cabin noise insulation, has less wetted area, i.e. lower drag, and much improved SFC relative to the base gFan+ engine on the airplane. The SUGAR High airplane with an Open Fan engine, sized to the same performance requirements as the SUGAR High airplane with the gFan+ engines, has a 7.2% block fuel / seat benefit as shown in Table 6.10. This sizing was done without regard to community noise considerations.

Table 6.10 – 765-095 Open Fan Trade

MODEL Sizing Level		Ducted Fan	With Open Fan
PASSENGERS / CLASS		154 / Dual	154 / Dual
MAX TAKEOFF WEIGHT	LB	140,100	144,900
MAX LANDING WEIGHT	LB	136,000	143,100
MAX ZERO FUEL WEIGHT	LB	128,000	135,100
OPERATING EMPTY WEIGHT	LB	82,000	89,100
FUEL CAPACITY REQ	USG	4,928	4,566
ENGINE MODEL		Scaled gFan+	Scaled gFan+ Open Fan
FAN DIAMETER	IN	78	~139
BOEING EQUIVLENT THRUST (BET)	LB	16,200	16,500
WING AREA / SPAN	FT^2 / FT	1292 / 187	1365 / 192
ASPECT RATIO (EFFECTIVE)		26.94	26.94
OPTIMUM CL		0.865	0.838
CRUISE L/D @ OPT CL		24.161	24.794
DESIGN MISSION RANGE	NMI	3,500	3,500
PERFORMANCE CRUISE MACH		0.70	0.70
LONG RANGE CRUISE MACH (LRC)		0.70	0.70
THRUST ICAC (MTOW, ISA)	FT	42,900	43,000
TIME / DIST (MTOW, 35k FT, ISA)	MIN / NMI	28 / 181	28 / 177
OPTIMUM ALTITUDE (MTOW, ISA)	FT	41,900	41,600
BUFFET ICAC (MTOW, ISA)	FT	42,900	43,300
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	8,150	8,190
APPROACH SPEED (MLW)	KT	120	120
BLOCK FUEL / SEAT (900 NMI)	LB	46.78 (Base)	43.39 (-7.2%)

A takeoff field length trade was done on the SUGAR High airplane using the same approach as on the Refined SUGAR airplane. The trade numbers are similar between the airplanes as shown in Table 6.11.

Table 6.11 – 765-095 TOFL Trade

MODEL Sizing Level		+500 ft	Base	-500 ft	-1000 ft
PASSENGERS / CLASS		154 / Dual	154 / Dual	154 / Dual	154 / Dual
MAX TAKEOFF WEIGHT	LB	138,900	140,100	142,100	144,200
MAX LANDING WEIGHT	LB	134,800	136,000	137,700	139,400
MAX ZERO FUEL WEIGHT	LB	126,800	128,000	129,700	131,400
OPERATING EMPTY WEIGHT	LB	80,800	82,000	83,700	85,400
FUEL CAPACITY REQ	USG	4,907	4,928	4,968	5,032
ENGINE MODEL		Scaled gFan+	Scaled gFan+	Scaled gFan+	Scaled gFan+
FAN DIAMETER	IN	77	78	79	80
BOEING EQUIVLENT THRUST (BET)	LB	15,700	16,200	16,600	17,300
WING AREA / SPAN	FT^2 / FT	1231 / 182	1292 / 187	1365 / 192	1431 / 196
ASPECT RATIO (EFFECTIVE)		26.94	26.94	26.94	26.94
OPTIMUM CL		0.873	0.865	0.843	0.839
CRUISE L/D @ OPT CL		23.892	24.161	24.508	24.742
DESIGN MISSION RANGE	NMI	3,500	3,500	3,500	3,500
PERFORMANCE CRUISE MACH		0.70	0.70	0.70	0.70
LONG RANGE CRUISE MACH (LRC)		0.70	0.70	0.70	0.70
THRUST ICAC (MTOW, ISA)	FT	42,300	42,900	43,400	44,000
TIME / DIST (MTOW, 35k FT, ISA)	MIN / NMI	28 / 178	28 / 181	28 / 179	28 / 178
OPTIMUM ALTITUDE (MTOW, ISA)	FT	41,200	41,900	42,200	42,700
BUFFET ICAC (MTOW, ISA)	FT	42,100	42,900	43,700	44,400
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	8,690	8,150	7,680	7,190
TOFL (900 NMI MISS, SEA LEVEL, 86 DEG F)	FT	6,290	5,940	5,630	5,310
APPROACH SPEED (MLW)	KT	122	120	117	115
BLOCK FUEL / SEAT (900 NMI)	LB	46.27 (-1.1%)	46.78 (Base)	47.45 (+1.4%)	48.32 (+3.3%)

765-096 – SUGAR Volt:

"SUGAR Volt" is a hybrid fuel / electric powered airplane based on the SUGAR High platform. SUGAR Volt was sized to the same performance requirements as the other airplanes, but some of the energy normally provided by fuel is now being provided by battery power. The General Electric hybrid engine is designated hFan. The airplane was sized such that on the design mission, while provisioning for batteries is included, no batteries are actually used in the mission. The lack of batteries for the design mission results in an airplane with a lower MTOW than if batteries were used on that mission. As mission range is decreased, more and more potential weight is available for adding batteries and still remaining below MTOW for the mission. Table 6.12 shows the performance level of the SUGAR Volt airplane. This airplane uses 63.4% less fuel than the SUGAR Free airplane on a 900 nmi mission, while carrying 20,900 lb of batteries on that mission.

Table 6.12 – 765-096 Baseline Sizing

MODEL Sizing Level		SUGAR Volt
PASSENGERS / CLASS		154 / Dual
MAX TAKEOFF WEIGHT	LB	154,900
MAX LANDING WEIGHT	LB	148,600
MAX ZERO FUEL WEIGHT	LB	140,600
OPERATING EMPTY WEIGHT	LB	94,600
FUEL CAPACITY REQ	USG	5,250
ENGINE MODEL		Scaled hFan
FAN DIAMETER	IN	80
BOEING EQUIVLENT THRUST (BET)	LB	17,300
WING AREA / SPAN	FT^2 / FT	1498 / 201
ASPECT RATIO (EFFECTIVE)		26.94
OPTIMUM CL		0.831
CRUISE L/D @ OPT CL		24.992
DESIGN MISSION RANGE	NMI	3,500
PERFORMANCE CRUISE MACH		0.70
LONG RANGE CRUISE MACH (LRC)		0.70
THRUST ICAC (MTOW, ISA)	FT	42,800
TIME / DIST (MTOW, 35k FT, ISA)	MIN / NMI	29 / 178
OPTIMUM ALTITUDE (MTOW, ISA)	FT	42,000
BUFFET ICAC (MTOW, ISA)	FT	43,900
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	8,180
APPROACH SPEED (MLW)	KT	116
BLOCK FUEL / SEAT (900 NMI)	LB	33.83

Table 6.13 is a table that compares the SUGAR Volt to an airplane with the same design requirements, but no electric system (SUGAR High), and the trade in block fuel for using varying amounts of horsepower for the 900 nmi mission. The trade shows that as you use more horsepower during the mission, the fuel required for the mission decreases, however the amount of battery weight required also increases. Eventually the TOW required for the 900 nmi mission equals MTOW and no additional battery power can be added. The point at which TOW for the 900 nmi mission equals MTOW is the maximum benefit available, and is the block fuel value used in Table 6.12.

Table 6.13 – 765-096 Power Trade

MODEL Sizing Level		No Electric Systems	SUGAR Volt 0 lb Battery	1,250 hp 9,150 lb Battery	2,500 hp 16,700 lb Battery	3750 hp 24,250 lb Battery
PASSENGERS / CLASS		154 / Dual	154 / Dual	154 / Dual	154 / Dual	154 / Dual
MAX TAKEOFF WEIGHT	LB	140,100	154,900	154,900	154,900	154,900
MAX LANDING WEIGHT	LB	136,000	148,600	148,600	148,600	148,600
MAX ZERO FUEL WEIGHT	LB	128,000	140,600	140,600	140,600	140,600
OPERATING EMPTY WEIGHT	LB	82,000	94,600	94,600	94,600	94,600
FUEL CAPACITY REQ	USG	4,928	5,250	5,250	5,250	5,250
ENGINE MODEL		Scaled gFan+	Scaled hFan	Scaled hFan	Scaled hFan	Scaled hFan
FAN DIAMETER	IN	78	80	80	80	80
BOEING EQUIVLENT THRUST (BET)	LB	16,200	17,300	17,300	17,300	17,300
WING AREA / SPAN	FT^2 / FT	1292 / 187	1498 / 201	1498 / 201	1498 / 201	1498 / 201
ASPECT RATIO (EFFECTIVE)		26.94	26.94	26.94	26.94	26.94
OPTIMUM CL		0.865	0.831	0.831	0.831	0.831
CRUISE L/D @ OPT CL		24.161	24.992	24.992	24.992	24.992
DESIGN MISSION RANGE	NMI	3,500	3,500	3,500	3,500	3,500
PERFORMANCE CRUISE MACH		0.70	0.70	0.70	0.70	0.70
LONG RANGE CRUISE MACH (LRC)		0.70	0.70	0.70	0.70	0.70
THRUST ICAC (MTOW, ISA)	FT	42,900	42,800	42,800	42,800	42,800
TIME / DIST (MTOW, 35k FT, ISA)	MIN / NMI	28 / 181	29 / 178	29 / 178	29 / 178	29 / 178
OPTIMUM ALTITUDE (MTOW, ISA)	FT	41,900	42,000	42,000	42,000	42,000
BUFFET ICAC (MTOW, ISA)	FT	42,900	43,900	43,900	43,900	43,900
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	8,150	8,180	8,180	8,180	8,180
APPROACH SPEED (MLW)	KT	120	116	116	116	116
TAKEOFF WEIGHT REQUIRED (900 NMI)	LB	123,000	136,500	144,300	151,100	158,000
OPERATING EMPTY WEIGHT (900 NMI)	LB	82,000	94,600	103,750	111,300	118,850
BLOCK FUEL / SEAT (900 NMI)	LB	46.78 (Base)	50.64 (+8.25%)	42.05 (-10.1%)	36.64 (-21.7%)	31.67 (-32.3%)

The hybrid fuel / electric engine has maximum thrust characteristics unlike those of a fuel only engine. As horsepower applied to the engine is increased, maximum thrust is increased. There is then the potential to use increased levels of horsepower during periods of high thrust utilization, e.g. takeoff and climb, and less during periods of low thrust required, e.g. cruise and descent. Table 6.14 shows the results of one attempt at doing that. The airplane and engine were resized using 1,250 horsepower for just the takeoff and climb portion of the design mission. Since the engine has more thrust capability during takeoff and climb when horsepower is applied, and the engines are sized for climb and cruise thrust, engine scale for the airplane was reduced, as shown in the 1,250 hp column airplane. While the airplane sizes to be smaller and lighter, when the airplane reaches its cruise altitude, and battery power is exhausted, the airplane is no longer capable of remaining at the altitude achievable during climb, if that altitude is at or above the optimum altitude. Cruise thrust available without the added horsepower boost from the electric motor is not enough to sustain the airplane at its optimum altitude as shown by the cruise thrust Initial Cruise Altitude Capability (ICAC) being over 1,000 ft below the airplane optimum altitude.

Table 6.14 – 765-096 Power Trade for Core Sizing

MODEL Sizing Level		**No Electric Systems**	**SUGAR Volt 0 lb Battery**	**1,250 hp 1,800 lb Battery**
PASSENGERS / CLASS		154 / Dual	154 / Dual	154 / Dual
MAX TAKEOFF WEIGHT	LB	140,100	154,900	152,500
MAX LANDING WEIGHT	LB	136,000	148,600	148,300
MAX ZERO FUEL WEIGHT	LB	128,000	140,600	140,300
OPERATING EMPTY WEIGHT	LB	82,000	94,600	94,300
FUEL CAPACITY REQ	USG	4,928	5,250	4,930
ENGINE MODEL		Scaled gFan+	Scaled hFan	Scaled hFan
FAN DIAMETER	IN	78	80	73
BOEING EQUIVLENT THRUST (BET)	LB	16,200	17,300	14,300
WING AREA / SPAN	FT^2 / FT	1292 / 187	1498 / 201	1592 / 207
ASPECT RATIO (EFFECTIVE)		26.94	26.94	26.94
OPTIMUM CL		0.865	0.831	0.837
CRUISE L/D @ OPT CL		24.161	24.992	25.751
DESIGN MISSION RANGE	NMI	3,500	3,500	3,500
PERFORMANCE CRUISE MACH		0.70	0.70	0.70
LONG RANGE CRUISE MACH (LRC)		0.70	0.70	0.70
CLIMB THRUST ICAC (MTOW, ISA)	FT	42,900	42,800	45,200
CRUISE THRUST ICAC (MTOW, ISA)	FT	44,800	44,900	**42,600**
TIME / DIST (MTOW, 35k FT, ISA)	MIN / NMI	28 / 181	29 / 178	29 / 182
OPTIMUM ALTITUDE (MTOW, ISA)	FT	41,900	42,000	43,700
BUFFET ICAC (MTOW, ISA)	FT	42,900	43,900	45,400
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	8,150	8,180	8,190
APPROACH SPEED (MLW)	KT	120	116	113
BLOCK FUEL / SEAT (900 NMI)	LB	46.78 (Base)	50.64 (+8.25%)	45.67 (-2.4%)

Because the amount of batteries the airplane can carry on shorter range missions is directly proportional to the difference between the airplane’s MTOW and Zero Fuel Weight (ZFW = Operational Empty Weight + Payload Weight), the airplane can carry more batteries, i.e. decrease fuel burn, by increasing MTOW. This is exactly the opposite effect of fuel only airplanes. Increasing the difference between MTOW and ZFW is effectively increasing the design range of the airplane. This trend is illustrated in Table 6.15. As design range is increased, the airplane becomes bigger and heavier, but because the airplane can carry more batteries on a 900 nmi mission and utilize that extra power instead of burning fuel, the actual fuel burn on that mission decreases. If the airplane is sized large enough to carry enough batteries, the fuel burn can reach the NASA goal of a 70% block fuel reduction.

Table 6.15 – 765-096 MTOW Trade

MODEL Sizing Level		SUGAR Free	SUGAR Volt	SUGAR VOLT Increase MTOW	SUGAR VOLT Increase MTOW
PASSENGERS / CLASS		154 / Dual	154 / Dual	154 / Dual	154 / Dual
MAX TAKEOFF WEIGHT	LB	184,800	154,900	163,100	179,700
MAX LANDING WEIGHT	LB	151,000	148,600	152,300	159,600
MAX ZERO FUEL WEIGHT	LB	142,000	140,600	144,300	151,600
OPERATING EMPTY WEIGHT	LB	96,000	94,600	98,300	105,600
FUEL CAPACITY REQ	USG	9,710	5,250	5,948	7,373
ENGINE MODEL		Scaled CFM56-7B27	Scaled hFan	Scaled hFan	Scaled hFan
FAN DIAMETER	IN	62	80	82	86
BOEING EQUIVLENT THRUST (BET)	LB	28,200	17,300	18,000	23,600
WING AREA / SPAN	FT^2 / FT	1429 / 122	1498 / 201	1597 / 207	1769 / 218
ASPECT RATIO (EFFECTIVE)		10.41	26.94	26.94	26.94
OPTIMUM CL		0.583	0.831	0.827	0.826
CRUISE L/D @ OPT CL		18.068	24.992	25.365	25.894
DESIGN MISSION RANGE	NMI	3,500	3,500	4,000	4,900
PERFORMANCE CRUISE MACH		0.785	0.70	0.70	0.70
LONG RANGE CRUISE MACH (LRC)		0.785	0.70	0.70	0.70
CLIMB THRUST ICAC (MTOW, ISA)	FT	37,200	42,800	42,900	43,100
TIME / DIST (MTOW, 35k FT, ISA)	MIN / NMI	23 / 148	29 / 178	29 / 181	29 / 177
OPTIMUM ALTITUDE (MTOW, ISA)	FT	35,000	42,000	42,200	42,300
BUFFET ICAC (MTOW, ISA)	FT	36,200	43,900	44,200	44,300
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	8,190	8,180	8,190	8,200
APPROACH SPEED (MLW)	KT	126	116	114	111
BATTERIES CARRIED (900 NMI)	LB	0	20,900	25,200	35,500
OPERATING EMPTY WEIGHT (900 NMI)	LB	96,000	116,500	123,500	141,100
BLOCK FUEL / SEAT (900 NMI)	LB	92.35 (Base)	33.83 (-63.4%)	31.54 (-65.8%)	**26.23 (-71.6%)**

Another possibility for exploiting the increased thrust capability of the hybrid engine is to use it to reduce TOFL. If the engine is sized using fuel only thrust capability to the TOFL requirement, applying horsepower to the engine will have the effect of reducing that TOFL. This effect is illustrated in Table 6.16. As more horsepower is applied, the TOFL of the airplane at MTOW, and on a 900 nmi mission, is significantly reduced. It was assumed takeoff thrust capability would need to be available for 5 minutes, and the weight of the batteries carried is reflected in the slight penalty in both design range and block fuel.

Table 6.16 – 765-096 TOFL Trade

MODEL Sizing Level		SUGAR Volt Base	1,250 hp	2,500 hp	3,750 hp
MAX TAKEOFF WEIGHT	LB	154,900	154,900	154,900	154,900
BATTERY WEIGHT	LB	0	320	530	740
OPERATING EMPTY WEIGHT	LB	94,600	94,600	94,600	94,600
ENGINE MODEL		Scaled hFan	Scaled hFan	Scaled hFan	Scaled hFan
FAN DIAMETER	IN	80	80	80	80
BOEING EQUIVLENT THRUST (BET)	LB	17,300	19,400	21,300	23,000
DESIGN MISSION RANGE	NMI	3,500	3,450	3,420	3,385
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	8,180	6,800	6,040	5,600
TAKEOFF WEIGHT REQUIRED (900 NMI)	LB	136,500	136,800	137,000	137,200
TOFL (900 NMI, SEA LEVEL, 86 DEG F)	FT	5,980	5,140	4,740	**4,425**
BLOCK FUEL / SEAT (900 NMI)	LB	50.64 (Base)	50.71 (+0.1%)	50.76 (+0.2%)	50.81 (+0.3%)

Similar to the SUGAR High airplane, a trade was done to examine the effect of applying an Open Fan engine to SUGAR Volt. While the SUGAR Volt with Open Fan sizes similar to the SUGAR High with Open Fan airplane, the block fuel benefit is not nearly as great. This is because, as discussed earlier, the increased efficiency of the Open fan engine decreases the difference between MTOW and ZFW, i.e. the amount of batteries the airplane can carry on the 900 nmi mission, and this difference decreases the ability of the airplane to offset the installation weight penalties of both the Open Fan engines and batteries, plus because the airplane is burning far less fuel, the overall effectiveness of the Open Fan's SFC benefit on block fuel is reduced. The results of this trade are shown in Table 6.17.

Table 6.17 – 765-096 Open Fan Trade

MODEL Sizing Level		**SUGAR Volt**	**SUGAR Volt Open Fan**
PASSENGERS / CLASS		154 / Dual	154 / Dual
MAX TAKEOFF WEIGHT	LB	154,900	159,200
MAX LANDING WEIGHT	LB	148,600	155,500
MAX ZERO FUEL WEIGHT	LB	140,600	147,500
OPERATING EMPTY WEIGHT	LB	94,600	101,500
FUEL CAPACITY REQ	USG	5,250	4,854
ENGINE MODEL		Scaled hFan	Scaled hFan Open Fan
FAN DIAMETER	IN	80	~144
BOEING EQUIVLENT THRUST (BET)	LB	17,300	17,600
WING AREA / SPAN	FT^2/ FT	1498 / 201	1558 / 205
ASPECT RATIO (EFFECTIVE)		26.94	26.94
OPTIMUM CL		0.831	0.827
CRUISE L/D @ OPT CL		24.992	25.457
DESIGN MISSION RANGE	NMI	3,500	3,500
PERFORMANCE CRUISE MACH		0.70	0.70
LONG RANGE CRUISE MACH (LRC)		0.70	0.70
THRUST ICAC (MTOW, ISA)	FT	42,800	42,900
TIME / DIST (MTOW, 35k FT, ISA)	MIN / NMI	29 / 178	29 / 179
OPTIMUM ALTITUDE (MTOW, ISA)	FT	42,000	42,200
BUFFET ICAC (MTOW, ISA)	FT	43,900	44,100
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	8,180	8,190
APPROACH SPEED (MLW)	KT	116	117
BLOCK FUEL / SEAT (900 NMI)	LB	33.83 (Base)	32.97 (-2.5%)

A battery power trade was done for the hybrid Open Fan engine similar to the hybrid turbofan engine. The results of that trade are shown in Table 6.18. While SUGAR Volt with the hybrid turbofan engine was capable of carrying 20,900 lb of batteries on the 900 nmi mission, the reduced difference between MTOW and ZFW on the hybrid Open Fan engine only allows it to carry 18,700 lb of batteries before reaching MTOW.

Table 6.18 – 765-096 Open Fan Power Trade

MODEL Sizing Level		No Electric Systems	SUGAR Volt 0 lb Battery	1,250 hp 9,150 lb Battery	2,500 hp 16,700 lb Battery	3750 hp 24,250 lb Battery
PASSENGERS / CLASS		154 / Dual	154 / Dual	154 / Dual	154 / Dual	154 / Dual
MAX TAKEOFF WEIGHT	LB	140,100	159,200	159,200	159,200	159,200
MAX LANDING WEIGHT	LB	136,000	155,500	155,500	155,500	155,500
MAX ZERO FUEL WEIGHT	LB	128,000	147,500	147,500	147,500	147,500
OPERATING EMPTY WEIGHT	LB	82,000	101,500	101,500	101,500	101,500
FUEL CAPACITY REQ	USG	4,928	4,854	4,854	4,854	4,854
ENGINE MODEL		Scaled gFan+	Scaled hFan Open Fan	Scaled hFan Open Fan	Scaled hFan Open Fan	Scaled hFan Open Fan
FAN DIAMETER	IN	78	~144	~144	~144	~144
BOEING EQUIVLENT THRUST (BET)	LB	16,200	17,600	17,600	17,600	17,600
WING AREA / SPAN	FT^2 / FT	1292 / 187	1558 / 205	1558 / 205	1558 / 205	1558 / 205
ASPECT RATIO (EFFECTIVE)		26.94	26.94	26.94	26.94	26.94
OPTIMUM CL		0.865	0.827	0.827	0.827	0.827
CRUISE L/D @ OPT CL		24.161	25.457	25.457	25.457	25.457
DESIGN MISSION RANGE	NMI	3,500	3,500	3,500	3,500	3,500
PERFORMANCE CRUISE MACH		0.70	0.70	0.70	0.70	0.70
LONG RANGE CRUISE MACH (LRC)		0.70	0.70	0.70	0.70	0.70
THRUST ICAC (MTOW, ISA)	FT	42,900	42,900	42,900	42,900	42,900
TIME / DIST (MTOW, 35k FT, ISA)	MIN / NMI	28 / 181	29 / 179	29 / 179	29 / 179	29 / 179
OPTIMUM ALTITUDE (MTOW, ISA)	FT	41,900	42,200	42,200	42,200	42,200
BUFFET ICAC (MTOW, ISA)	FT	42,900	44,100	44,100	44,100	44,100
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	8,150	8,190	8,190	8,190	8,190
APPROACH SPEED (MLW)	KT	120	117	117	117	117
TAKEOFF WEIGHT REQUIRED (900 NMI)	LB	123,000	142,500	150,600	157,400	**164,300**
OPERATING EMPTY WEIGHT (900 NMI)	LB	82,000	101,500	110,700	118,200	125,800
BLOCK FUEL / SEAT (900 NMI)	LB	46.78 (Base)	46.82 (+0.09%)	39.12 (-16.4%)	34.19 (-26.9%)	29.72 (-36.5%)

765-097 – SUGAR Ray:

Another alternative airplane configuration looked at was a Hybrid Wing Body (HWB), dubbed SUGAR Ray. SUGAR Ray was primarily looked at as an airplane which leveraged maximum airframe shielding in order to reduce airplane community noise. The performance of SUGAR Ray is shown in Table 6.19. The airplane has a block fuel / seat benefit of 43.3% relative to the baseline SUGAR Free configuration.

Table 6.19 – 765-097 Baseline Sizing

MODEL Sizing Level		SUGAR Ray
PASSENGERS / CLASS		154 / Dual
MAX TAKEOFF WEIGHT	LB	172,600
MAX LANDING WEIGHT	LB	165,300
MAX ZERO FUEL WEIGHT	LB	157,300
OPERATING EMPTY WEIGHT	LB	111,300
FUEL CAPACITY REQ	USG	5,392
ENGINE MODEL		Scaled gFan+
FAN DIAMETER	IN	81
BOEING EQUIVLENT THRUST (BET)	LB	17,500
WING AREA / SPAN	FT^2 / FT	4139 / 180
ASPECT RATIO (EFFECTIVE)		26.94
OPTIMUM CL		0.316
CRUISE L/D @ OPT CL		27.471
DESIGN MISSION RANGE	NMI	3,500
PERFORMANCE CRUISE MACH		0.70
LONG RANGE CRUISE MACH (LRC)		0.70
THRUST ICAC (MTOW, ISA)	FT	42,400
TIME / DIST (MTOW, 35k FT, ISA)	MIN / NMI	28 / 180
OPTIMUM ALTITUDE (MTOW, ISA)	FT	40,800
BUFFET ICAC (MTOW, ISA)	FT	
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	7,900
APPROACH SPEED (MLW)	KT	103
BLOCK FUEL / SEAT (900 NMI)	LB	52.37

Because of the relative uncertainty of an HWB’s OEW, a trade was done to look at the sensitivity of the airplane’s performance to weight. The results of that trade are shown in Table 6.20. Because of the highly integrated nature of the wing area and cabin area, which is not present on “tube-and-wing” airplanes, the trade did not include variation in wing area. This results in a trade which is not very sensitive to OEW, but also results in airplanes which are not consistent in performance level.

Table 6.20 – 765-097 OEW Trade

MODEL Sizing Level		-10,000 lb	Cycled for Thrust	+10,000 lb
PASSENGERS / CLASS		154 / Dual	154 / Dual	154 / Dual
MAX TAKEOFF WEIGHT	LB	161,500	172,600	184,400
MAX LANDING WEIGHT	LB	155,200	165,300	175,900
MAX ZERO FUEL WEIGHT	LB	147,200	157,300	167,900
OPERATING EMPTY WEIGHT	LB	101,200	111,300	121,900
FUEL CAPACITY REQ	USG	5,232	5,392	5,576
ENGINE MODEL		Scaled gFan+	Scaled gFan+	Scaled gFan+
FAN DIAMETER	IN	82	81	81
BOEING EQUIVLENT THRUST (BET)	LB	18,100	17,500	17,400
WING AREA / SPAN	FT^2/ FT	4139 / 180	4139 / 180	4139 / 180
ASPECT RATIO (EFFECTIVE)		26.94	26.94	26.94
OPTIMUM CL		0.323	0.316	0.313
CRUISE L/D @ OPT CL		26.91	27.471	27.96
DESIGN MISSION RANGE	NMI	3,500	3,500	3,500
PERFORMANCE CRUISE MACH		0.70	0.70	0.70
LONG RANGE CRUISE MACH (LRC)		0.70	0.70	0.70
THRUST ICAC (MTOW, ISA)	FT	44,000	42,400	41,200
TIME / DIST (MTOW, 35k FT, ISA)	MIN / NMI	28 / 178	28 / 180	28 / 178
OPTIMUM ALTITUDE (MTOW, ISA)	FT	42,700	40,800	39,200
BUFFET ICAC (MTOW, ISA)	FT			
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	6,700	7,900	9,100
APPROACH SPEED (MLW)	KT	100	103	106
BLOCK FUEL / SEAT (900 NMI)	LB	50.89 (-2.6%)	52.37 (Base)	54.18 (+3.7%)

6.3 – Vehicle Opportunities Trades

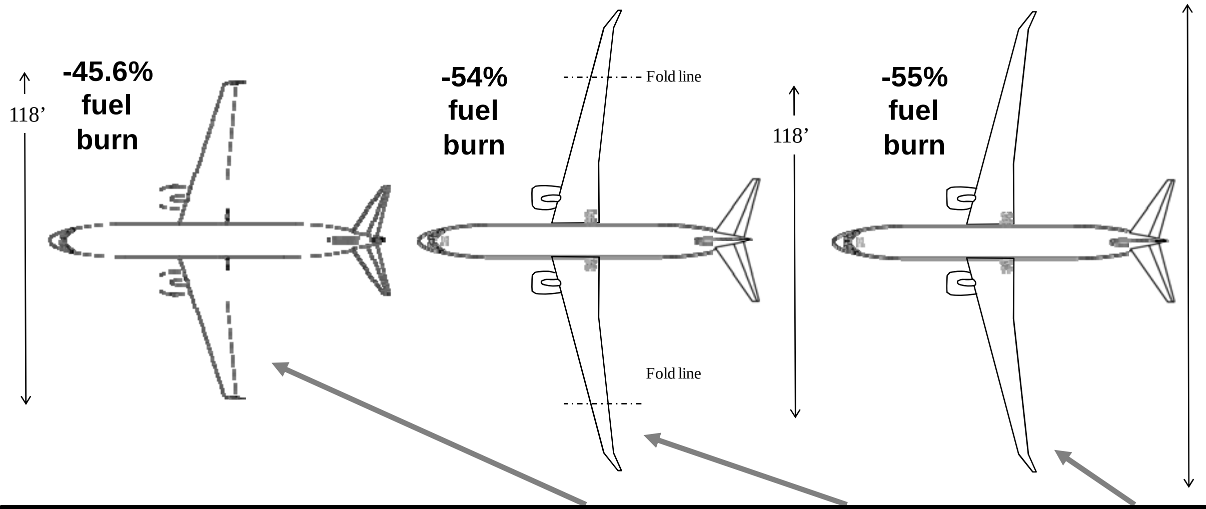
After the completion of the higher order analysis for each vehicle (covered in Section 5.3 thru Section 5.7) the initial sizing methods (used for Section 5.1.3) were calibrated and re-run to determine how close to optimum each configuration came. It also allowed for low level trade studies to be performed that were calibrated to the higher level analyses. The data in this section is a result of these calibrated lower fidelity methods.

Contrails may contribute to global climate change and can be avoided by flying at altitudes that prevent their formation. An extreme solution is to restrict all air traffic to 27,000 feet which would adversely affect vehicle performance. To quantify this, a Refined SUGAR configuration was sized with both unrestricted and restricted initial cruise altitude allowing thrust, wing area, and aspect ratio to change. Maximum span was constrained to 118 feet. The results of this sizing is shown in Figure 6.8

	Refined SUGAR gfan+ Engine	Refined SUGAR gFan+ Engine
Cruise Altitude (MTOW, ISA)	39,600	27,000
Max Takeoff Weight (lbs)	139,500	141,000
Wing Area (ft^2)	1407	1240
Aspect Ratio (Effective)	11.63	13.5
Wing Span (effective)	128	128
Performance Cruise Mach	0.70	0.672
Performance Cruise Knots	402	402
Block Fuel / Seat (900 NMI)	48.31	51.4 (+6.4%)

Figure 6.8 – Restricting Cruise Altitude to 27,000 ft

The Refined SUGAR configuration was also developed to a different technology level than the other three advanced configurations. The application of those advanced technologies was investigated as an opportunities trade. Figure 6.9 shows the potential for Refined SUGAR with the same advanced technologies applied (primarily to propulsion and aerodynamics) both with and without a span constraint. The advanced technologies do not reduce fuel burn as much as increased span. The non-span constrained version of the Refined SUGAR with the gFan+ engine is referred to as the "Super Refined SUGAR".



MODEL Sizing Level		Refined SUGAR gFan	Refined SUGAR gFan+	Refined SUGAR gFan+ Span 118 ft	Refined SUGAR gFan+ Span 118 ft SUGAR High Aero	Refined SUGAR gFan+ No Span Constraint SUGAR High Aero Fold Wt	Refined SUGAR gFan+ No Span Constraint SUGAR High Aero 2 x Fold Wt	Refined SUGAR gFan+ No Span Constraint SUGAR High Aero No Fold
CRUISE ALTITUDE (MTOW, ISA)	ft	38,400	39,600	39,600	39,600	41,500	41,500	41,500
MAX TAKE OFF WEIGHT	Lb	139,700	139,500	139,400	139,500	141,905	143,336	140,100
WING AREA	ft^2	1,440	1,407	1,407	1,407	1,600	1,600	1,600
ASPECT RATIO (EFFECTIVE)		11.63	11.63	11.63	11.63	16.0	16.0	16.0
WING SPAN (TRUE)	ft	129	128	118	118	160	160	160
CRUISE L/D		21.98	21.4	20.4	21.6	24.8	24.8	25.33
CRUISE MACH NUMBER		0.70	0.70	0.70	0.70	0.70	0.70	0.70
FUEL BURN / SEAT (900 NMI)	lb	51.3	48.31	50.19	47.0	42.50	42.92	41.57

"Super Refined SUGAR"

Figure 6.9 – Potential for a Super Refined SUGAR

SUGAR High, as well as Super Refined SUGAR will benefit from further optimization. This is due to the unknowns surrounding the OEW associated with a wing aspect ratio much higher than other Boeing transports. Figure 6.10 shows the potential for the SUGAR High configuration. This includes the lower wing weight discussed in Section 5.5.3, a more favorable lift distribution, as well as some configuration changes that may reduce parasite and compressibility drag.

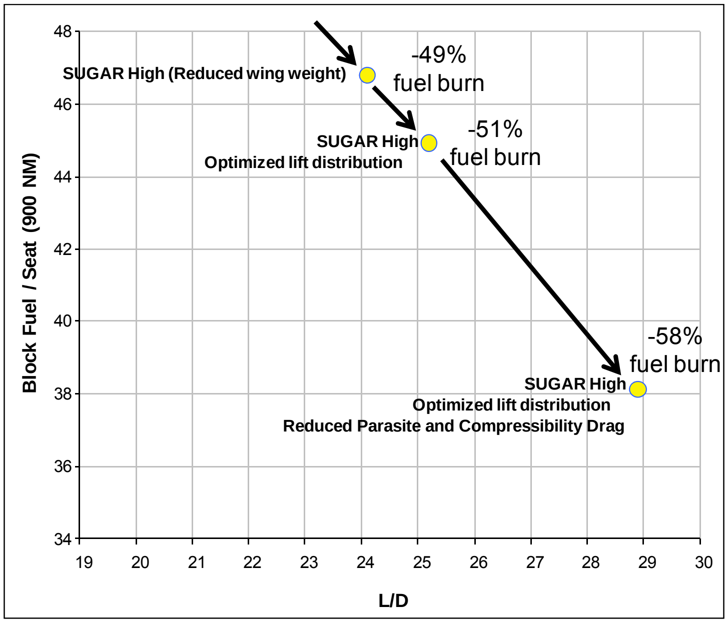


Figure 6.10 – SUGAR High Opportunities

SUGAR Volt, with the same improvements discussed for SUGAR High, can be designed to a selectable Maximum Takeoff Gross Weight (TOGW). The vehicle fuel burn will depend on what TOGW is selected and what level of battery technology is available. Figure 6.11 shows the vehicle's fuel burn and energy utilization sensitivity to TOGW and battery energy density. As TOGW is increased, more batteries are carried, which decreases fuel burn. What is not obvious is that, above a critical battery energy density, the energy used starts to decrease also. If fuel burn minimization is the only metric and one does not care about wing span or vehicle TOGW, maximizing TOGW results in the minimum fuel burn. There is a limit on how little fuel is burned that is caused by the operational restrictions placed on the engine.

As previously stated, the fuel burn is being measured for the average 900 nautical mile mission that was an output from the future scenario. In order to verify that increasing TOGW and minimizing fuel burn for the 900 nautical mile mission was not increasing fleet fuel burn a weighted average was calculated based on projected Medium sized airplane frequencies verses range. Figure 6.12 shows that after 220,000 pounds there is diminishing return from a fleet standpoint.

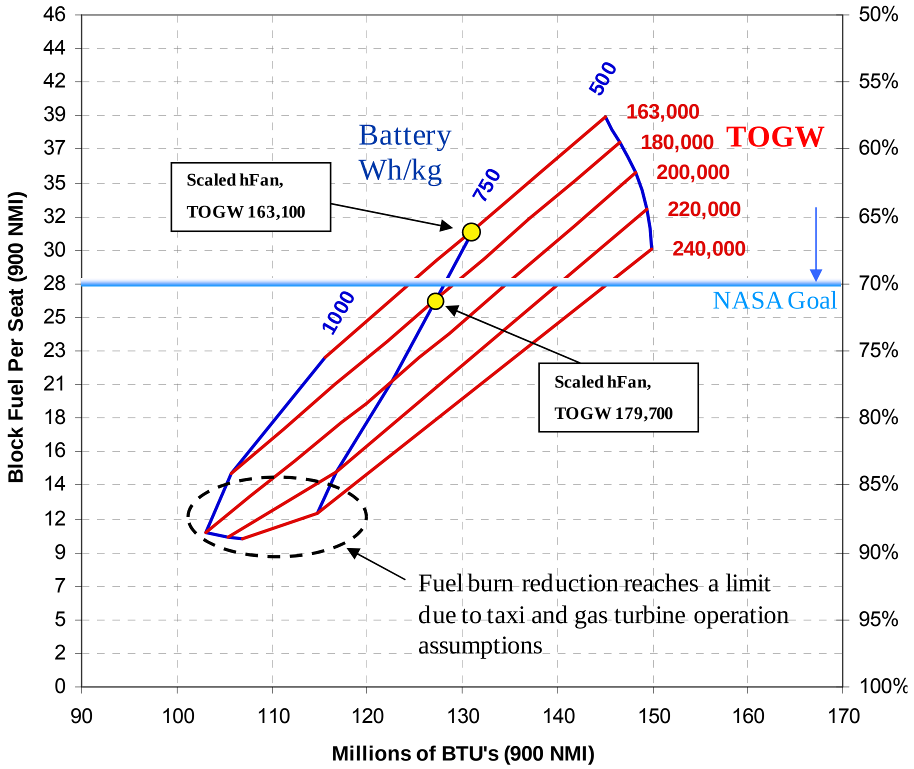


Figure 6.11 – SUGAR Volt Fuel Burn Opportunities

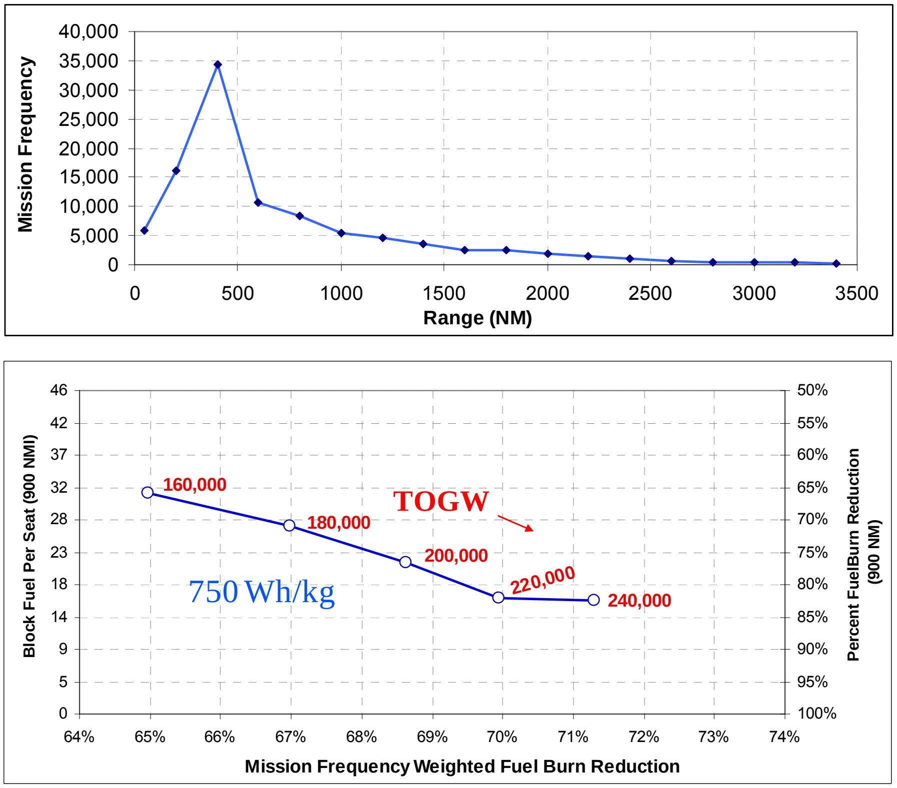


Figure 6.12 – Medium Airplane Frequencies vs. Range and SUGAR Volt Fleet Fuel Burn

6.4 – Evaluation of NASA Metrics

The following section contains charts that illustrate the range of the charted variable for each configuration that was generated with the low and high fidelity methods. These charts should NOT be interpreted as the minimum and maximum attainable values for the configuration. A note on the right of each of the bars indicates which trade dominated the variation of the plotted variable. For example for take-off field length (TOFL) one would expect to see TOFL on the right for all vehicles that have TOFL trades performed as that trade should dominate the range for that variable. Also included on the chart is a grey dot that represents the baseline configuration shown in the summary tables from the sizing analysis.

6.4.1 – Fuel Burned and Energy Consumed

The fuel burn for the five concepts at the average mission range of 900 nm was computed for a base vehicle and trade studies were performed using high fidelity methods. The results of these trades are illustrated in Figure 6.13. The only trade performed on SUGAR Free was for advanced air traffic management (ATM) and the size of the bar illustrates how powerful the ATM is at reducing fuel burn. Also of interest is the range of the metric for SUGAR High. Surprisingly 20,000 pounds of OEW doesn't affect the fuel burn as much as one would expect. It does show that the high span technology must be light in order to beat the Refined or SUPER Refined SUGAR. It does show that potential for the airplane to be better for this metric than the conventional arrangement.

SUGAR Volt is the only configuration that is capable of meeting or exceeding the NASA 70% fuel burn reduction goal. This hinges on advanced energy densities for batteries.

The chart also shows carbon emissions since it is directly proportional to the fuel burned. The carbon emissions shown are for JP based fuels and take no credit for biofuels.

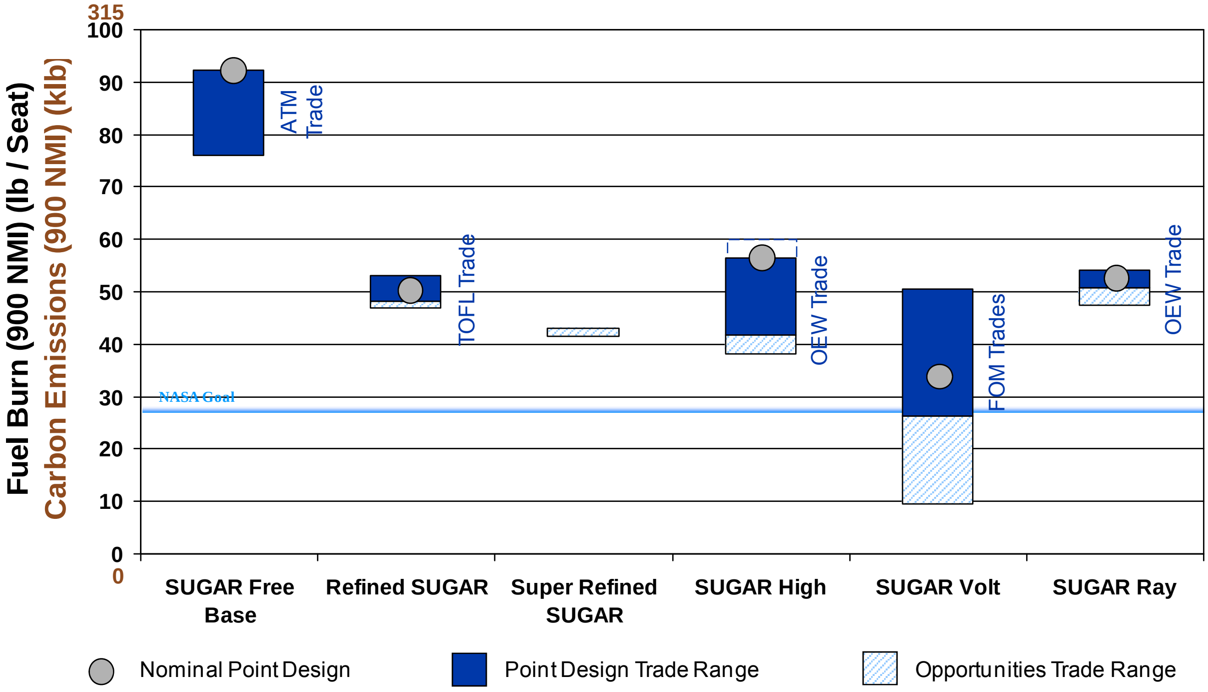


Figure 6.13 – Fuel Burn and Carbon Emissions

The 900 nautical mile mission was used for the fuel burn metric for SUGAR because it is average mission projected for 2030. The fuel burn reduction obviously varies with range. This variation is plotted in Figure 6.14. The mission fuel burn for each segment is shown in Table 6.21. For this figure and table, the reduced wing weight is used on the SUGAR High and SUGAR Volt.

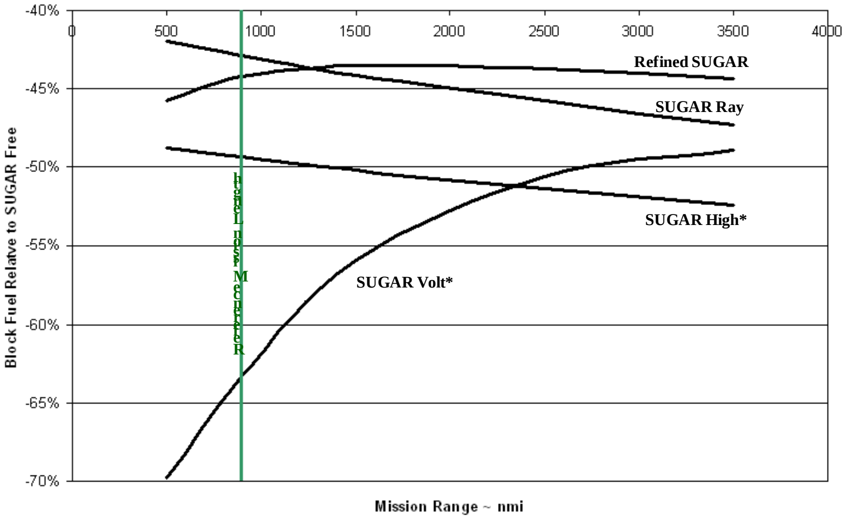


Figure 6.14 – Fuel Burn Reduction vs. Range

Table 6.21 – Vehicle Segment Fuel Burn

	SUGAR Free	**Refined SUGAR**	**SUGAR High**	**SUGAR Volt**
Taxi-Out (lb)	400	67	62	62
Takeoff / Climbout (lb)	498	382	394	493
Climb (lb)	3,762	2,212	2,127	1,521
Cruise (lb)	7,523	4,130	3,497	1,812
Descent (lb)	473	889	867	1,025
Loiter (lb)	1,091	-	-	-
Approach / Landing (lb)	225	190	195	232
Taxi-In (lb)	250	67	62	62
Total (lb)	14,222	7,937	7,204	5,207

The NRA stated that any form of energy, and its distribution prior to its use on the airplane is free. The purpose was to constrain the efforts of the study to air vehicle design. Using these rules, an electric airplane would burn no fuel. However, this may not be the intent of the rules outlined by the NRA as electric commercial airliners may have been viewed as an impractical solution. The total energy used by each configuration is shown in Figure 6.15. No configuration studied would meet the equivalent NASA goal of 70% energy utilization reduction, but a 60% energy reduction may be possible.

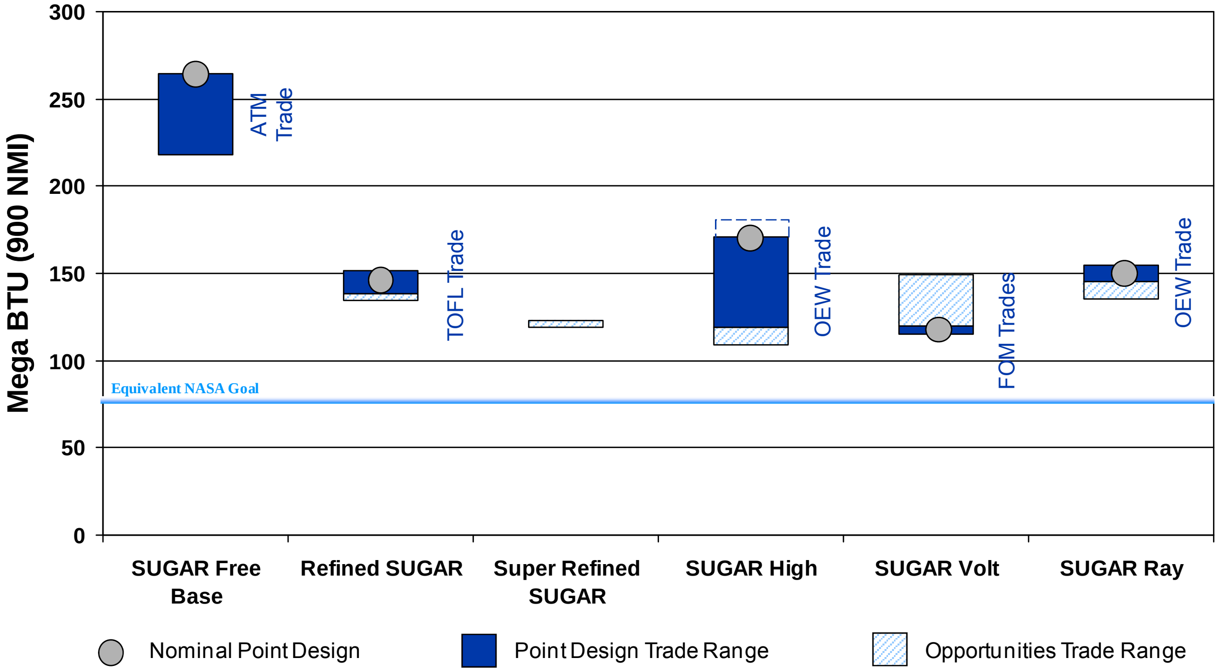


Figure 6.15 – Energy Utilization

6.4.2 – Takeoff Field Length and Metroplex Compatibility

A Takeoff Field Length (TOFL) of 8,200 feet at Maximum Takeoff Weight (MTOW) was a sizing parameter for all configurations. For Metroplex capability, it was assumed that a TOFL of 5,000 feet or better at the 900 nmi mission weight would be sufficient. Hence, TOFL was used as a surrogate to Metroplex compatibility. However, with unfolded spans reaching into 200 feet it is obvious that more work needs to be completed prior to declaring these configurations “Metroplex Compatible”.

Overall, achieving field lengths as low as 5,000 feet at the 900 nautical mile mission weight is not difficult though only three vehicles were analyzed at that condition. SUGAR Volt is of particular interest as it was found that the operator could choose the field length desired at the cost of efficiency. For a 900 nautical mile mission, the operator could choose to use JP fuel for the entire cruise and climb, thus reducing takeoff weight, and batteries for a thrust augmentation on takeoff. The engine has significantly more thrust when operated in the dual mode than with JP or batteries alone. That combined with wing areas sized for the long missions with heavy batteries yields very high thrust-to-weight and low wing loadings.

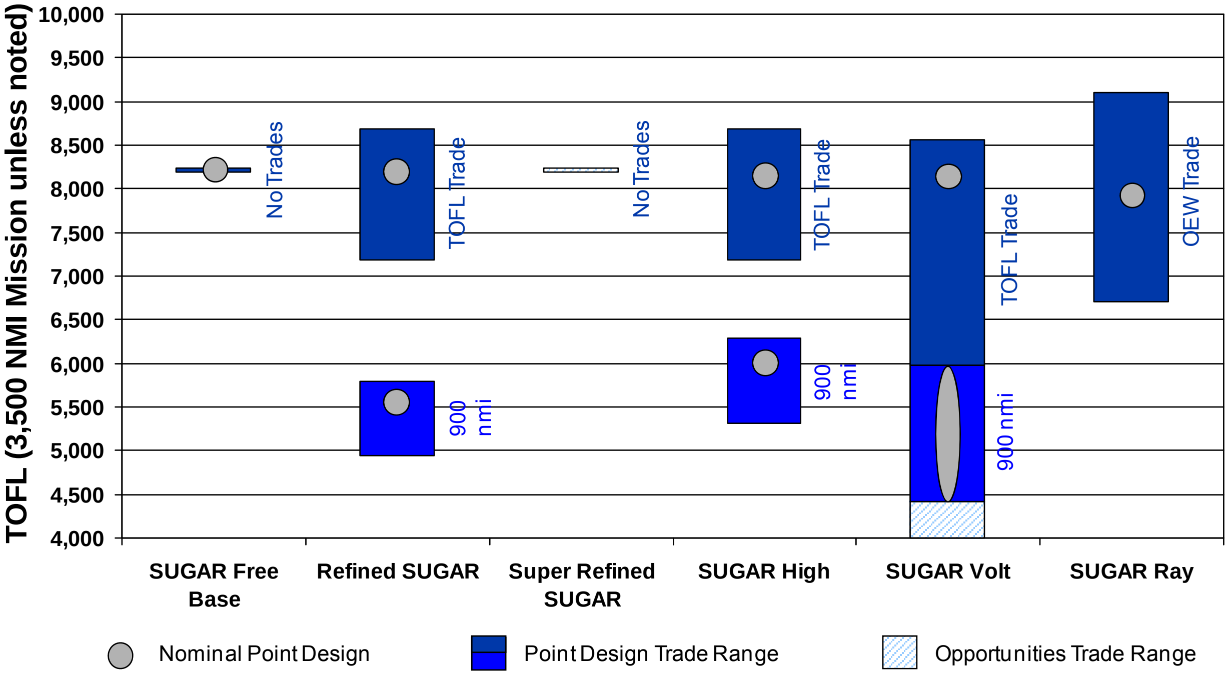


Figure 6.16 – Vehicle Field Length Capability

6.4.3 – LTO NOx Emissions

Figure 6.17 shows the results of the LTO NOx emissions. These trades were only a function of engine selection. The Refined SUGAR had the largest spread because it was run with both the gFan and gFan+. The SUGAR Volt concept, with its hybrid electric propulsion system could beat the NASA goal. If engines are not required to warm up prior to takeoff then the Volt concept could have virtually no LTO NOx emissions. It should also be noted that the CAEP/6 rating doesn’t take into account the amount of time the engine is running. Just switching to the advanced air traffic management system reduces emissions due to the significantly reduced ground delays assumed.

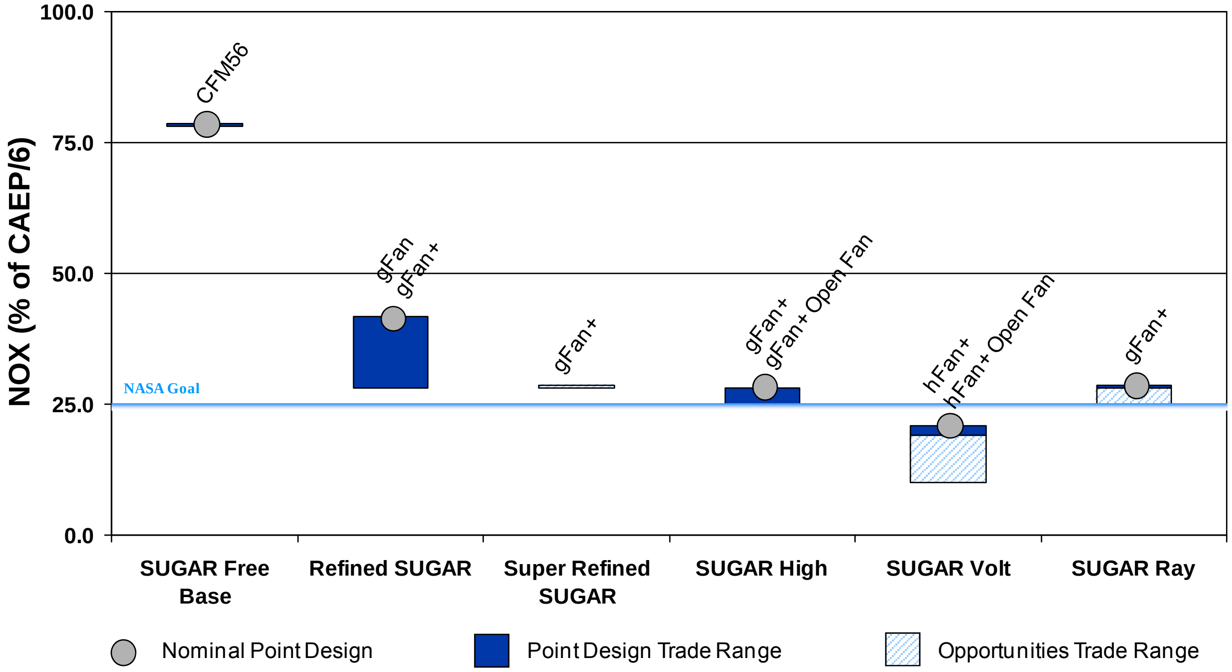


Figure 6.17 – Vehicle NOX Emissions

6.4.4 – Airport DNL Contours

Prior to the calculation of specific configuration noise performance, we conducted a parametric analysis to investigate the impact of projected fleet size and N+3 fleet percentage. These results are summarized in Table 6.22. 55 DNL contours were calculated for the actual 2008 fleet mix (2008 Calibration), and again with a reduced set of aircraft to approximate the 2008 fleet mix (2008 Generic) and serve as a reference to the future fleet mix calculations (2030 Generic & 2055 Generic). In the various scenarios, N+3 aircraft were assumed to be 30 db or 45 db lower than current generation aircraft.

Table 6.22 – Parametrics on dB Reduction and Extent of Noise Footprint

Increasing Operations

MODEL Sizing Level	55 DNL (MI^2)	55 DNL SW Extent (NMI)	55 DNL NE Extent (NMI)
2008 CALIBRATION (7 A/C)	8.6	4.8	5.1
2008 GENERIC (FORECAST FLEET MIX) (No N+3)	9.3	5.8	5.8
2030 GENERIC (FORECAST FLEET MIX) (N+3 =N -30 dB)	14.2	7.2	7.1
2055 GENERIC (FORECAST FLEET MIX) (N+3 =N -30 dB)	10.2	5.4	5.3
2008 GENERIC (N+3 ONLY) (N+3 = N -30 dB)	1.8	2.0	1.8
2030 GENERIC (N+3 ONLY) (N+3 = N -30 dB)	2.5	2.4	2.2
2055 GENERIC (N+3 ONLY) (N+3 = N -30 dB)	3.6	3.1	2.9
2008 GENERIC (N+3 ONLY) (N+3 = N -45 dB)	0.8	1.2	0.9
2030 GENERIC (N+3 ONLY) (N+3 = N -45 dB)	1.0	1.4	1.2
2055 GENERIC (N+3 ONLY) (N+3 = N -45 dB)	1.4	1.8	1.6
AIRPORT BOUNDARY	~3.5	1.7	1.0

For the assumed airport layout, the airport boundaries are at 1.7 and 1.0 miles. With projected fleet growth in 2055, the only scenario that resulted in the 55 DNL contour being at the 1.7 mile airport boundary (approximately, calculated at 1.8 miles) was a 100% N+3 fleet with a -45 db relative noise level (Figure 6.18). To meet the 1.0 mile boundary, only the scenario holding the fleet size at 2008 levels with 100% N+3 aircraft with -45 db relative noise was successful (0.9 miles). All forecast fleet mix scenarios predict a rise in aircraft noise for 2008, 2030, and 2055, as the fleet is expected to grow before N+3 aircraft with significant noise reduction become available in sufficient numbers to start reducing airport noise. The N+3 only scenarios that assume the current fleet is completely phased out, all show a reduction in the 55 DNL contour but are not contained within the airport boundary.

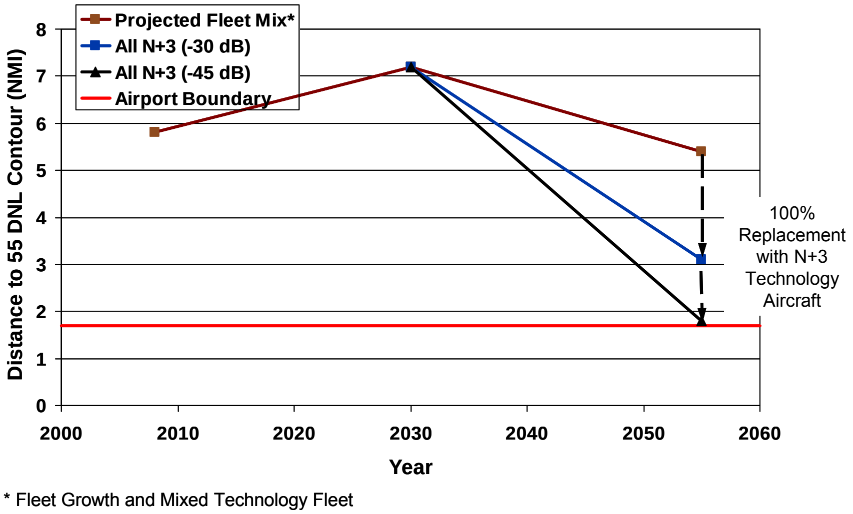


Figure 6.18 – 100% Replacement with N+3 Technology May Meet Goals

Using a list of technologies supplied by GE and Boeing noise engineers, a noise assessment was made for each aircraft concept. The GE noise reduction technologies are shown in Section 7.3.5. The following is a list of assumed airframe noise technologies:

- Airframe weight reduction from improved structures/materials, propulsion, and systems – reduces aircraft size, TOFL, and engine size
- Lightweight low speed high lift devices to reduce thrust required for cutback flyover and approach conditions
- Airframe noise reduction methods including wing planform (airfoil design), main gear fairings, lift & control surface treatments (sealing, etc.)
- Rear fan duct noise treatment methods
- Inlet noise shielding from top of wing mounted engines (SUGAR Ray)
- Rear jet and exhaust fan duct noise shielding from rear deck/platform for flyover and approach noise reduction and twin verticals for lateral noise reduction (need to assess noise shielding increments) and exhaust nozzle designs for distributed jet noise source reduction from shielding (SUGAR Ray)

The configuration noise results are shown in Table 6.23. The Refined SUGAR with the gFan engine acoustic technologies is calculated to have a noise reduction of 16 dB relative to the SUGAR Free CFM-56 Baseline. Adding advanced gFan+ engine acoustics technologies yields an additional 6 dB reduction for the SUGAR High configuration. The additional shielding provided by the HWB configuration, gives the SUGAR Ray an additional benefit of 15 dB. All of the quoted reductions are approximate. The noise build-ups are not necessarily as "linear" as we have assumed, as some technologies may not work together in a simple additive manner. The SUGAR Volt, which essentially uses a gFan+ engine with an added electric motor, was not specifically evaluated, because use of the electric system as part of the noise calculation procedure was not investigated. However, since the electric system is inherently quieter than conventional propulsion, any electric system use would tend to reduce the overall noise. If the best performing configuration, the SUGAR Ray (at -37 dB), is used, then the 55 DNL contour is at approximately 2.5 miles, which is 0.8 miles outside the 1.7 mile airport boundary with a 100% N+3 fleet (Figure 6.19). Additional noise reduction to achieve -45 dB, or a reduction in fleet size, is required to meet the 1.7 mile airport boundary. Both are required to meet the 1.0 mile airport boundary. Alternatively, significant aircraft and engine noise reduction (beyond -45 dB), would be required to bring the 55 DNL boundary inside the 1.0 mile airport boundary for the projected 2055 fleet size.

Table 6.23 – Vehicle Noise Comparison

MODEL		SUGAR Free	Refined SUGAR	SUGAR High	SUGAR Volt	SUGAR Ray
ENGINE MODEL		Scaled CFM56-7B27	Scaled gFan	Scaled gFan+	Scaled hFan	Scaled gFan+
NOISE	dB	0	-16	-22	Better than -22	-37

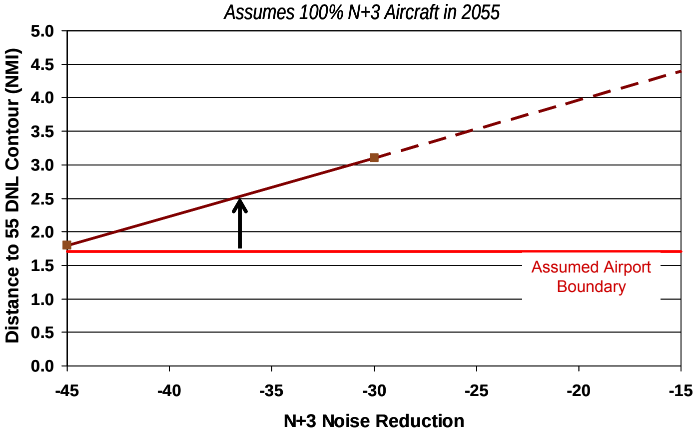


Figure 6.19 – Sensitivity of 55 DNL Distance to N+3 Noise Reduction

Looking at the impact of other N+3 propulsion options is recommended. This includes operational optimization of flight path and throttle cutbacks as well as technologies such as the hybrid electric engine and open fan.

6.4.5 – Environmental Impact of Cruise Emissions

The carbon emissions for each vehicle are calculated from the quantity of fuel burned. The emissions are summarized in Table 6.24. For biofuels, a 50% credit is used. Total life cycle emissions are assumed. Therefore, the CO2 absorbed by growing biomass can offset the CO2 emitted during processing and use in aircraft. A 50% credit assumes either a 50% blend of a carbon neutral biofuel, a pure biofuel which has a 50% reduction of life cycle CO2 emissions, or somewhere in between.

Table 6.24 – Vehicle Emissions Summary

MODEL Sizing Level		SUGAR Free	Refined SUGAR gFan	SUGAR High	SUGAR Volt hFan	SUGAR Ray
EMISSIONS (NOX)	CAEP/6	79.2%	41.7%	28.0%	21.0%	28.0%
EMISSIONS (CO_2) (900 NMI, JET A)	kLB	291 (Base)	162 (-44.2%)	178 (-38.9%)	107 (-63.4%)	148 (-49.1%)
EMISSIONS (CO_2) (900 NMI, BIOFUEL)	kLB	146 (Base)	81 (-44.5%)	89 (-39.0%)	54 (-63.0%)	74 (-49.3%)

6.5 – Sized Configuration Summary Table

The following table (Table 6.25) summarizes the sized aircraft characteristics and performance. Note that this is the summary of all the baseline configurations. Many trade studies had significantly better and worse performance depending on the trade and metric of interest.

Table 6.25 – Sized Baseline Vehicle Summary

MODEL Sizing Level		SUGAR Free	Refined SUGAR	SUGAR High	SUGAR Volt	SUGAR Ray
PASSENGERS / CLASS		154 / Dual	154 / Dual	154 / Dual	154 / Dual	154 / Dual
MAX TAKEOFF WEIGHT	LB	184,800	139,700	176,800	154,900	172,600
MAX LANDING WEIGHT	LB	151,000	131,800	167,300	148,600	165,300
MAX ZERO FUEL WEIGHT	LB	142,000	123,800	159,300	140,600	157,300
OPERATING EMPTY WEIGHT	LB	96,000	77,800	113,300	94,600	111,300
FUEL CAPACITY REQ	USG	9,710	5,512	5,754	5,250	5,392
ENGINE MODEL		Scaled CFM56-7B27	Scaled gFan	Scaled gFan+	Scaled hFan	Scaled gFan+
FAN DIAMETER	IN	62	66	86	80	81
BOEING EQUIVLENT THRUST (BET)	LB	28,200	15,700	19,600	17,300	17,500
WING AREA / SPAN	FT^2 / FT	1429 / 122	1440 / 129	1722 / 215	1498 / 201	4139 / 180
ASPECT RATIO (EFFECTIVE)		10.41	11.63	26.94	26.94	26.94
OPTIMUM CL		0.583	0.654	0.828	0.831	0.316
CRUISE L/D @ OPT CL		18.068	21.981	25.934	24.992	27.471
DESIGN MISSION RANGE	NMI	3,500	3,500	3,500	3,500	3,500
PERFORMANCE CRUISE MACH		0.785	0.70	0.70	0.70	0.70
LONG RANGE CRUISE MACH (LRC)		0.785	0.70	0.70	0.70	0.70
THRUST ICAC (MTOW, ISA)	FT	37,200	38,800	43,300	42,800	42,400
TIME / DIST (MTOW, 35k FT, ISA)	MIN / NMI	23 / 148	29 / 182	29 / 182	29 / 178	28 / 180
OPTIMUM ALTITUDE (MTOW, ISA)	FT	35,000	38,400	42,100	42,000	40,800
BUFFET ICAC (MTOW, ISA)	FT	36,200	45,200	44,000	43,900	
TOFL (MTOW, SEA LEVEL, 86 DEG F)	FT	8,190	8,190	8,190	8,180	7,900
APPROACH SPEED (MLW)	KT	126	115	115	116	103
BLOCK FUEL / SEAT (900 NMI)	LB	92.35 (Base)	51.53 (-44.2%)	56.43 (-38.9%)	33.83 (-63.4%)	52.37 (-43.3%)
NOISE	dB	0 (Base)	-16	-22	<=-22	-37
EMISSIONS (NOX)	CAEP/6	79.2%	41.7%	28.0%	21.0%	28.0%
EMISSIONS (CO_2) (900 NMI, JET A)	LB	291 (Base)	162 (-44.2%)	178 (-38.9%)	107 (-63.4%)	148 (-43.3%)

Figure 6.20 shows the baseline configuration payload-range curves. Notice the TOGW curves of the advanced concepts have significantly lower slope than SUGAR Free. This is a direct result of the advanced technologies and stems from the improvements made in lift-to-drag ratio, specific fuel consumption, and empty weight fraction.

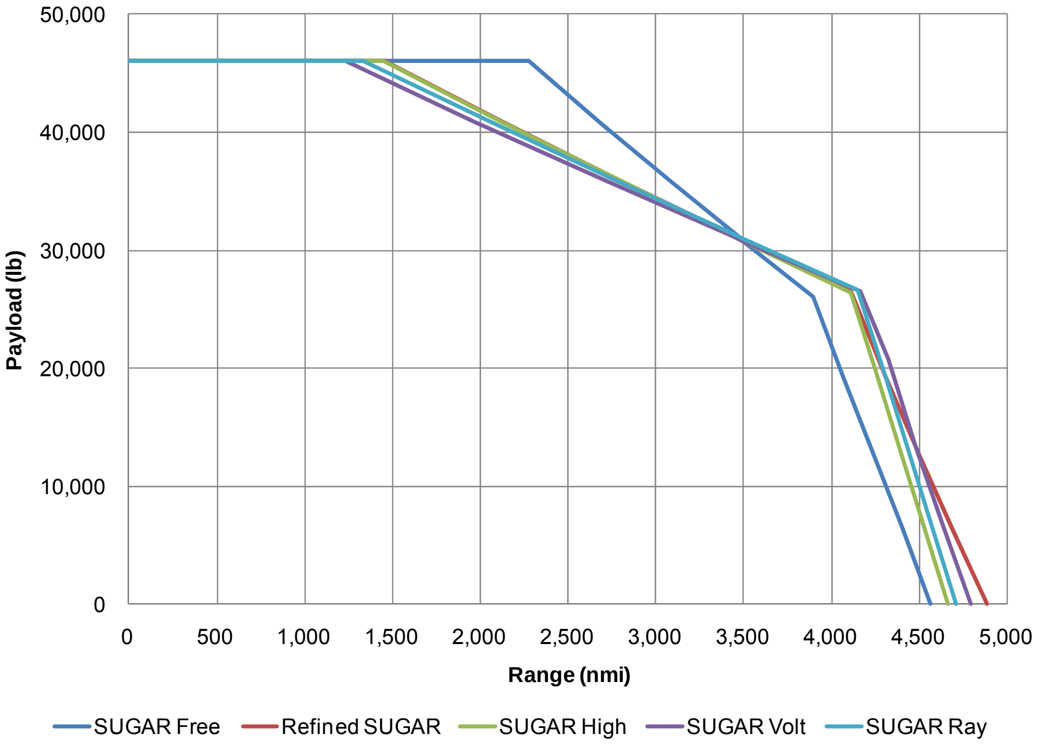
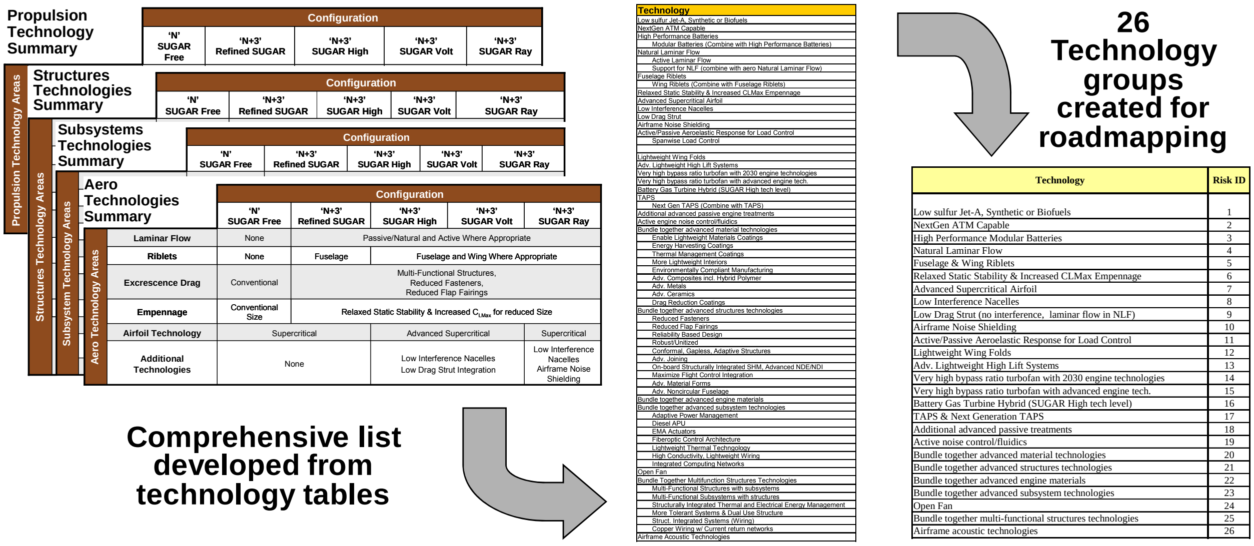


Figure 6.20 – Sized Baseline Configuration Payload-Range

7.0 – Technology Roadmaps and Risk Assessment

The technology suites generated previously for each configuration were used as the starting point for this assessment. These technology tables are in Section 4.0. A comprehensive list containing approximately 75 technologies was generated from these technology tables (Figure 7.1). These technologies were then grouped into 26 technology groups for sensitivity analysis, ranking, and roadmapping.



	Configuration				
	'N' SUGAR Free	'N+3' Refined SUGAR	'N+3' SUGAR High	'N+3' SUGAR Volt	'N+3' SUGAR Ray
Laminar Flow	None	Passive/Natural and Active Where Appropriate			
Riblets	None	Fuselage	Fuselage and Wing Where Appropriate		
Excrescence Drag	Conventional	Multi-Functional Structures, Reduced Fasteners, Reduced Flap Fairings			
Empennage	Conventional Size	Relaxed Static Stability & Increased C_{LMax} for reduced Size			
Airfoil Technology	Supercritical		Advanced Supercritical		Supercritical
Additional Technologies	None		Low Interference Nacelles Low Drag Strut Integration		Low Interference Nacelles Airframe Noise Shielding

Technology
Low sulfur Jet-A, Synthetic or Biofuels
NextGen ATM Capable
High Performance Batteries
Modular Batteries (Combine with High Performance Batteries)
Natural Laminar Flow
Active Laminar Flow
Support for NLF (combine with aero Natural Laminar Flow)
Fuselage Riblets
Wing Riblets (Combine with Fuselage Riblets)
Relaxed Static Stability & Increased CLMax Empennage
Advanced Supercritical Airfoil
Low Interference Nacelles
Low Drag Strut
Airframe Noise Shielding
Active/Passive Aeroelastic Response for Load Control
Spanwise Load Control
Lightweight Wing Folds
Adv. Lightweight High Lift Systems
Very high bypass ratio turbofan with 2030 engine technologies
Very high bypass ratio turbofan with advanced engine tech.
Battery Gas Turbine Hybrid (SUGAR High tech level)
TAPS
Next Gen TAPS (Combine with TAPS)
Additional advanced passive engine treatments
Active engine noise control/fluidics
Bundle together advanced material technologies
Enable Lightweight Materials Coatings
Energy Harvesting Coatings
Thermal Management Coatings
More Lightweight Interiors
Environmentally Compliant Manufacturing
Adv. Composites incl. Hybrid Polymer
Adv. Metals
Adv. Ceramics
Drag Reduction Coatings
Bundle together advanced structures technologies
Reduced Fasteners
Reduced Flap Fairings
Reliability Based Design
Robust/Unitized
Conformal, Gapless, Adaptive Structures
Adv. Joining
On-board Structurally Integrated SHM, Advanced NDE/NDI
Maximize Flight Control Integration
Adv. Material Forms
Adv. Noncircular Fuselage
Bundle together advanced engine materials
Bundle together advanced subsystem technologies
Adaptive Power Management
Diesel APU
EMA Actuators
Fiberoptic Control Architecture
Lightweight Thermal Techngology
High Conductivity, Lightweight Wiring
Integrated Computing Networks
Open Fan
Bundle Together Multifunction Structures Technologies
Multi-Functional Structures with subsystems
Multi-Functional Subsystems with structures
Structurally Integrated Thermal and Electrical Energy Management
More Tolerant Systems & Dual Use Structure
Struct. Integrated Systems (Wiring)
Copper Wiring w/ Current return networks
Airframe Acoustic Technologies

Technology	Risk ID
Low sulfur Jet-A, Synthetic or Biofuels	1
NextGen ATM Capable	2
High Performance Modular Batteries	3
Natural Laminar Flow	4
Fuselage & Wing Riblets	5
Relaxed Static Stability & Increased CLMax Empennage	6
Advanced Supercritical Airfoil	7
Low Interference Nacelles	8
Low Drag Strut (no interference, laminar flow in NLF)	9
Airframe Noise Shielding	10
Active/Passive Aeroelastic Response for Load Control	11
Lightweight Wing Folds	12
Adv. Lightweight High Lift Systems	13
Very high bypass ratio turbofan with 2030 engine technologies	14
Very high bypass ratio turbofan with advanced engine tech.	15
Battery Gas Turbine Hybrid (SUGAR High tech level)	16
TAPS & Next Generation TAPS	17
Additional advanced passive treatments	18
Active noise control/fluidics	19
Bundle together advanced material technologies	20
Bundle together advanced structures technologies	21
Bundle together advanced engine materials	22
Bundle together advanced subsystem technologies	23
Open Fan	24
Bundle together multi-functional structures technologies	25
Airframe acoustic technologies	26

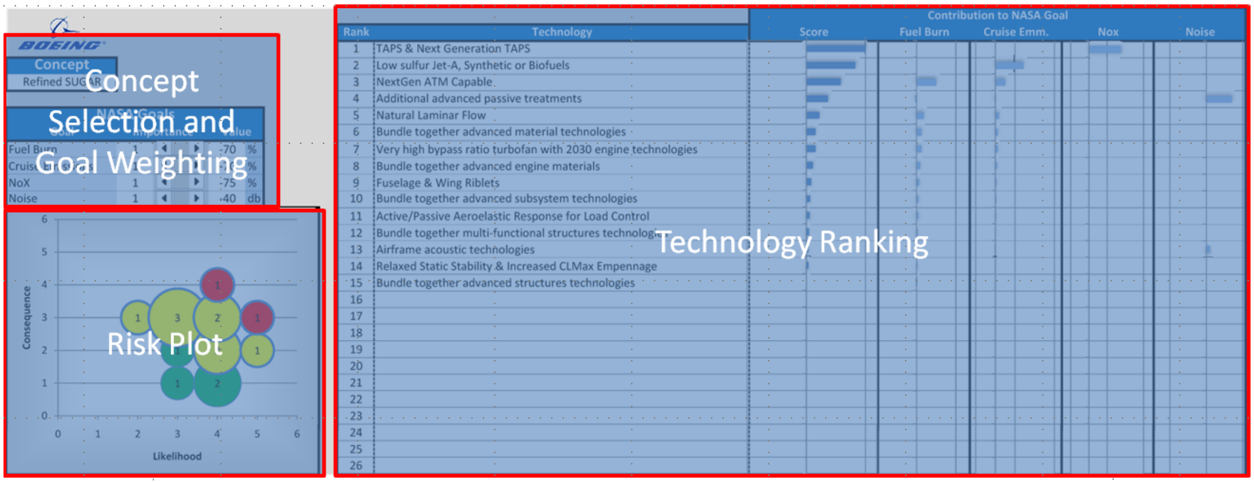
Figure 7.1 – Generation of Technology Groups

After preparation of these technology lists and groups, and an initial assessment, a virtual Technology Workshop was held with all members of the SUGAR team. At this workshop, the team accelerated the generation of inputs and validated results to support the technology risk assessment and roadmapping process. The risk assessment results are documented here. This information was used as a starting point for the generation of the technology roadmaps.

7.1 – Technology Ranking

Technology impacts were obtained through either the direct modeling of the technologies on the vehicles or sensitivity analysis of certain parameters which they affect. At the top level each technology is scored against how much improvement of each NASA goal it produces and then these impacts are rolled up to a total value based on weightings for each of the goals. It should be noted that these rankings do not capture the compounded effect of synergistic technologies, as the sensitivity of each goal to each technology was evaluated independently. All the information was compiled into a front end dashboard tool which allowed for dynamic tradeoffs to occur and be visualized.

The dashboard allows for goal weighting tradeoffs to be made and the impacts on the technology ranking to be assessed in real time. The layout shows several pieces of information which are highlighted in Figure 7.2. The top left corner contains the concept selection and goal weightings where the user can determine which technologies to assess and how much priority to assign to each of the goals in the calculation of the overall score. The majority of the screen is dominated by the technology ranking itself where each tech is listed in order based on its impact to the goals. If a Technology is not applicable to the concept selected or has no impact on the goals then it is hidden from view. Next to the rankings the graphs depict the overall score of the technologies based on the goal weightings as well as the individual goal contribution that each provides. The plot in the lower left hand corner shows the risk of the technologies which appear in the ranking with the size of the bubble indicating how many technologies have the associated likelihood and consequence value.



Rank	Technology
1	TAPS & Next Generation TAPS
2	Low sulfur Jet-A, Synthetic or Biofuels
3	NextGen ATM Capable
4	Additional advanced passive treatments
5	Natural Laminar Flow
6	Bundle together advanced material technologies
7	Very high bypass ratio turbofan with 2030 engine technologies
8	Bundle together advanced engine materials
9	Fuselage & Wing Riblets
10	Bundle together advanced subsystem technologies
11	Active/Passive Aeroelastic Response for Load Control
12	Bundle together multi-functional structures technologies
13	Airframe acoustic technologies
14	Relaxed Static Stability & Increased CLMax Empennage
15	Bundle together advanced structures technologies
16	
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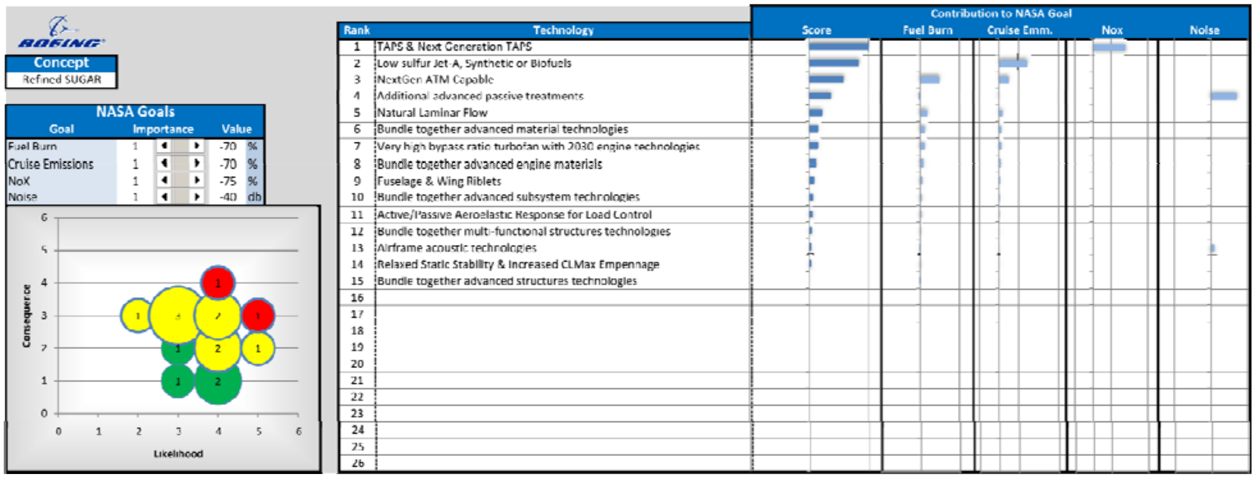
Figure 7.2 – Technology Ranking Dashboard Layout

This dashboard was utilized to create the following technology ranking figures. For the purpose of the final report the technologies were ranked for each aircraft using a variety of weightings: equal weighting, fuel burn only, cruise emissions only, NOx only, and noise only (Figure 7.3 – Figure 7.22).

A wide range of technologies contribute to the fuel burn reduction goal. The highest ranking fuel burn technologies are the Next Generation Air Traffic Management System, laminar flow, and engine technologies. However, 10-15 technologies make significant contributions. For cruise greenhouse gas emissions, biofuels and the Next Generation Air Traffic Management System have the highest rankings. TAPS & next generation TAPS combustor technologies are key to reducing LTO NOx. Finally, engine and airframe noise technologies, as well as airframe shielding, are critical to the NASA noise goal.



Concept
Refined SUGAR

NASA Goals		
Goal	**Importance**	**Value**
Fuel Burn	1	-70 %
Cruise Emissions	1	-70 %
NoX	1	-75 %
Noise	1	-40 db

Rank	Technology
1	TAPS & Next Generation TAPS
2	Low sulfur Jet-A, Synthetic or Biofuels
3	NextGen ATM Capable
4	Additional advanced passive treatments
5	Natural Laminar Flow
6	Bundle together advanced material technologies
7	Very high bypass ratio turbofan with 2030 engine technologies
8	Bundle together advanced engine materials
9	Fuselage & Wing Riblets
10	Bundle together advanced subsystem technologies
11	Active/Passive Aeroelastic Response for Load Control
12	Bundle together multi-functional structures technologies
13	Airframe acoustic technologies
14	Relaxed Static Stability & Increased CLMax Empennage
15	Bundle together advanced structures technologies
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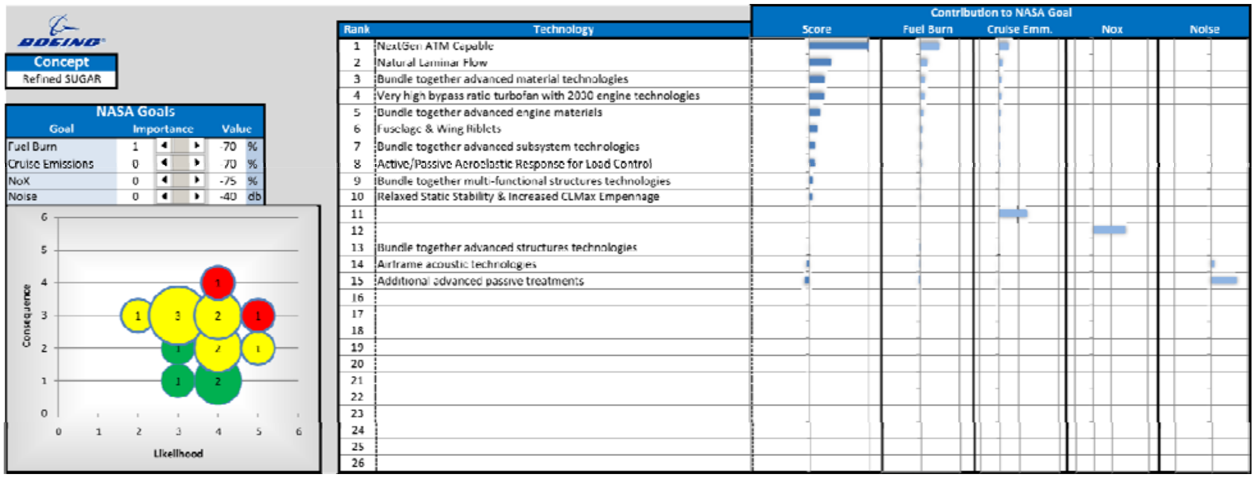
Figure 7.3 – Refined SUGAR Technology Ranking with Equal Goal Weighting



Concept
Refined SUGAR

NASA Goals		
Goal	**Importance**	**Value**
Fuel Burn	1	-70 %
Cruise Emissions	0	-70 %
NoX	0	-75 %
Noise	0	-40 db

Rank	Technology
1	NextGen ATM Capable
2	Natural Laminar Flow
3	Bundle together advanced material technologies
4	Very high bypass ratio turbofan with 2030 engine technologies
5	Bundle together advanced engine materials
6	Fuselage & Wing Riblets
7	Bundle together advanced subsystem technologies
8	Active/Passive Aeroelastic Response for Load Control
9	Bundle together multi-functional structures technologies
10	Relaxed Static Stability & Increased CLMax Empennage
11	
12	
13	Bundle together advanced structures technologies
14	Airframe acoustic technologies
15	Additional advanced passive treatments
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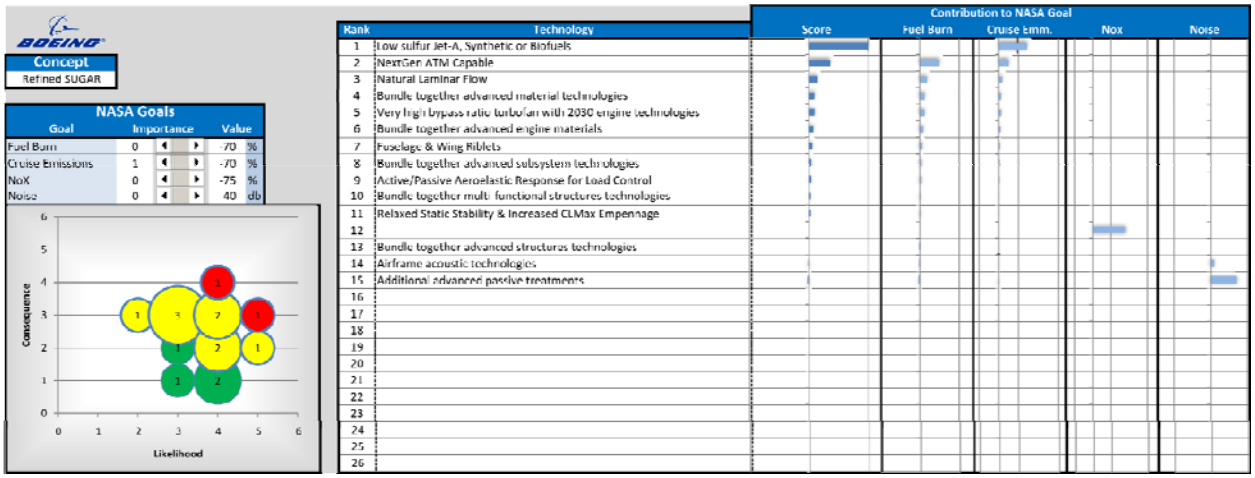
Figure 7.4 – Refined SUGAR Technology Ranking for Fuel Burn Goal



Concept
Refined SUGAR

NASA Goals		
Goal	**Importance**	**Value**
Fuel Burn	0	-70 %
Cruise Emissions	1	-70 %
NoX	0	-75 %
Noise	0	40 db

Rank	Technology
1	Low sulfur Jet-A, Synthetic or Biofuels
2	NextGen ATM Capable
3	Natural Laminar Flow
4	Bundle together advanced material technologies
5	Very high bypass ratio turbofan with 2030 engine technologies
6	Bundle together advanced engine materials
7	Fuselage & Wing Riblets
8	Bundle together advanced subsystem technologies
9	Active/Passive Aeroelastic Response for Load Control
10	Bundle together multi-functional structures technologies
11	Relaxed Static Stability & Increased CLMax Empennage
12	
13	Bundle together advanced structures technologies
14	Airframe acoustic technologies
15	Additional advanced passive treatments
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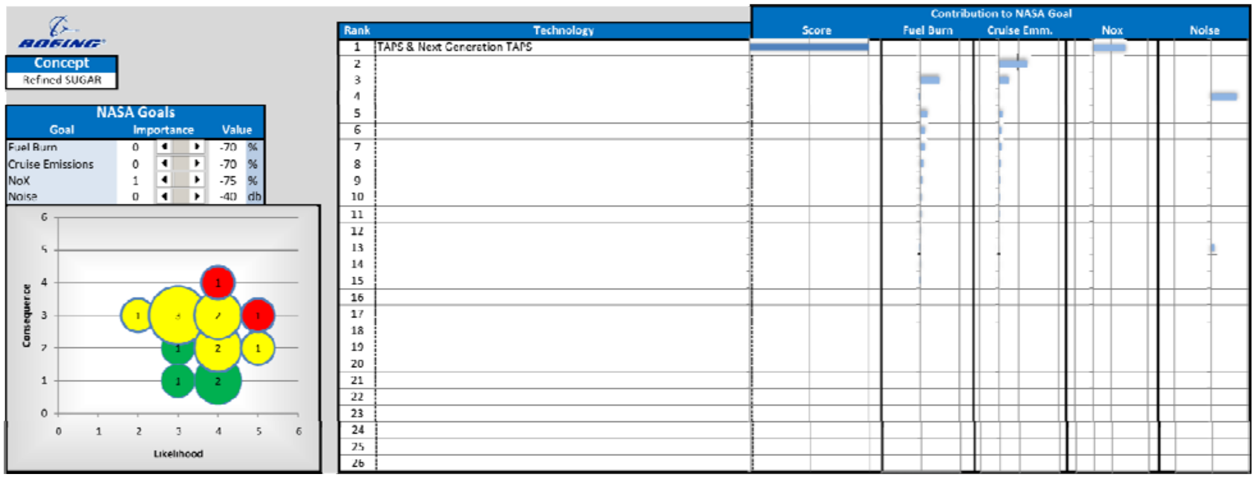
Figure 7.5 – Refined SUGAR Technology Ranking for Cruise Emissions Goal



Concept
Refined SUGAR

NASA Goals			
Goal	**Importance**	**Value**	
Fuel Burn	0	-70	%
Cruise Emissions	0	-70	%
NoX	1	-75	%
Noise	0	-40	db

Rank	Technology
1	TAPS & Next Generation TAPS
2	
3	
4	
5	
6	
7	
8	
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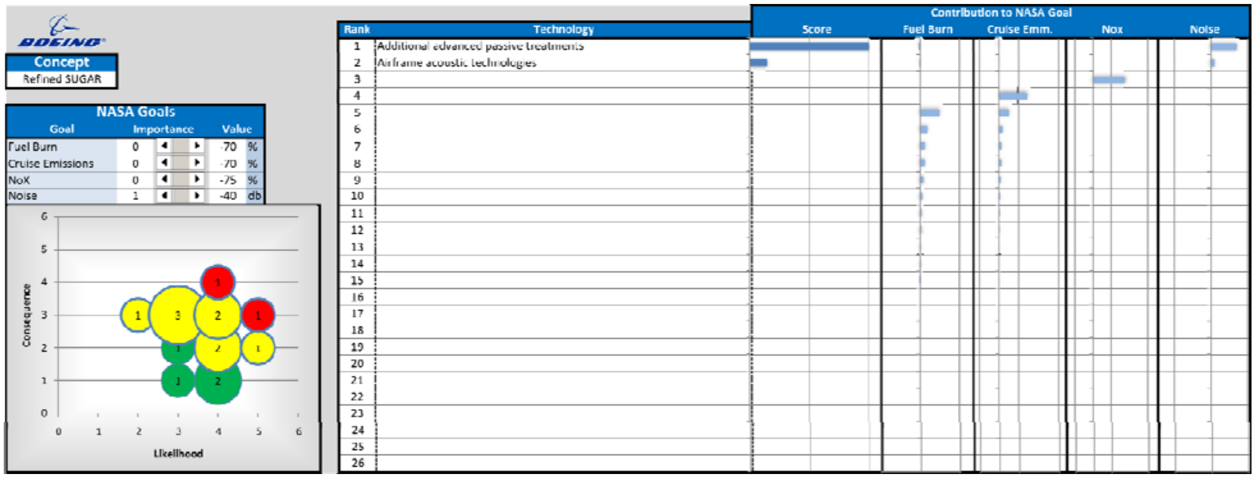
Figure 7.6 – Refined SUGAR Technology Ranking for NOx Reduction Goal



Concept
Refined SUGAR

NASA Goals			
Goal	**Importance**	**Value**	
Fuel Burn	0	-70	%
Cruise Emissions	0	-70	%
NoX	0	-75	%
Noise	1	-40	db

Rank	Technology
1	Additional advanced passive treatments
2	Airframe acoustic technologies
3	
4	
5	
6	
7	
8	
9	
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11	
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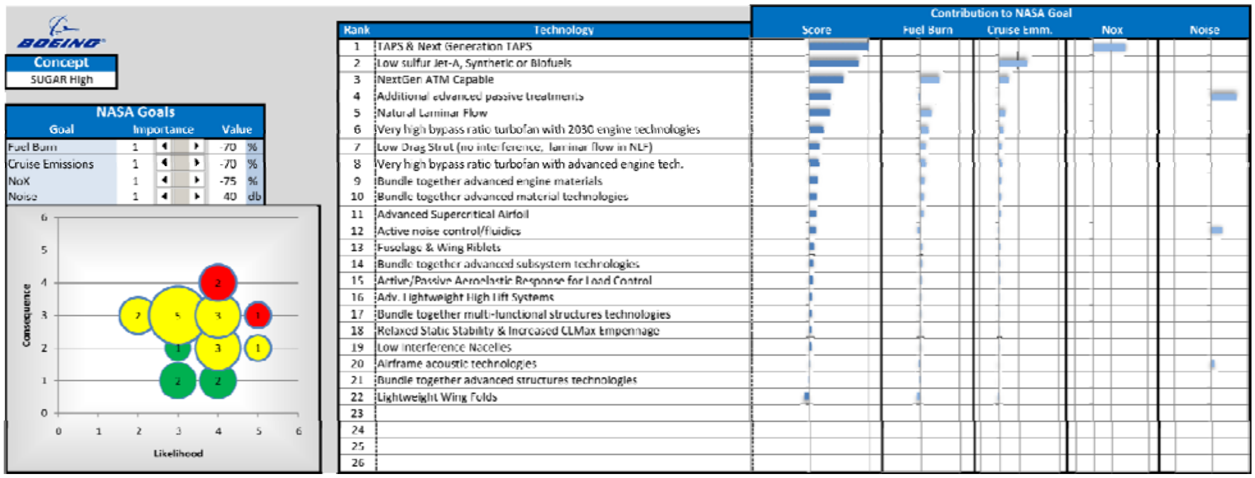
Figure 7.7 – Refined SUGAR Technology Ranking for Noise Reduction Goal



Concept
SUGAR High

NASA Goals			
Goal	**Importance**	**Value**	
Fuel Burn	1	-70	%
Cruise Emissions	1	-70	%
NoX	1	-75	%
Noise	1	40	db

Rank	Technology
1	TAPS & Next Generation TAPS
2	Low sulfur Jet-A, Synthetic or Biofuels
3	NextGen ATM Capable
4	Additional advanced passive treatments
5	Natural Laminar Flow
6	Very high bypass ratio turbofan with 2030 engine technologies
7	Low Drag Strut (no interference, laminar flow in NLF)
8	Very high bypass ratio turbofan with advanced engine tech.
9	Bundle together advanced engine materials
10	Bundle together advanced material technologies
11	Advanced Supercritical Airfoil
12	Active noise control/fluidics
13	Fuselage & Wing Riblets
14	Bundle together advanced subsystem technologies
15	Active/Passive Aeroelastic Response for Load Control
16	Adv. Lightweight High Lift Systems
17	Bundle together multi-functional structures technologies
18	Relaxed Static Stability & Increased CLMax Empennage
19	Low Interference Nacelles
20	Airframe acoustic technologies
21	Bundle together advanced structures technologies
22	Lightweight Wing Folds
23	
24	
25	
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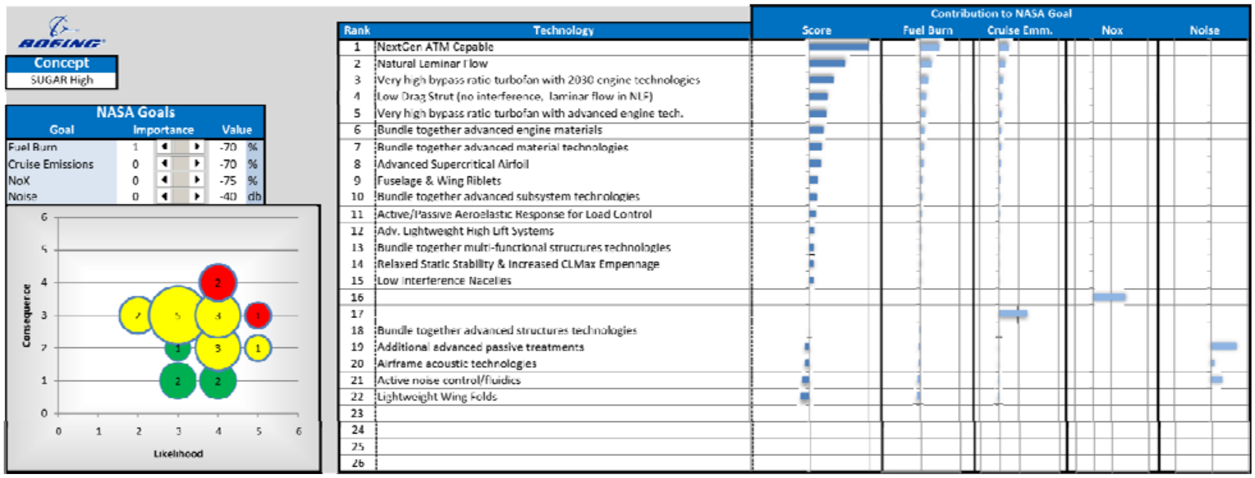
Figure 7.8 – SUGAR High Technology Ranking with Equal Goal Weighting



NASA Goals		
Goal	Importance	Value
Fuel Burn	1	-70 %
Cruise Emissions	0	-70 %
NoX	0	-75 %
Noise	0	-40 db

Rank	Technology
1	NextGen ATM Capable
2	Natural Laminar Flow
3	Very high bypass ratio turbofan with 2030 engine technologies
4	Low Drag Strut (no interference, laminar flow in NLF)
5	Very high bypass ratio turbofan with advanced engine tech.
6	Bundle together advanced engine materials
7	Bundle together advanced material technologies
8	Advanced Supercritical Airfoil
9	Fuselage & Wing Riblets
10	Bundle together advanced subsystem technologies
11	Active/Passive Aeroelastic Response for Load Control
12	Adv. Lightweight High Lift Systems
13	Bundle together multi-functional structures technologies
14	Relaxed Static Stability & Increased CLMax Empennage
15	Low Interference Nacelles
16	
17	
18	Bundle together advanced structures technologies
19	Additional advanced passive treatments
20	Airframe acoustic technologies
21	Active noise control/fluidics
22	Lightweight Wing Folds
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24	
25	
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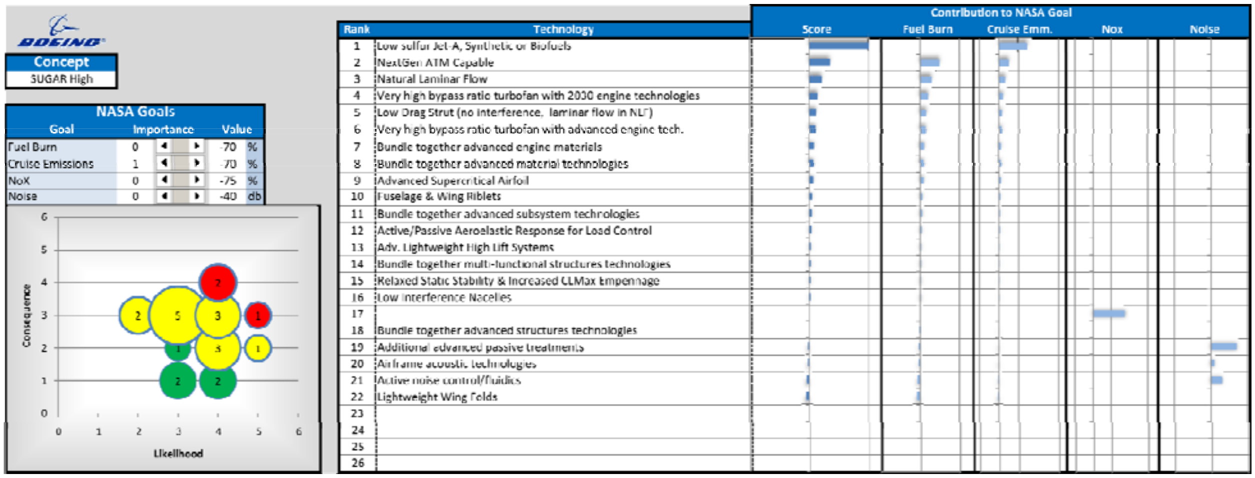
Figure 7.9 – SUGAR High Technology Ranking for Fuel Burn Goal



NASA Goals		
Goal	Importance	Value
Fuel Burn	0	-70 %
Cruise Emissions	1	-70 %
NoX	0	-75 %
Noise	0	-40 db

Rank	Technology
1	Low sulfur Jet-A, Synthetic or Biofuels
2	NextGen ATM Capable
3	Natural Laminar Flow
4	Very high bypass ratio turbofan with 2030 engine technologies
5	Low Drag Strut (no interference, laminar flow in NLF)
6	Very high bypass ratio turbofan with advanced engine tech.
7	Bundle together advanced engine materials
8	Bundle together advanced material technologies
9	Advanced Supercritical Airfoil
10	Fuselage & Wing Riblets
11	Bundle together advanced subsystem technologies
12	Active/Passive Aeroelastic Response for Load Control
13	Adv. Lightweight High Lift Systems
14	Bundle together multi-functional structures technologies
15	Relaxed Static Stability & Increased CLMax Empennage
16	Low Interference Nacelles
17	
18	Bundle together advanced structures technologies
19	Additional advanced passive treatments
20	Airframe acoustic technologies
21	Active noise control/fluidics
22	Lightweight Wing Folds
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25	
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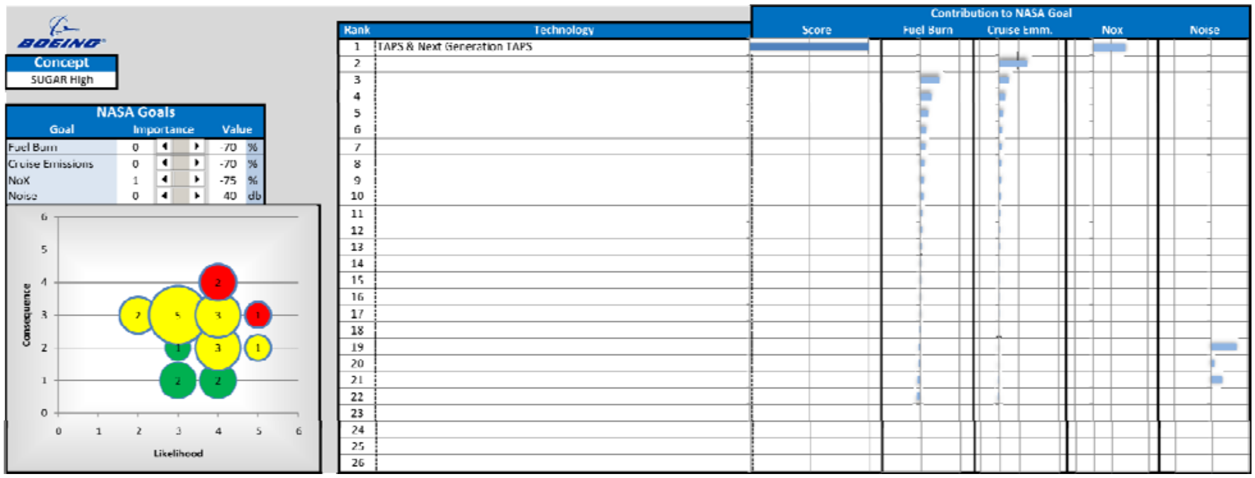
Figure 7.10 – SUGAR High Technology Ranking for Cruise Emissions Goal



NASA Goals		
Goal	Importance	Value
Fuel Burn	0	-70 %
Cruise Emissions	0	-70 %
NoX	1	-75 %
Noise	0	40 db

Rank	Technology
1	TAPS & Next Generation TAPS
2	
3	
4	
5	
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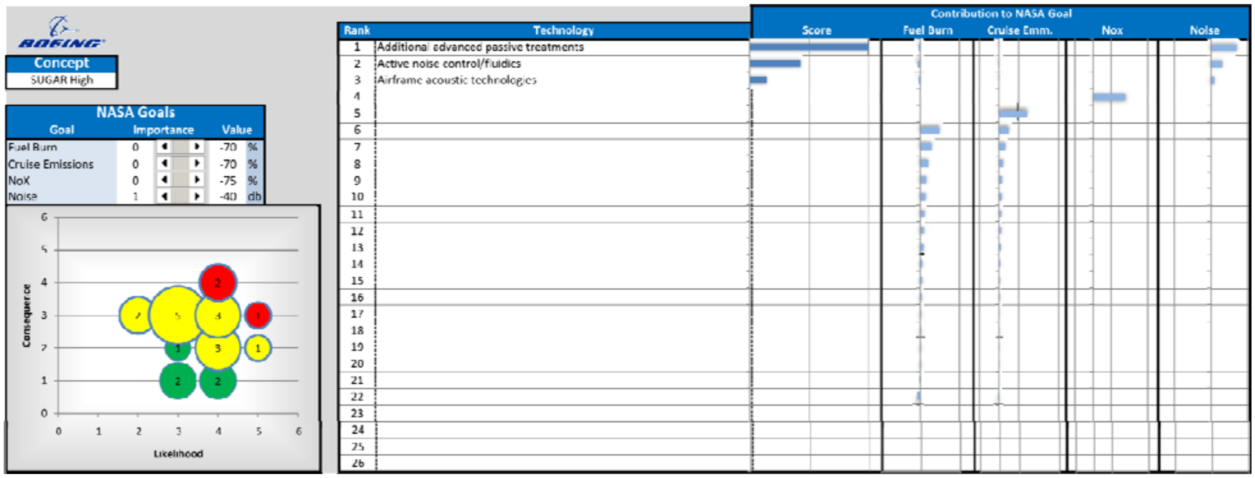
Figure 7.11 – SUGAR High Technology Ranking for NOx Reduction Goal



Concept
SUGAR High

Goal	Importance	Value	
Fuel Burn	0	-70	%
Cruise Emissions	0	-70	%
NoX	0	-75	%
Noise	1	-40	db

Rank	Technology
1	Additional advanced passive treatments
2	Active noise control/fluidics
3	Airframe acoustic technologies
4	
5	
6	
7	
8	
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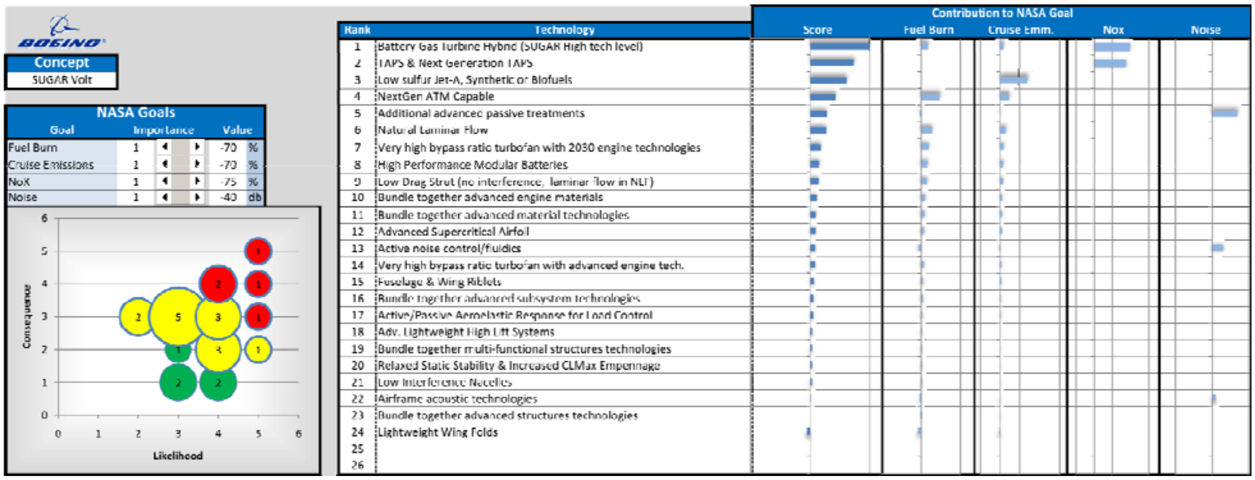
Figure 7.12 – SUGAR High Technology Ranking for Noise Reduction Goal

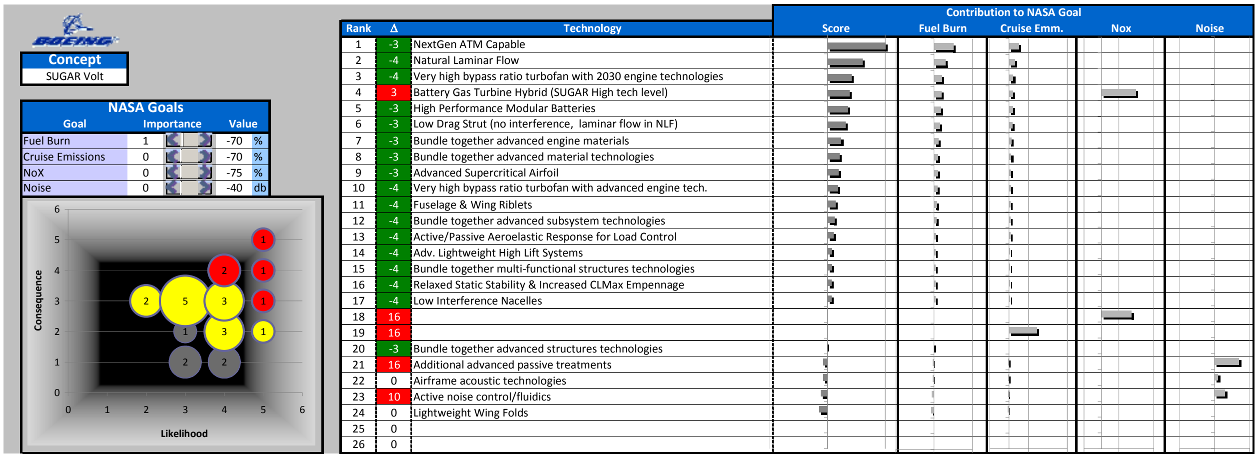


Concept
SUGAR Volt

Goal	Importance	Value	
Fuel Burn	1	-70	%
Cruise Emissions	1	-70	%
NoX	1	-75	%
Noise	1	-40	db

Rank	Technology
1	Battery Gas Turbine Hybrid (SUGAR High tech level)
2	TAPS & Next Generation TAPS
3	Low sulfur Jet-A, Synthetic or Biofuels
4	NextGen ATM Capable
5	Additional advanced passive treatments
6	Natural Laminar Flow
7	Very high bypass ratio turbofan with 2030 engine technologies
8	High Performance Modular Batteries
9	Low Drag Strut (no interference, laminar flow in NLF)
10	Bundle together advanced engine materials
11	Bundle together advanced material technologies
12	Advanced Supercritical Airfoil
13	Active noise control/fluidics
14	Very high bypass ratio turbofan with advanced engine tech.
15	Fuselage & Wing Riblets
16	Bundle together advanced subsystem technologies
17	Active/Passive Aeroelastic Response for Load Control
18	Adv. Lightweight High Lift Systems
19	Bundle together multi-functional structures technologies
20	Relaxed Static Stability & Increased CLMax Empennage
21	Low Interference Nacelles
22	Airframe acoustic technologies
23	Bundle together advanced structures technologies
24	Lightweight Wing Folds
25	
26	

Figure 7.13 – SUGAR Volt Technology Ranking with Equal Goal Weighting

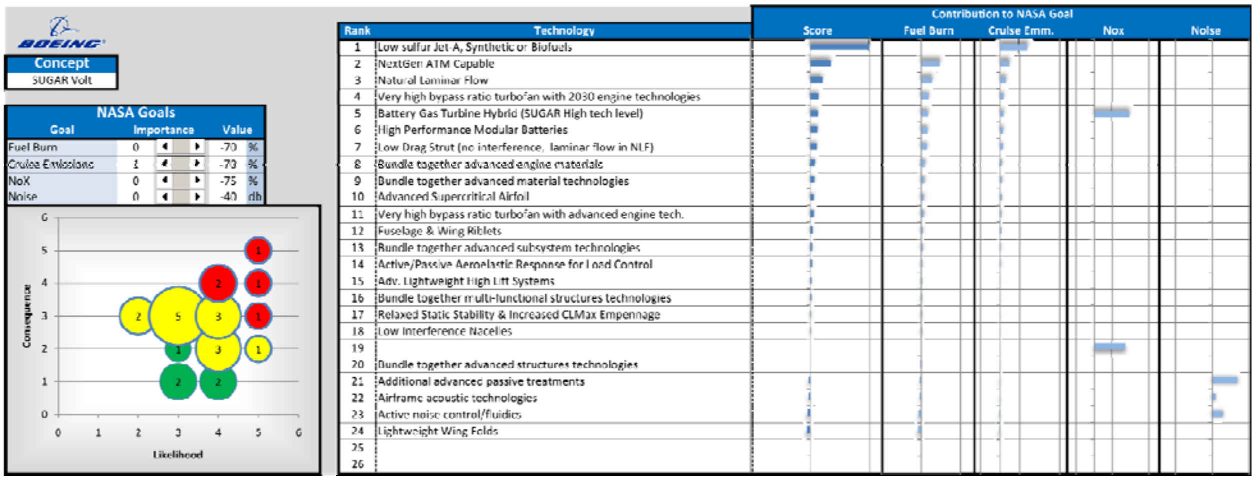


Concept
SUGAR Volt

Goal	Importance	Value	
Fuel Burn	1	-70	%
Cruise Emissions	0	-70	%
NoX	0	-75	%
Noise	0	-40	db

Rank	Δ	Technology
1	-3	NextGen ATM Capable
2	-4	Natural Laminar Flow
3	-4	Very high bypass ratio turbofan with 2030 engine technologies
4	3	Battery Gas Turbine Hybrid (SUGAR High tech level)
5	-3	High Performance Modular Batteries
6	-3	Low Drag Strut (no interference, laminar flow in NLF)
7	-3	Bundle together advanced engine materials
8	-3	Bundle together advanced material technologies
9	-3	Advanced Supercritical Airfoil
10	-4	Very high bypass ratio turbofan with advanced engine tech.
11	-4	Fuselage & Wing Riblets
12	-4	Bundle together advanced subsystem technologies
13	-4	Active/Passive Aeroelastic Response for Load Control
14	-4	Adv. Lightweight High Lift Systems
15	-4	Bundle together multi-functional structures technologies
16	-4	Relaxed Static Stability & Increased CLMax Empennage
17	-4	Low Interference Nacelles
18	16	
19	16	
20	-3	Bundle together advanced structures technologies
21	16	Additional advanced passive treatments
22	0	Airframe acoustic technologies
23	10	Active noise control/fluidics
24	0	Lightweight Wing Folds
25	0	
26	0	

Figure 7.14 – SUGAR Volt Technology Ranking for Fuel Burn Goal

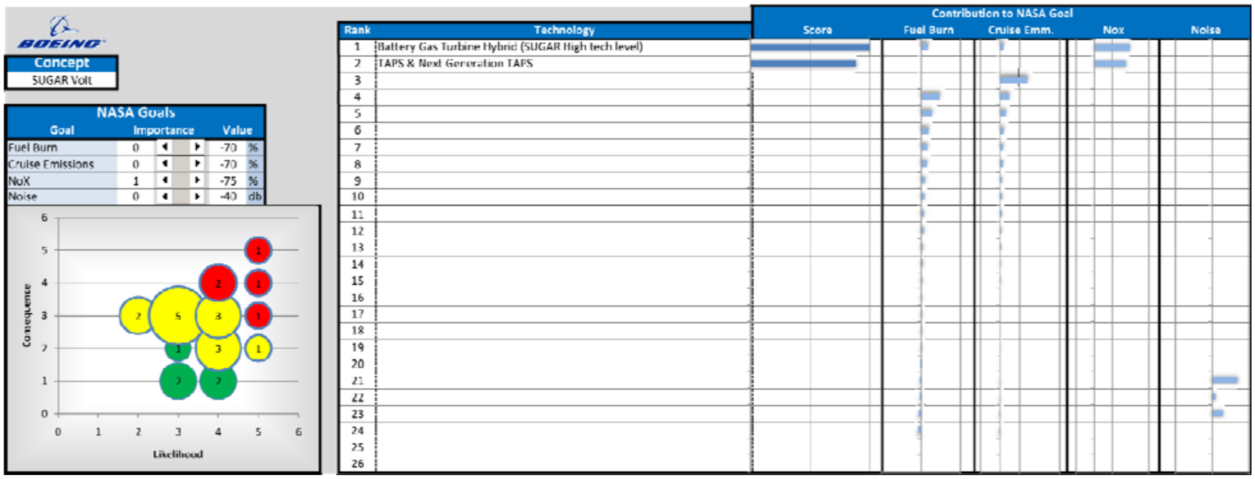


Concept
SUGAR Volt

NASA Goals			
Goal	Importance	Value	
Fuel Burn	0	-70	%
Cruise Emissions	1	-70	%
NoX	0	-75	%
Noise	0	-40	db

Rank	Technology	Score	Fuel Burn	Cruise Emm.	Nox	Noise
1	Low sulfur Jet-A, Synthetic or Biofuels					
2	NextGen ATM Capable					
3	Natural Laminar Flow					
4	Very high bypass ratio turbofan with 2030 engine technologies					
5	Battery Gas Turbine Hybrid (SUGAR High tech level)					
6	High Performance Modular Batteries					
7	Low Drag Strut (no interference, laminar flow in NLF)					
8	Bundle together advanced engine materials					
9	Bundle together advanced material technologies					
10	Advanced Supercritical Airfoil					
11	Very high bypass ratio turbofan with advanced engine tech.					
12	Fuselage & Wing Riblets					
13	Bundle together advanced subsystem technologies					
14	Active/Passive Aeroelastic Response for Load Control					
15	Adv. Lightweight High Lift Systems					
16	Bundle together multi-functional structures technologies					
17	Relaxed Static Stability & Increased CLMax Empennage					
18	Low Interference Nacelles					
19						
20	Bundle together advanced structures technologies					
21	Additional advanced passive treatments					
22	Airframe acoustic technologies					
23	Active noise control/fluidics					
24	Lightweight Wing Folds					
25						
26						

Figure 7.15 – SUGAR Volt Technology Ranking for Cruise Emissions Goal



Concept
SUGAR Volt

NASA Goals			
Goal	Importance	Value	
Fuel Burn	0	-70	%
Cruise Emissions	0	-70	%
NoX	1	-75	%
Noise	0	-40	db

Rank	Technology	Score	Fuel Burn	Cruise Emm.	Nox	Noise
1	Battery Gas Turbine Hybrid (SUGAR High tech level)					
2	TAPS & Next Generation TAPS					
3						
4						
5						
6						
7						
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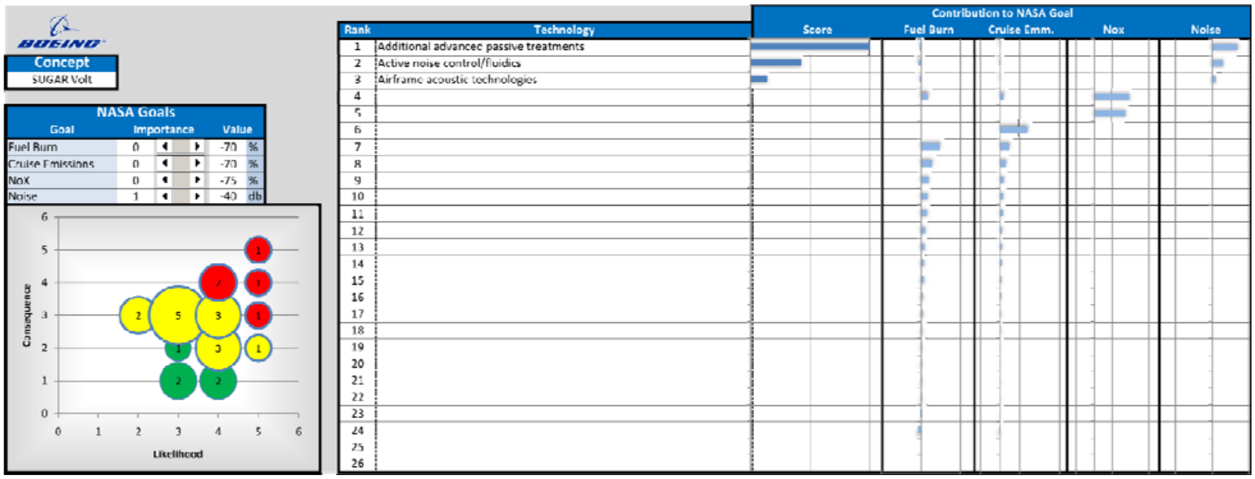
Figure 7.16 – SUGAR Volt Technology Ranking for NOx Reduction Goal



Concept
SUGAR Volt

NASA Goals			
Goal	Importance	Value	
Fuel Burn	0	-70	%
Cruise Emissions	0	-70	%
NoX	0	-75	%
Noise	1	-40	db

Rank	Technology	Score	Fuel Burn	Cruise Emm.	Nox	Noise
1	Additional advanced passive treatments					
2	Active noise control/fluidics					
3	Airframe acoustic technologies					
4						
5						
6						
7						
8						
9						
10						
11						
12						
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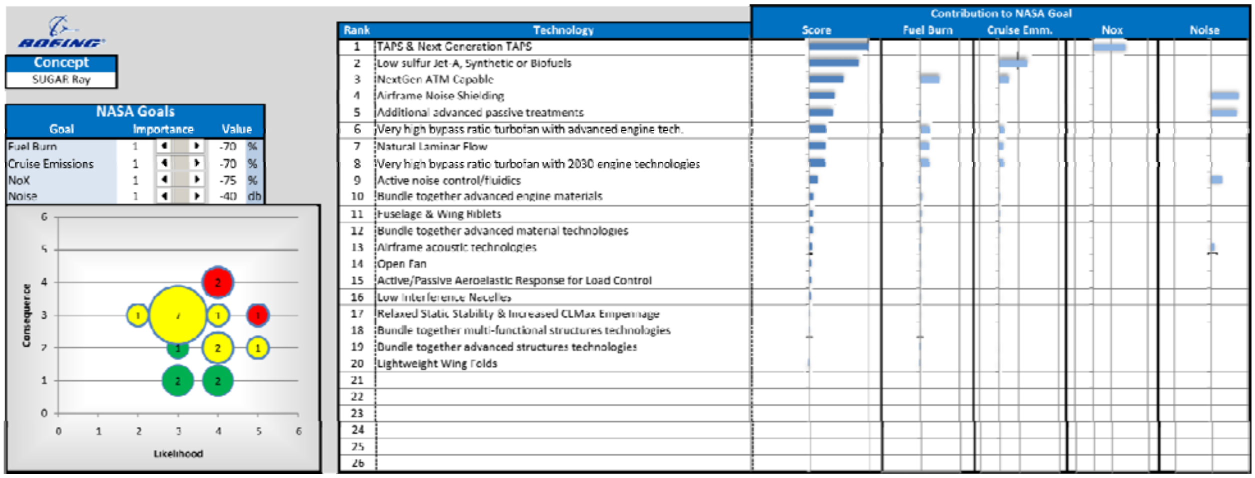
23						
24						
25						
26						

Figure 7.17 – SUGAR Volt Technology Ranking for Noise Reduction Goal

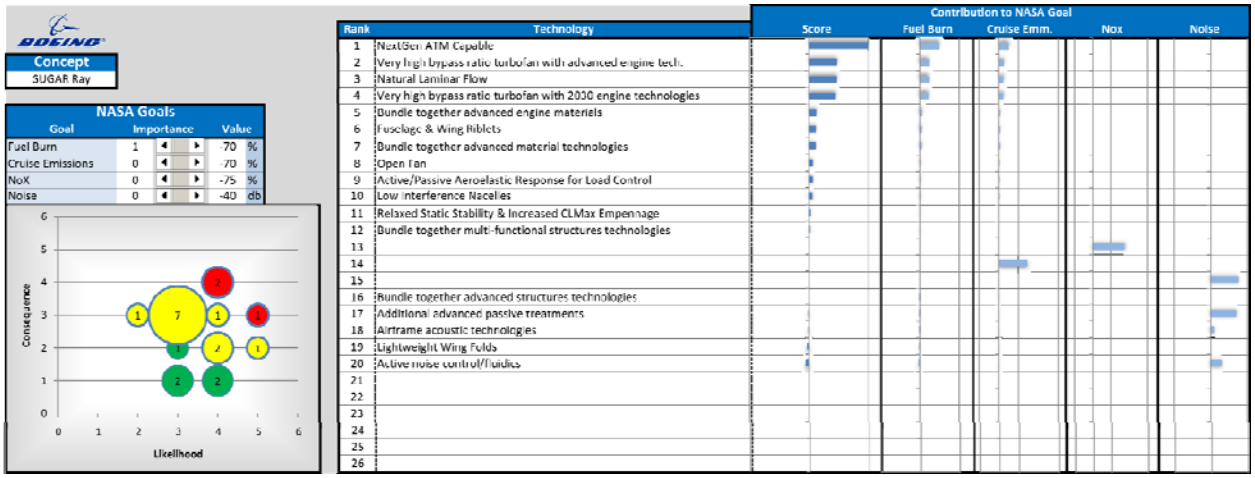


Concept
SUGAR Ray

NASA Goals			
Goal	Importance	Value	
Fuel Burn	1	-70	%
Cruise Emissions	1	-70	%
NoX	1	-75	%
Noise	1	-40	db

Rank	Technology
1	TAPS & Next Generation TAPS
2	Low sulfur Jet-A, Synthetic or Biofuels
3	NextGen ATM Capable
4	Airframe Noise Shielding
5	Additional advanced passive treatments
6	Very high bypass ratio turbofan with advanced engine tech.
7	Natural Laminar Flow
8	Very high bypass ratio turbofan with 2030 engine technologies
9	Active noise control/fluidics
10	Bundle together advanced engine materials
11	Fuselage & Wing Riblets
12	Bundle together advanced material technologies
13	Airframe acoustic technologies
14	Open Fan
15	Active/Passive Aeroelastic Response for Load Control
16	Low Interference Nacelles
17	Relaxed Static Stability & Increased CLMax Empennage
18	Bundle together multi-functional structures technologies
19	Bundle together advanced structures technologies
20	Lightweight Wing Folds
21	
22	
23	
24	
25	
26	

Figure 7.18 – SUGAR Ray Technology Ranking with Equal Goal Weighting

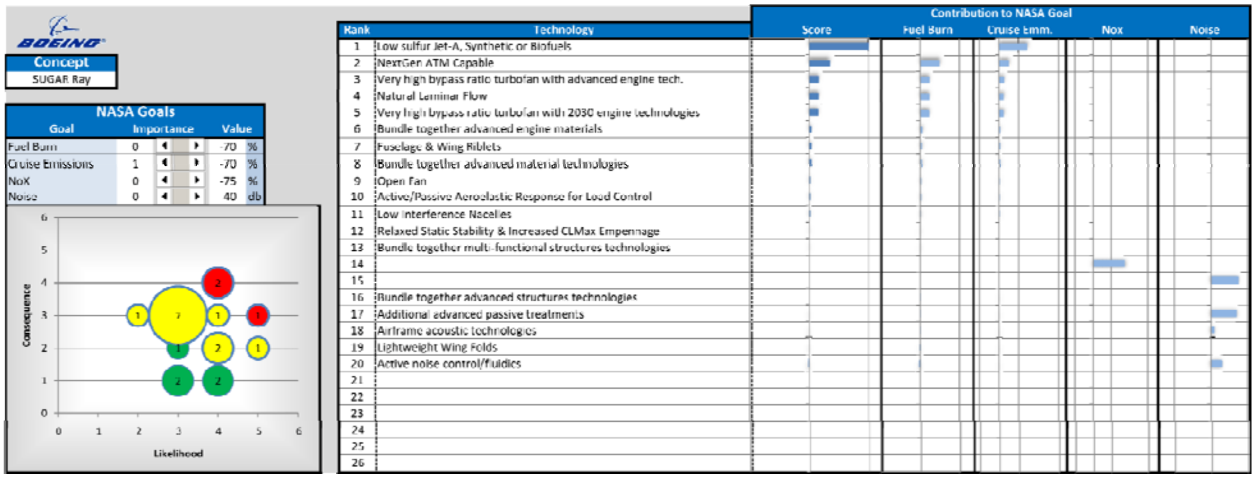


Concept
SUGAR Ray

NASA Goals			
Goal	Importance	Value	
Fuel Burn	1	-70	%
Cruise Emissions	0	-70	%
NoX	0	-75	%
Noise	0	-40	db

Rank	Technology
1	NextGen ATM Capable
2	Very high bypass ratio turbofan with advanced engine tech.
3	Natural Laminar Flow
4	Very high bypass ratio turbofan with 2030 engine technologies
5	Bundle together advanced engine materials
6	Fuselage & Wing Riblets
7	Bundle together advanced material technologies
8	Open Fan
9	Active/Passive Aeroelastic Response for Load Control
10	Low Interference Nacelles
11	Relaxed Static Stability & Increased CLMax Empennage
12	Bundle together multi-functional structures technologies
13	
14	
15	
16	Bundle together advanced structures technologies
17	Additional advanced passive treatments
18	Airframe acoustic technologies
19	Lightweight Wing Folds
20	Active noise control/fluidics
21	
22	
23	
24	
25	
26	

Figure 7.19 – SUGAR Ray Technology Ranking for Fuel Burn Reduction

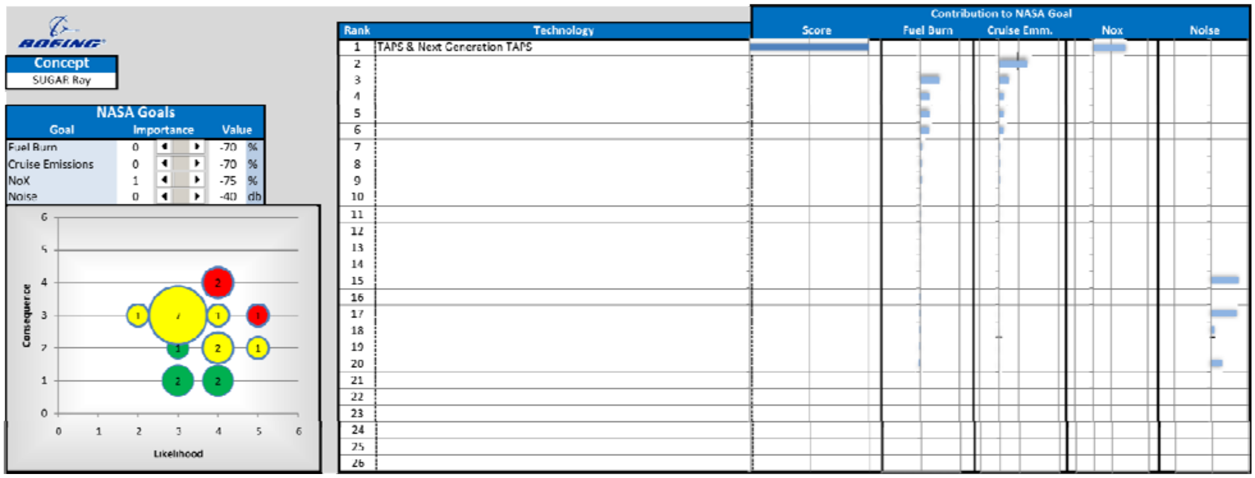


Concept
SUGAR Ray

NASA Goals			
Goal	Importance	Value	
Fuel Burn	0	-70	%
Cruise Emissions	1	-70	%
NoX	0	-75	%
Noise	0	40	db

Rank	Technology
1	Low sulfur Jet-A, Synthetic or Biofuels
2	NextGen ATM Capable
3	Very high bypass ratio turbofan with advanced engine tech.
4	Natural Laminar Flow
5	Very high bypass ratio turbofan with 2030 engine technologies
6	Bundle together advanced engine materials
7	Fuselage & Wing Riblets
8	Bundle together advanced material technologies
9	Open Fan
10	Active/Passive Aeroelastic Response for Load Control
11	Low Interference Nacelles
12	Relaxed Static Stability & Increased CLMax Empennage
13	Bundle together multi-functional structures technologies
14	
15	
16	Bundle together advanced structures technologies
17	Additional advanced passive treatments
18	Airframe acoustic technologies
19	Lightweight Wing Folds
20	Active noise control/fluidics
21	
22	
23	
24	
25	
26	

Figure 7.20 – SUGAR Ray Technology Ranking for Cruise Emissions



Concept
SUGAR Ray

Goal	Importance	Value	
Fuel Burn	0	-70	%
Cruise Emissions	0	-70	%
NoX	1	-75	%
Noise	0	-40	db

Rank	Technology
1	TAPS & Next Generation TAPS
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
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24	
25	
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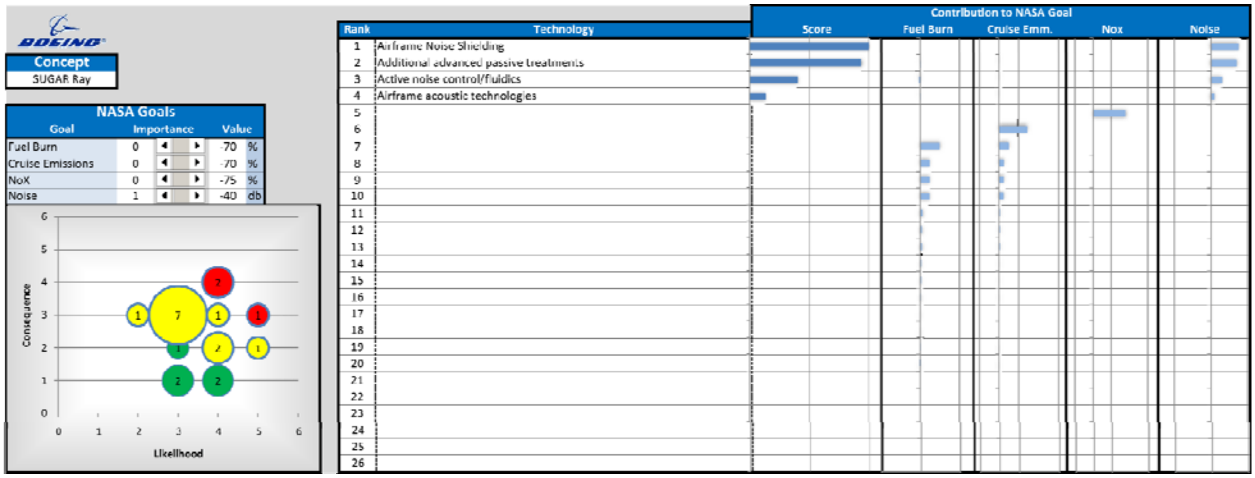
Figure 7.21 – SUGAR Ray Technology Ranking for NOx Reduction Goal



Concept
SUGAR Ray

Goal	Importance	Value	
Fuel Burn	0	-70	%
Cruise Emissions	0	-70	%
NoX	0	-75	%
Noise	1	-40	db

Rank	Technology
1	Airframe Noise Shielding
2	Additional advanced passive treatments
3	Active noise control/fluidics
4	Airframe acoustic technologies
5	
6	
7	
8	
9	
10	
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Figure 7.22 – SUGAR Ray Technology Ranking for Noise Reduction Goal

7.2 – Technology Risk Assessment

7.2.1 – Candidate Technologies

Table 7.1 shows a list of the candidate technologies and their application to each of the candidate concept airplanes. The 26 items listed are consolidated from the original list of 75, combined by logical grouping, and organized to allow a quantitative ranking of impact on each configuration.

Table 7.1 – Candidate Technologies by Concept

		SUGAR Concepts				
Technology	**Risk ID**	**SUGAR Free**	**Refined SUGAR**	**SUGAR High**	**SUGAR Volt**	**SUGAR Ray**
Low sulfur Jet-A, Synthetic or Biofuels	1	-	X	X	X	X
NextGen ATM Capable	2	-	X	X	X	X
High Performance Modular Batteries	3	-			X	
Natural Laminar Flow	4	-	X	X	X	X
Fuselage & Wing Riblets	5	-	X	X	X	X
Relaxed Static Stability & Increased CLMax Empennage	6	-	X	X	X	X
Advanced Supercritical Airfoil	7	-		X	X	
Low Interference Nacelles	8	-		X	X	X
Low Drag Strut (no interference, laminar flow in NLF)	9	-		X	X	
Airframe Noise Shielding	10	-				X
Active/Passive Aeroelastic Response for Load Control	11	-	X	X	X	X
Lightweight Wing Folds	12	-		X	X	X
Adv. Lightweight High Lift Systems	13	-		X	X	
Very high bypass ratio turbofan with 2030 engine technologies	14	-	X	X	X	X
Very high bypass ratio turbofan with advanced engine tech.	15	-		X	X	X
Battery Gas Turbine Hybrid (SUGAR High tech level)	16	-			X	
TAPS & Next Generation TAPS	17	-	X	X	X	X
Additional advanced passive treatments	18	-		X	X	X
Active noise control/fluidics	19	-		X	X	X
Bundle together advanced material technologies	20	-	X	X	X	X
Bundle together advanced structures technologies	21	-	X	X	X	X
Bundle together advanced engine materials	22	-	X	X	X	X
Bundle together advanced subsystem technologies	23	-	X	X	X	X
Open Fan	24	-		X	X	
Bundle together multi-functional structures technologies	25	-	X	X	X	X
Airframe acoustic technologies	26		X	X	X	X

Table 7.2 shows the applicability of the candidate technologies by NASA N+3 goal. Note that there are few areas in which a range is quoted because the technology has a stronger influence on some concepts than others. In general, cruise emission impact is directly related to fuel burn, but in the case of biofuels, the effective impact on cruise CO_2 is substantial, although fuel burn per seat is unchanged. It is apparent that most technologies are aimed at fuel burn reduction, several at noise and relatively few are targeted at landing and takeoff NOx and takeoff field length.

Table 7.2 – Candidate Technologies by NASA N+3 goal

		NASA N+3 Goals				
Technology	**Risk ID**	**Fuel Burn**	**LTO Nox**	**Noise**	**TOFL**	**Cruise Emissions**
Low sulfur Jet-A, Synthetic or Biofuels	1		Low-Med			High (biofuels only)
NextGen ATM Capable	2	High				High
High Performance Modular Batteries	3	High	Med	Med	Low	High
Natural Laminar Flow	4	High				High
Fuselage & Wing Riblets	5	Med				Med
Relaxed Static Stability & Increased CLMax Empennage	6	Med				Med
Advanced Supercritical Airfoil	7	Med				Med
Low Interference Nacelles	8	Med				Med
Low Drag Strut (no interference, laminar flow in NLF)	9	Med				Med
Airframe Noise Shielding	10			High		
Active/Passive Aeroelastic Response for Load Control	11	High-Med				
Lightweight Wing Folds	12	Low				Low
Adv. Lightweight High Lift Systems	13	Low		Med	High	Low
Very high bypass ratio turbofan with 2030 engine technologies	14	High	High	High		High
Very high bypass ratio turbofan with advanced engine tech.	15	High	High	High		High
Battery Gas Turbine Hybrid (SUGAR High tech level)	16	High				High
TAPS & Next Generation TAPS	17	Med	High			Med
Additional advanced passive treatments	18			High		
Active noise control/fluidics	19			High		
Bundle together advanced material technologies	20	High				High
Bundle together advanced structures technologies	21	High				High
Bundle together advanced engine materials	22	High				High
Bundle together advanced subsystem technologies	23	High				High
Open Fan	24	High		-Med		HIgh
Bundle together multi-functional structures technologies	25	High				High
Airframe acoustic technologies	26			Med		

7.2.2 – TRL Assessment

An initial assessment of Technology Readiness Level (TRL) is shown in Table 7.3. A range of values is shown in some cases, especially for the bundled technologies. These TRLs will be refined and developed further in the roadmapping exercise.

Table 7.3 – Estimated TRL

Technology	Risk ID	Current TRL Level
Low sulfur Jet-A, Synthetic or Biofuels	1	8=syn 6=bio
NextGen ATM Capable	2	6+
High Performance Modular Batteries	3	2
Natural Laminar Flow	4	5
Fuselage & Wing Riblets	5	5
Relaxed Static Stability & Increased CLMax Empennage	6	4
Advanced Supercritical Airfoil	7	4
Low Interference Nacelles	8	3
Low Drag Strut (no interference, laminar flow in NLF)	9	2 to 3
Airframe Noise Shielding	10	4
Active/Passive Aeroelastic Response for Load Control	11	4
Lightweight Wing Folds	12	3
Adv. Lightweight High Lift Systems	13	3
Very high bypass ratio turbofan with 2030 engine technologies	14	3
Very high bypass ratio turbofan with advanced engine tech.	15	2
Battery Gas Turbine Hybrid (SUGAR High tech level)	16	1
TAPS & Next Generation TAPS	17	3
Additional advanced passive treatments	18	3
Active noise control/fluidics	19	2
Bundle together advanced material technologies	20	4
Bundle together advanced structures technologies	21	3 to 5
Bundle together advanced engine materials	22	2
Bundle together advanced subsystem technologies	23	2 to 5
Open Fan	24	2 to 3
Bundle together multi-functional structures technologies	25	2 to 5
Airframe acoustic technologies	26	4

7.2.3 – Risk Assessment

These risks were then assigned a number from 1 to 5 on a scale of consequence of failure and a scale of 1 to 5 on a scale of likelihood of failure. This helps to differentiate the risks, especially the medium ones, as some are more “hard fail” (high consequence), but can be low likelihood of failure. Others are “soft fail”, in that the consequence of failure is lower, but the likelihood of not reaching the full potential is higher.

Table 7.4 shows the assessment of risk for each of the candidate technology groups. First, the technologies were assessed by subject matter experts on a simple High/Medium/Low scale. Imbalances between disciplines were addressed and the risk level assessed on a universal scale.

Risks were assessed primarily for technical impact. For instance, Risk ID 1, *Low sulfur Jet A, synthetic fuel and biofuels*, the technical risk of integrating the fuels into the airplanes is low – noted as “*X int*” in the table, alternative fuels have been demonstrated at a fairly high TRL. The risk for synthetics and especially biofuels are being able to produce them in a large enough quantity to make an impact. This is more of an economic and political issue than a technical one, and is thus beyond the scope of consideration here.

For most technologies, the risk across the spectrum of airplane concepts is broadly equal. One item where this is not the case is risk item 11, *Active/Passive Aeroelastic Response for Load*

Control. In this case, the technology is much more critical to the high aspect ratio, high wing concepts, Sugar High and Sugar Volt, so they have been designated with a consequence of 5, versus 3 for the other concepts. However, as the technology is reasonably well understood, the risk of failure is designated fairly low, at 2.

Table 7.4 – Candidate Technologies Risk Assessment

		Technical Risk				
Technology	**Risk ID**	**High**	**Med**	**Low**	**Consequence (1-5)**	**Likelihood of Failure (1-5)**
Low sulfur Jet-A, Synthetic or Biofuels	1		X Prod	X Int	4	1
NextGen ATM Capable	2			X	4	1
High Performance Modular Batteries	3	X			5	5
Natural Laminar Flow	4	X			5	3
Fuselage & Wing Riblets	5		X		4	3
Relaxed Static Stability & Increased CLMax Empennage	6			X	3	2
Advanced Supercritical Airfoil	7		X		4	2
Low Interference Nacelles	8		X		3	3
Low Drag Strut (no interference, laminar flow in NLF)	9		X		4	3
Airframe Noise Shielding	10		X		3	3
Active/Passive Aeroelastic Response for Load Control	11		X		5 (HV) 3(oth)	2
Lightweight Wing Folds	12			X	3	1
Adv. Lightweight High Lift Systems	13		X		2	3
Very high bypass ratio turbofan with 2030 engine technologies	14			X	3	1
Very high bypass ratio turbofan with advanced engine tech.	15		X		3	3
Battery Gas Turbine Hybrid (SUGAR High tech level)	16	X			5	4
TAPS & Next Generation TAPS	17		X		3	3
Additional advanced passive treatments	18		X		2	3
Active noise control/fluidics	19	X			4	4
Bundle together advanced material technologies	20		X		4	2
Bundle together advanced structures technologies	21		X		4	2
Bundle together advanced engine materials	22	X			4	4
Bundle together advanced subsystem technologies	23		X		4	3
Open Fan	24		X		3	3
Bundle together multi-functional structures technologies	25		X		3	3
Airframe acoustic technologies	26		X		3	3

Figure 7.23 shows the basic 5x5 risk map that shows how the grid maps to high, moderate and low risk.

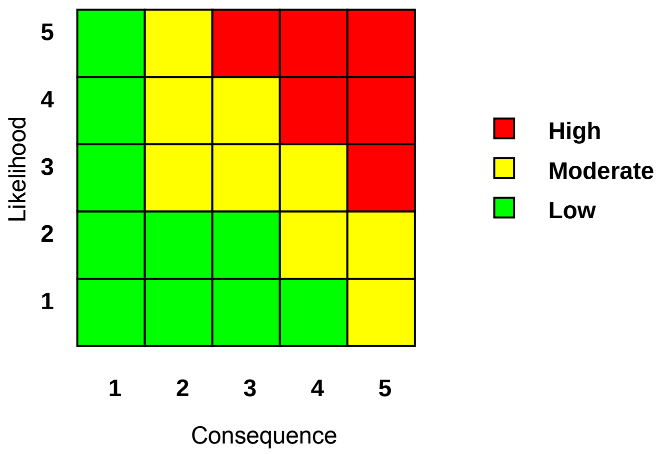


Figure 7.23 – Risk Map

7.2.4 – Risk Breakdown by Concept

Table 7.1 showed how the risks map to the four different concept airplanes and Table 7.4 shows the risk levels for the technologies. The following four figures show how the risks map onto the risk grid for each concept. Figure 7.24 shows the map for the Refined SUGAR concept.

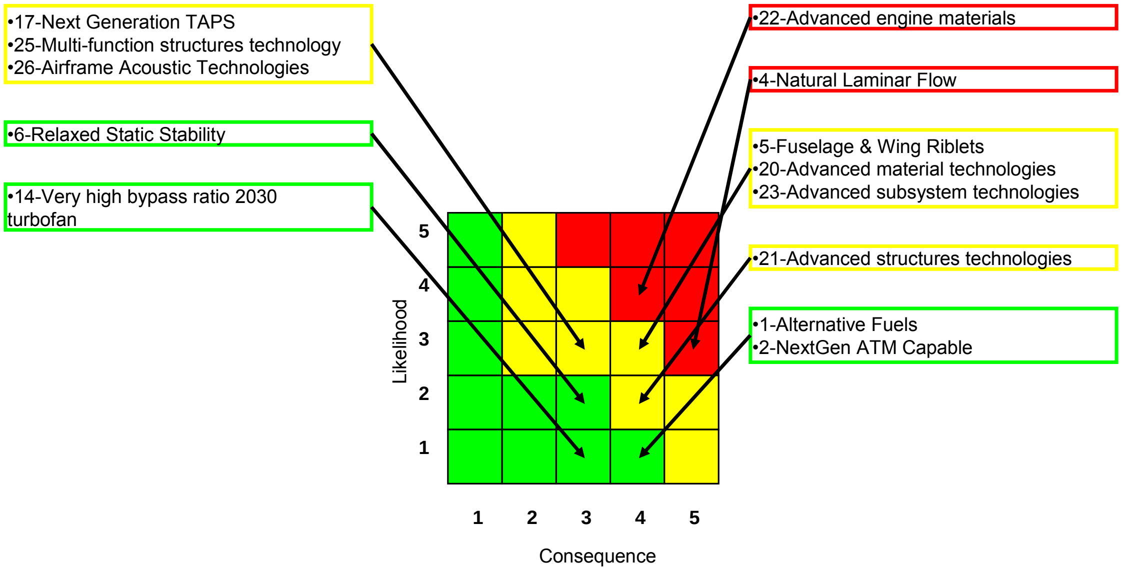


Figure 7.24 – Risk Map for Refined SUGAR

Only about half of the technologies apply to this relatively low risk refinement of the basic concept. None of the risks rate in the top three categories (5,5; 5,4; 4,5). The only high risk technologies are advanced engine materials – a combination of several technologies, and natural laminar flow. While the latter has been around for a very long time, the real challenge is making it work reliably in an operational environment.

Figure 7.25 shows the risk map for the SUGAR High concept. It is very similar to that of the Refined SUGAR with a few additional risks added. The only additional high risk technology is active engine noise control with fluidics.

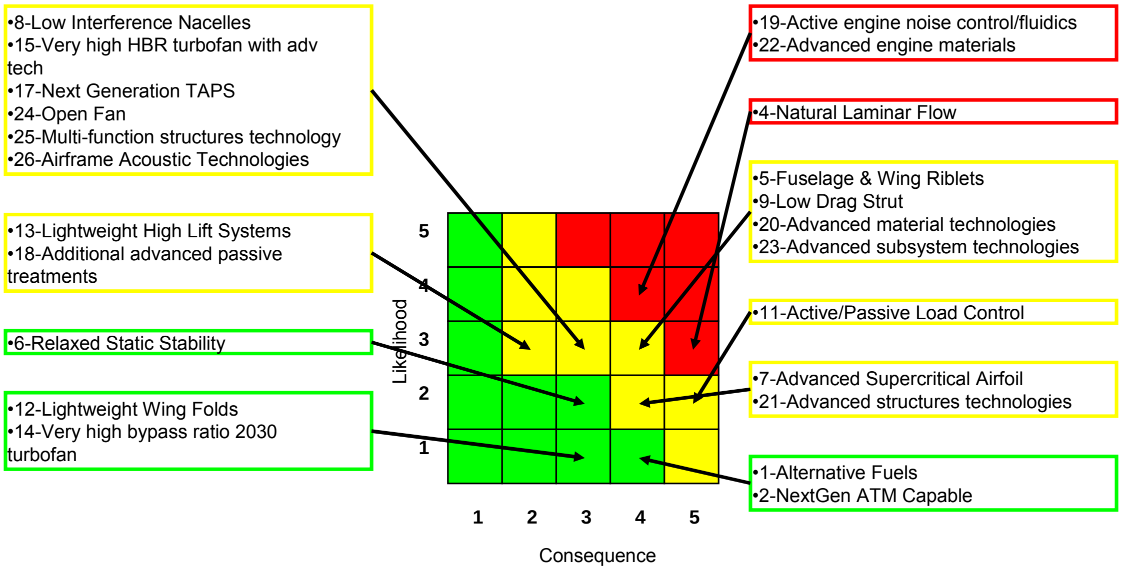


Figure 7.25 – Risk Map for SUGAR High

Figure 7.26 shows the risk map for the SUGAR Volt concept. This includes nearly all of the risks, including the highest rated: high performance batteries, and the slightly less risky gas turbine/electric hybrid motor. Obtaining batteries with the energy density required to make the concept viable is probably the most difficult technology challenge in the portfolio. The concept is able to benefit from most of the other technologies too, particularly those found on its "parent" aircraft, SUGAR High.

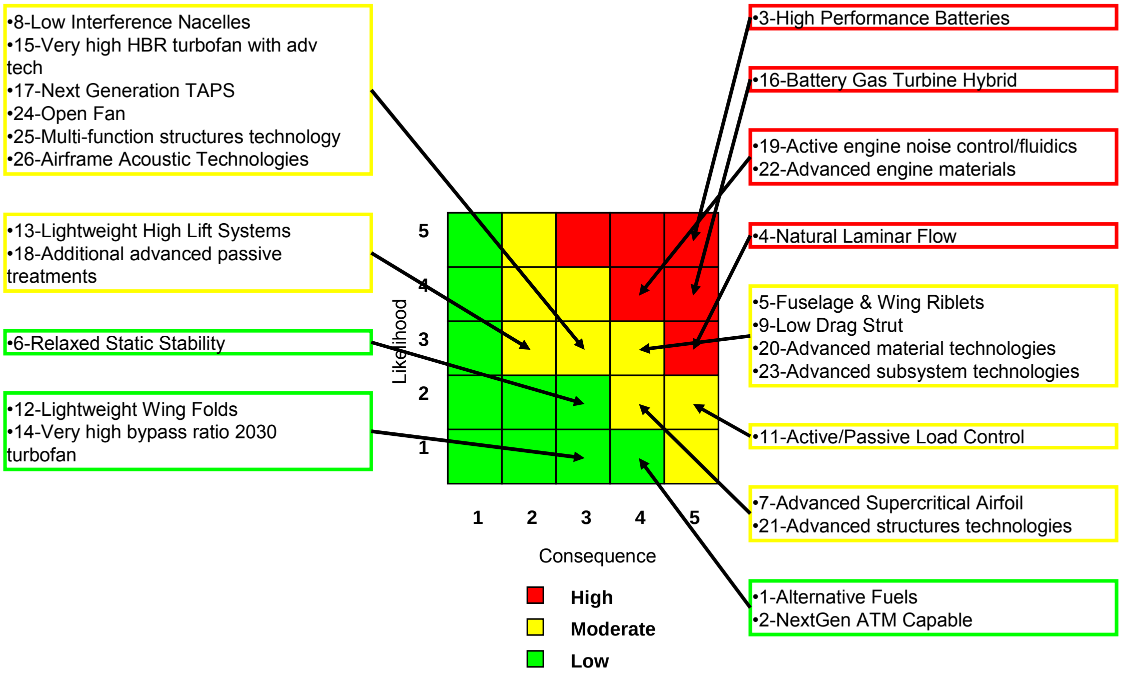


Figure 7.26 – Risk Map for SUGAR Volt

Figure 7.27 shows the risk map for the SUGAR Ray concept. The technology list is very similar to the SUGAR High concept, with the addition of a medium risk technology of noise shielding.

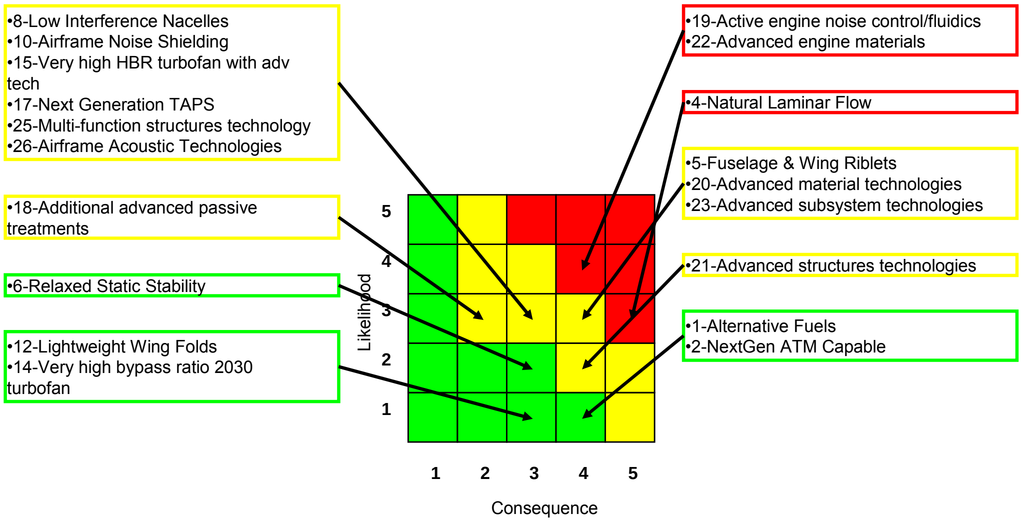


Figure 7.27 – Risk Map for SUGAR Ray

7.2.5 – Risk Breakdown by Technology Impact

In this section we show how the risks map by Technology Impact area that map to the N+3 goals of Fuel burn (hence also Cruise emissions), Landing and takeoff NOx, Noise and Takeoff field length.

Figure 7.28, the risk map for fuel burn, shows clearly that most of the technologies have an impact on fuel burn. Given that, all other things being equal, reduced fuel burn leads to smaller, lighter vehicles overall. This impact ripples through to secondary impacts on the other goals.

The biggest impacts and the biggest risks are propulsion related: advanced engine materials and the battery/gas turbine hybrid engine system (including the batteries). Natural laminar flow rounds out the high payoff/high risk items. There are ten moderate risk technologies with moderate dividends.

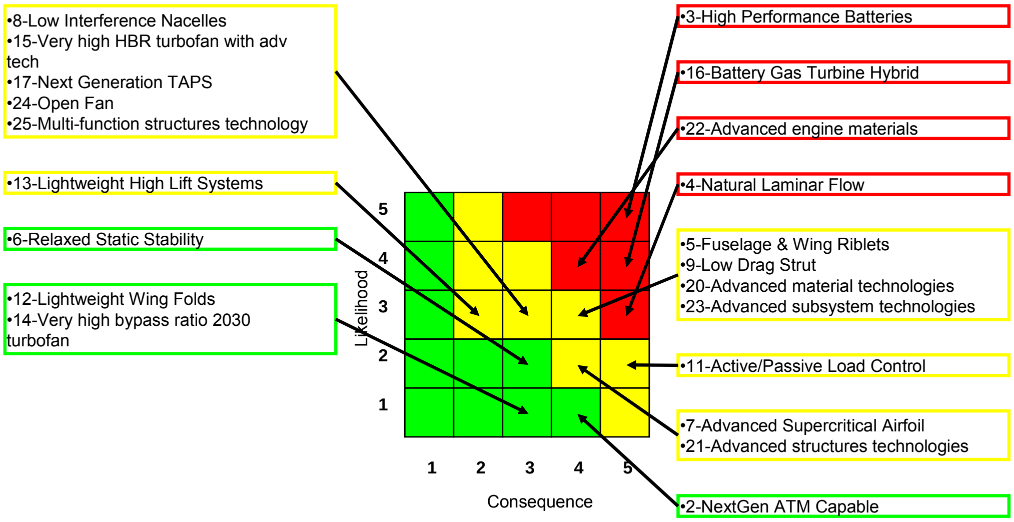


Figure 7.28 – Risk Map for the Fuel Burn Technologies

Figure 7.29 shows the risk map for Cruise Emissions technologies which adds Alternative Fuels in the low technical risk category to the fuel burn map.

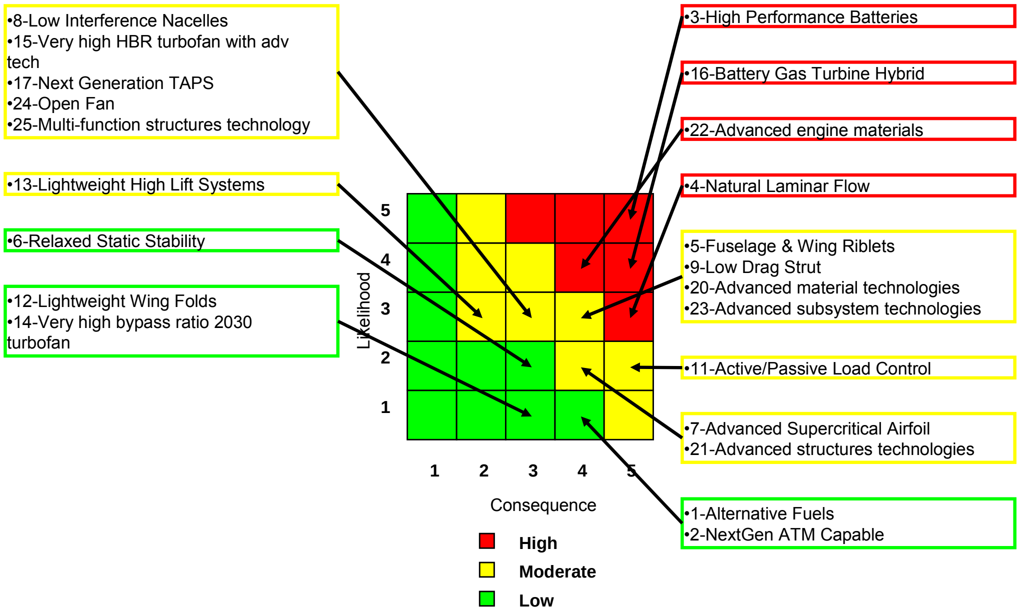


Figure 7.29 – Risk Map for the Cruise Emissions Technologies

Figure 7.30 shows the risk map for LTO NOx with a few impacting technologies, all in the propulsion field.

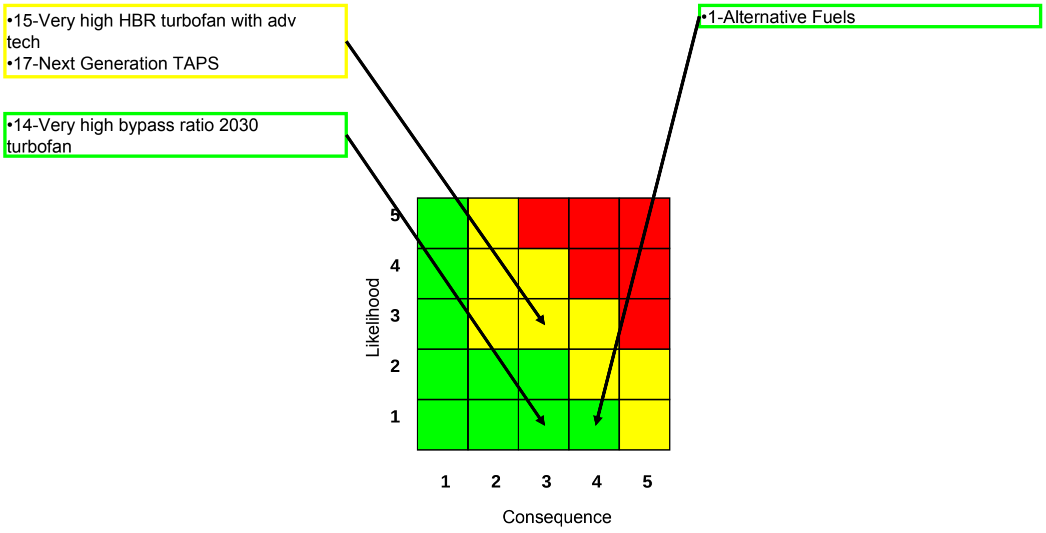


Figure 7.30 – Risk Map for the LTO NOx Technologies

Figure 7.31 shows the risk map for Noise with a few impacting technologies, mostly in the propulsion field. Airframe acoustic technologies, airframe noise shielding and lightweight high-lift systems are the airframe related technologies that will contribute to noise reduction.

Note that the Open Fan is included here not because it provides an inherent reduction in noise, but because the Open Fan technology package must include design techniques and treatments to mitigate the noise characteristics of the counter-rotating fan blade sets.

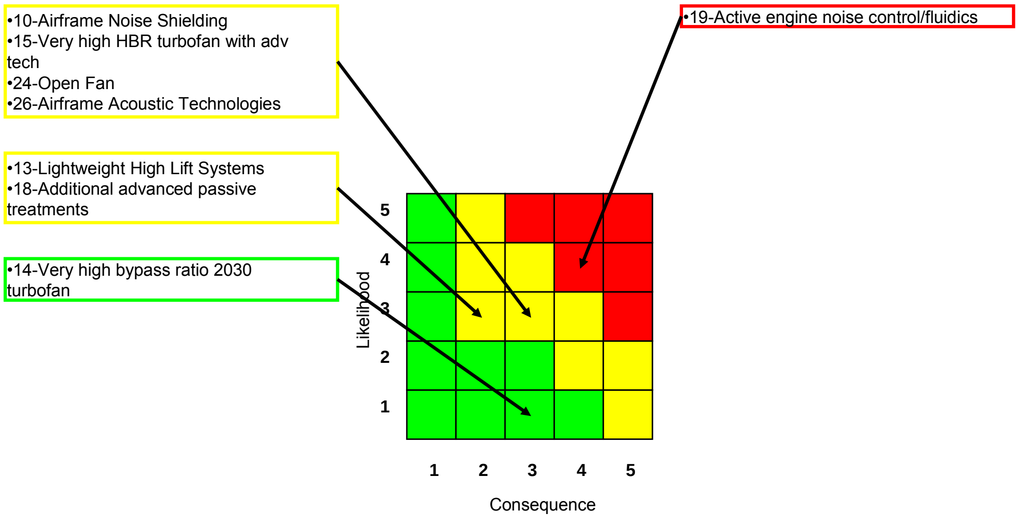


Figure 7.31 – Risk Map for the Noise Technologies

Figure 7.32 shows the risk map for takeoff field length reduction. While some technologies may contribute some small effects to improved field performance, only the lightweight high lift system technology will contribute directly and primarily to improved field length.

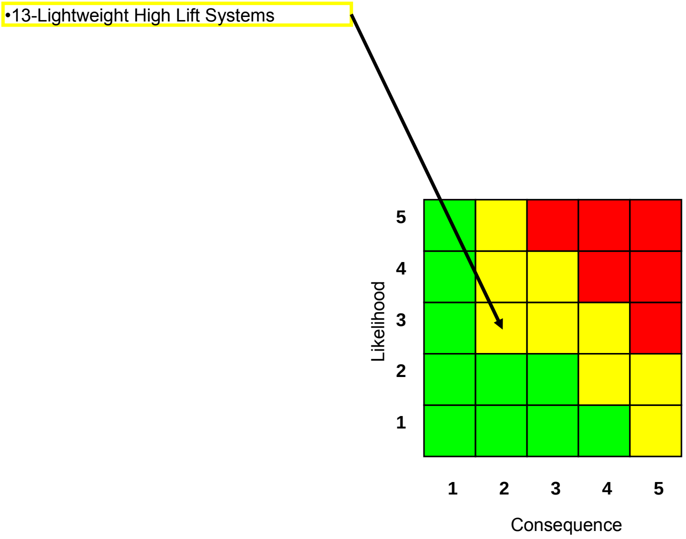


Figure 7.32 – Risk Map for the TOFL Technologies

7.3 – Technology Roadmapping

7.3.1 – Next Generation Air Traffic Management

Goals and Objectives:

The goal of this project is to integrate avionics components into the aircraft in order to make it compatible with the Next generation Air Transportation System (NextGen). This research and development plan seeks to increase capacity, reduce delays, and improve safety throughout the ATS through technological improvements both on the ground and in the air.

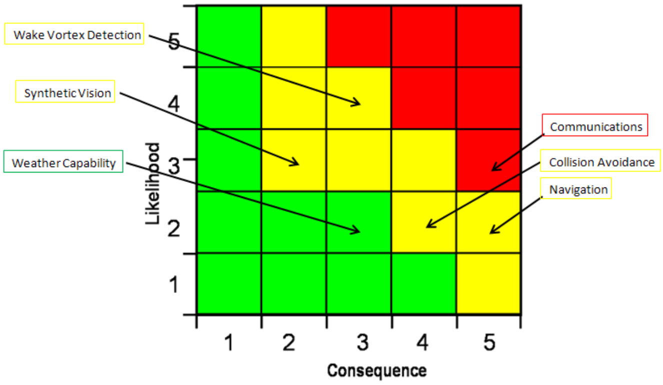
Performance Area and Impact:

LTO NOx	Substantial Reduction (reduced taxi time)
Fuel Burn	Substantial Reduction (17% for current technology vehicles)
Cruise Emissions	Substantial Reduction (17% for current technology vehicles)
System Capacity	Substantial Increase (increased capacity at airport and increase airports)

Technical Description:

NextGEN as a program encompasses all the aircraft and ground related improvements that must be accomplished in order to realize the benefits to fuel efficiency, capacity and safety. For the purposes of this roadmap the technology is limited to the on-aircraft components only. Overall these new concepts will impact every phase of flight in some way. Increased situational awareness of other aircraft will allow for reduced taxi times. Better aircraft positioning data and route planning will allow for a more fuel optimized climb and reduced separation requirements. Better weather detection means that pilots can optimize their route in flight to find the compromise in avoiding the weather while still retaining a fuel efficient trajectory. Increased communications and optimized planning will allow for better descent profiles to save fuel, increase safety, and reduce noise.

Risk Assessment:



Current TRL:

Wake Vortex Detection	6
Synthetic Vision	4
Weather Capability	6
Communications	3
Collision Avoidance	9
Navigation	5

Major Milestones:

Integrate Ground/Air Voice/Data Network	2025
Wake Detection and Avoidance Protocols	2016
Aircraft-Aircraft Weather Information Sharing	2019
Enhanced Vision Systems – Level 3	2017

Dependency:

Ground Communications Architecture
Integrated Route Planning and Optimization
Airport Operations Improvements

Success Criteria:

Table 7.5 – Next Generation Air Traffic Management Success Criteria

Task Number	Task Name	Success Criteria	Alternate Steps if Unsuccessful
1	**Communications**	Aircraft and ground controllers can share information and voice communications simultaneously	Current SoA
2	**Navigation**	Ability of the controller to accurately predict and control the location of aircraft at any point in the flight profile	Current SoA
3	**Collision Avoidance**		
4	**Weather Capability**	Aircraft-Aircraft weather detection and information sharing	Current SoA
5	**Wake Vortex Detection**	Aircraft wake prediction based off type of aircraft and atmospheric conditions allows for decreased separation distance	Current SoA
6	**Synthetic Vision**		

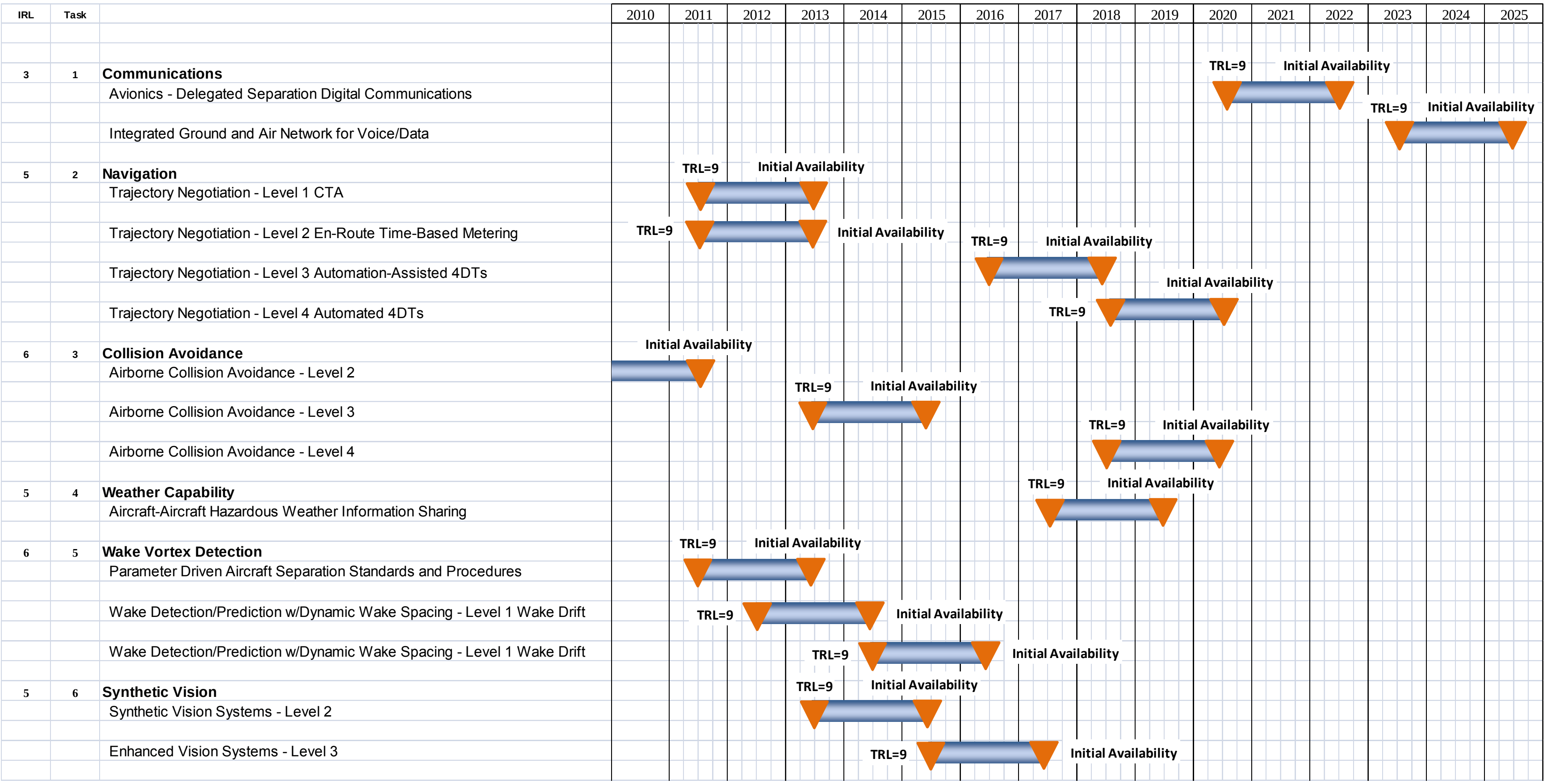
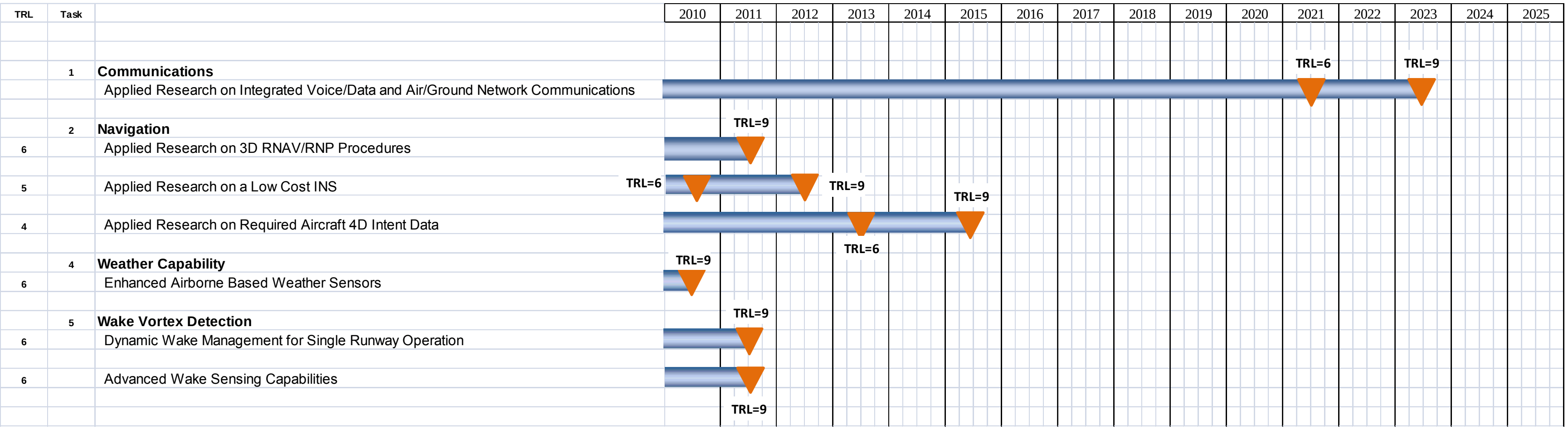


Figure 7.33 – Next Generation Air Traffic Management Operational Roadmap



TRL	Task	
	1	**Communications**
		Applied Research on Integrated Voice/Data and Air/Ground Network Communications
	2	**Navigation**
6		Applied Research on 3D RNAV/RNP Procedures
5		Applied Research on a Low Cost INS
4		Applied Research on Required Aircraft 4D Intent Data
	4	**Weather Capability**
6		Enhanced Airborne Based Weather Sensors
	5	**Wake Vortex Detection**
6		Dynamic Wake Management for Single Runway Operation
6		Advanced Wake Sensing Capabilities

Figure 7.34 – Next Generation Air Traffic Management Technical Roadmap

7.3.2 – Alternative Fuels

Goals and Objectives:

Develop drop-in replacement alternative fuels with comparable performance to conventional fuel and lower life cycle GHG and airport emissions

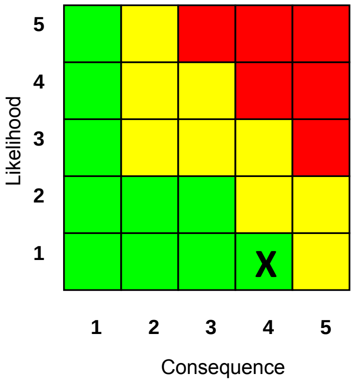
Performance Area and Impact:

LTO NOx	Small to Medium Reduction
Cruise Emissions	Substantial Reduction (for biofuels)

Technical Description:

Fuel Testing (Engine & fuel system components)
Life Cycle Assessment
Emissions Testing
Fuel Testing (Engine System)
Certification Documentation
System Changes for Near Drop-In fuels (Alternate)
Certification of Engine and Aircraft Systems for Near Drop-In fuels (Alternate)
Low Sulfur Jet-A Implementation (Alternate)

Risk Assessment:



Current TRL:

Synthetic Fuel	8
Biofuel	6

Major Milestones:

Approval of 50% FT fuel in commercial aircraft	2009
Approval of 50% HRJ biofuel in commercial aircraft	2010
Approval of near 100% FT fuel in commercial aircraft	2011
Approval of near 100% HRJ biofuel in commercial aircraft	2013
Approval of 50% SPK (generic processes and feedstocks) in commercial aircraft	2014
Approval of near 100% SPK (generic processes and feedstocks) in commercial aircraft	2015
USAF 50% Alternative Fuel Use	2015
Significant Airline Use of Alternative Fuel	2015
Widespread Airline Use of Renewable Fuels to reduce GHG	2020

Dependency:

None

Success Criteria:

Table 7.6 – Alternative Fuels Success Criteria

Task Number	Task Name	Success Criteria	Alternate Steps if Unsuccessful
1	**Fuel Testing (Engine & fuel system components)**	Comparable performance and compatibility with existing fuel and engine systems	Reduce blend % or initiate modification of systems (Task 6 & 7)
2	**Life Cycle Assessment**	Verifiable reduction in lifecycle GHG at competitive cost	Choose sustainable feedstock and processes. Ultimate fall back is to continue to use fossil fuels from oil, natural gas, or coal.
3	**Emissions Testing**	Emissions better than existing fuels.	Fall back to conventional fuels (Task 8)
4	**Fuel Testing (Engine System)**	Comparable performance and compatibility with existing and future engines	Reduce blend % or initiate modification of systems (Task 6 & 7)
5	**Certification Documentation**	Research report and ballot	Additional testing or analysis to resolve issues
6	**System Changes for Near Drop-In fuels (Alternate)**	Compatible system design for near drop-in fuels	Fall back to conventional fuels (Task 8)
7	**Certification of Engine and Aircraft Systems for Near Drop-In fuels (Alternate)**	Verification of compatibility and performance assumptions	Fall back to conventional fuels (Task 8)
8	**Low Sulfur Jet-A Implementation (Alternate)**	Verification of compatibility and emissions performance	
9	**Feedstock Technologies**		
10	**Production Technologies**		

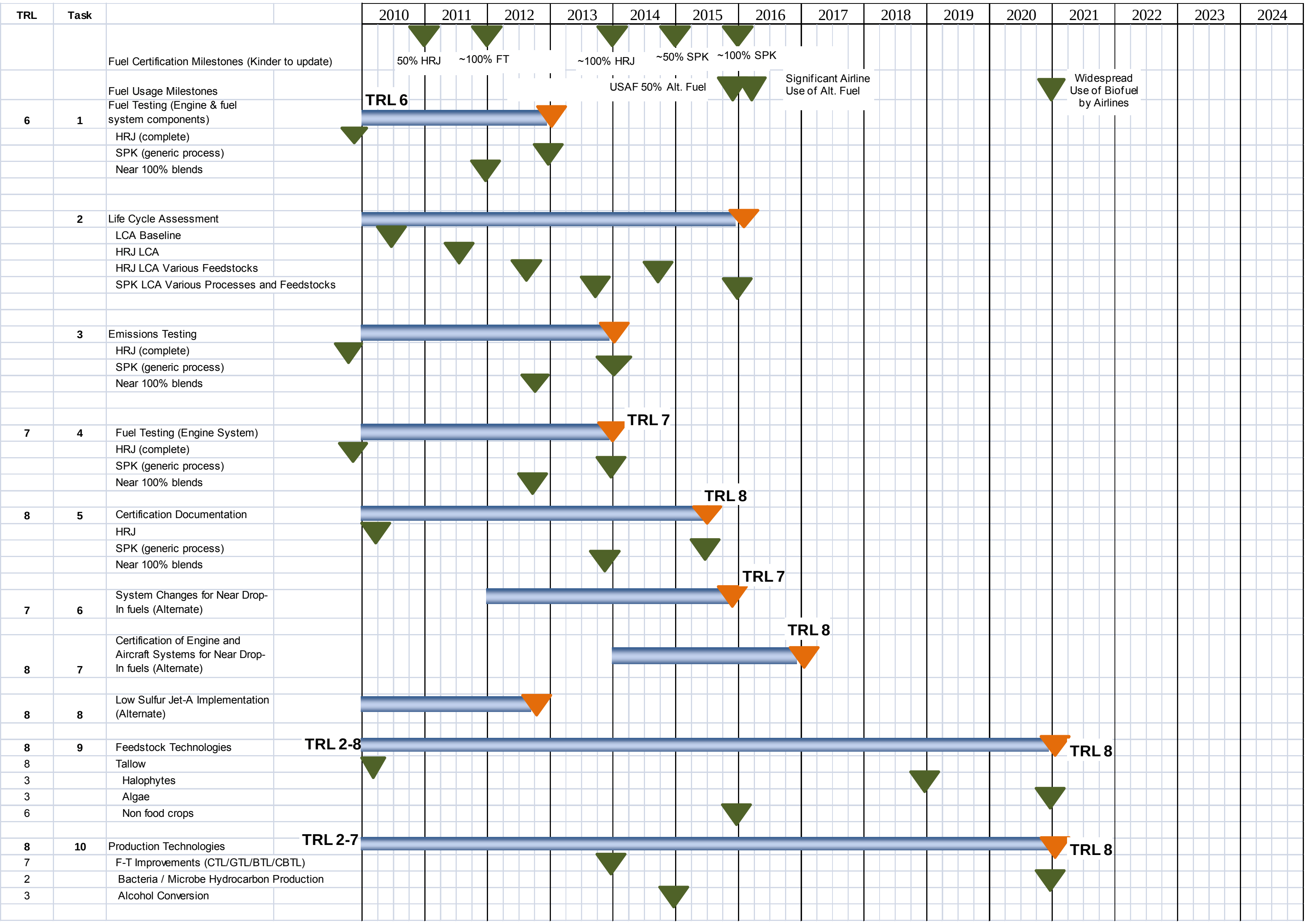


Figure 7.35 – Alternative Fuels Roadmap

7.3.3 – Aerodynamic Technologies for Improved Airplane Performance

Goals and Objectives:

Develop and Implement Aerodynamic Technologies enabling the design of Airplanes in 2030 timeframe. These technologies will contribute to the 30% improvement in fuel efficiency relative to current fleet.

Performance Area and Impact:

Improved Airplane Performance through drag reduction

Technical Description:

Aerodynamic technologies have been identified to provide significant improvement toward an Airplane in 2030 (N+3) timeframe.

Laminar flow on any component reduces skin friction drag and pressure drag on the laminarized area.

Riblets reduces skin friction drag by modifying turbulent structure in the turbulent boundary layer.

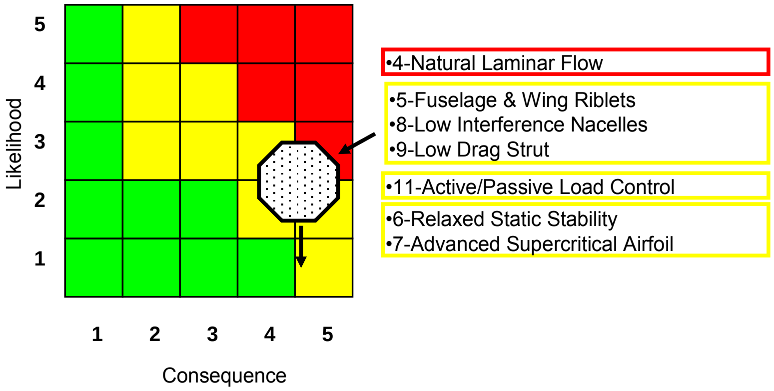
Improve design integration of Nacelles in the presence of wings to reduce interference drag.

Improve design integration of Strut braced configuration in the presence of wings and body to reduce interference drag.

Reduced static stability reduces trim drag and increased CLmax tail designs reduces tail area and weight.

Wing design to accommodate active/passive aeroelastic response for load control allows tailoring of wing spanloads to improve overall mission performance. This technology is shared with Structures.

Risk Assessment:



Current TRL:

3 to 4

Major Milestones:

Natural laminar flow wing design without HLFC systems to achieve a viable configuration. Roadmap will address passive/active systems to achieve Aerodynamic goals. Identity system benefits for go-no-go.	2020
Integration of low interference drag struts on high span wing configurations. Improvement in interference drag is significant. Identity system benefits for go-no-go.	2020
Advanced Super-critical wings with improved efficiency. Identify system benefits for go-no-go.	2020
Design, implement and demonstrate achievable drag improvements of Riblets on fuselage and wings. Identity system benefits for go-no-go.	2020
Integration of low interference drag nacelles on high span wing configurations. Improvement in interference drag is significant. Identity system benefits for go-no-go.	2020
Incorporate aggressive relaxed static stability and improve empennage performance. Identity system benefits for go-no-go.	2020
Collaborate integration of active/passive aeroelastic response for load control. Identity system benefits for go-no-go.	2020

Dependency:

Configuration Development

Technologies impact on each other (one technology could prevent another technology from maturing)

Success Criteria:

Table 7.7 – Aerodynamic Technologies Success Criteria

Task Number	Task	Success Criteria	Alternative steps if unsuccessful
1	**Laminar Flow**		
	Passive LFC	NLF laminar design matches Active LFC	Achieve 50% of an Active LFC laminar Run
	Active LFC	Achieve Laminar to shocks with low power consumption	Establish break even points between NLF/Passive/Active
2	**Low Interference Drag Struts**	Integrate strut into wing-body for only strut parasite drag	Establish low interference levels
3	**Advanced Super-Critical Wing**	Target 3% airplane drag improvement while attaining high design lift coefficient	Achieve 50% of target drag improvement
4	**Riblet Integration**	Target 2% - 3% airplane drag improvement	
5	**Low Interference Drag Nacelles**	Integrate nacelle/pylon to wing body for only nacelle/pylon parasite drag	Establish low interference levels
6	**Relaxed static stability Increased CLmax Empennage**	Achieve neutral static stability to reduce tail size. Improve empennage CLmax to reduce tail size	Demonstrate some reduction in tail size
7	**Aeroelastic Load Control**	Span load traded for Aerodynamics and structural efficiencies to improve overall mission performance	Achieve improvement for one discipline

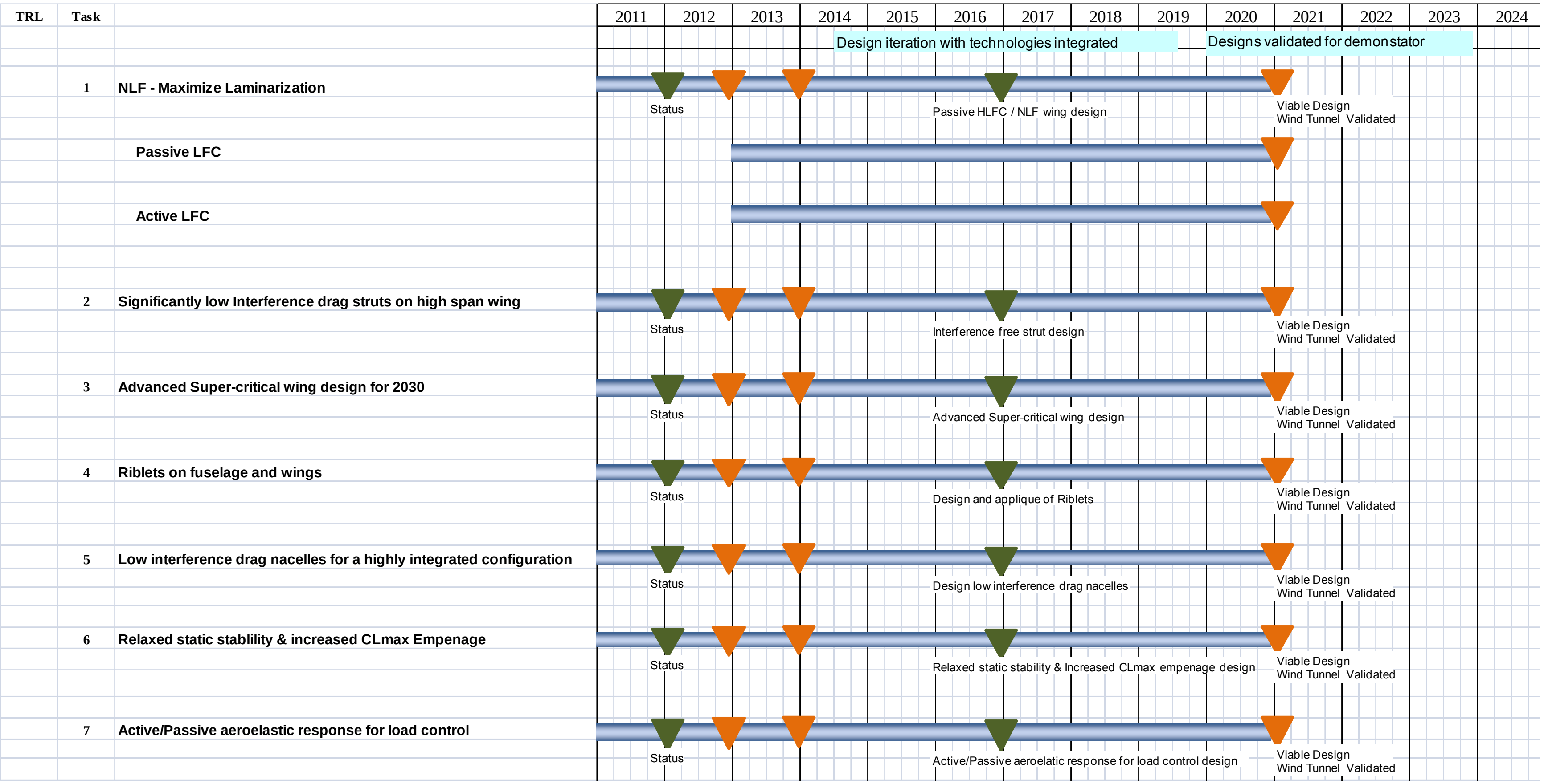


Figure 7.36 – Aerodynamic Technologies Roadmap

7.3.4 – Airframe Acoustic Technologies

Goals and Objectives:

Develop airplane designs and technologies that reduce airframe noise and increase shielding of engine noise, in order to meet future strict noise regulations in airport environments

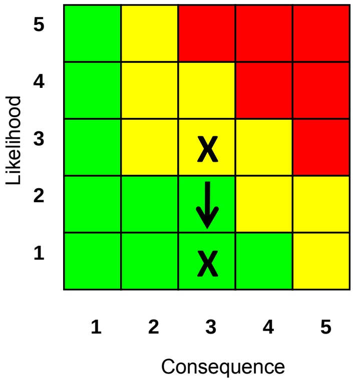
Performance Area and Impact:

Engine noise dominance at take-off (cutback and sideline), and airframe noise dominance at approach
Impact on Aerodynamics, Propulsion, and Airframe Design

Technical Description:

Develop inherently quiet landing gear designs (includes main and nose gear)
Develop inherently quiet high-lift system designs with good aerodynamic characteristics (includes leading and trailing edge devices, and wing trailing edge)
Develop integrated engine-airframe designs with inherent shielding (includes jet, inlet and aft-fan)
Develop technologies to reduce landing gear noise, high-lift system noise, jet noise, and aft-fan noise
Develop technologies to maximize engine noise shielding (includes shielding of jet, inlet, and aft-fan)
Evaluate and down-select design ideas and technology concepts using the following: (a) acoustics integrated into multidisciplinary design, (b) airframe noise and engine noise shielding testing including model-scale and full-scale flight tests, and (c) development of tools for acoustic design, analysis, and prediction of airframe noise and engine noise shielding

Risk Assessment:



Current TRL:

Landing Gear	3
High-Lift System	2
Source Noise	5
Noise Shielding	2

Major Milestones:

Acoustic design, analysis, and prediction tools (Landing Gear, Shielding, and High-Lift System Tools)	2018
Selection of promising airframe designs and technology concepts for model-scale noise testing	2015
Model-scale acoustic (airframe noise and engine noise shielding) testing for initial assessments and candidate down-selection	2015
Model-scale acoustic (airframe noise and engine noise shielding) testing for optimization and final candidate selection	2018
Selection of best airframe designs and technology concepts for full-scale flight testing	2017
Full-scale flight testing for final validation and TRL8 assessment of best airframe designs and technology concepts	2022

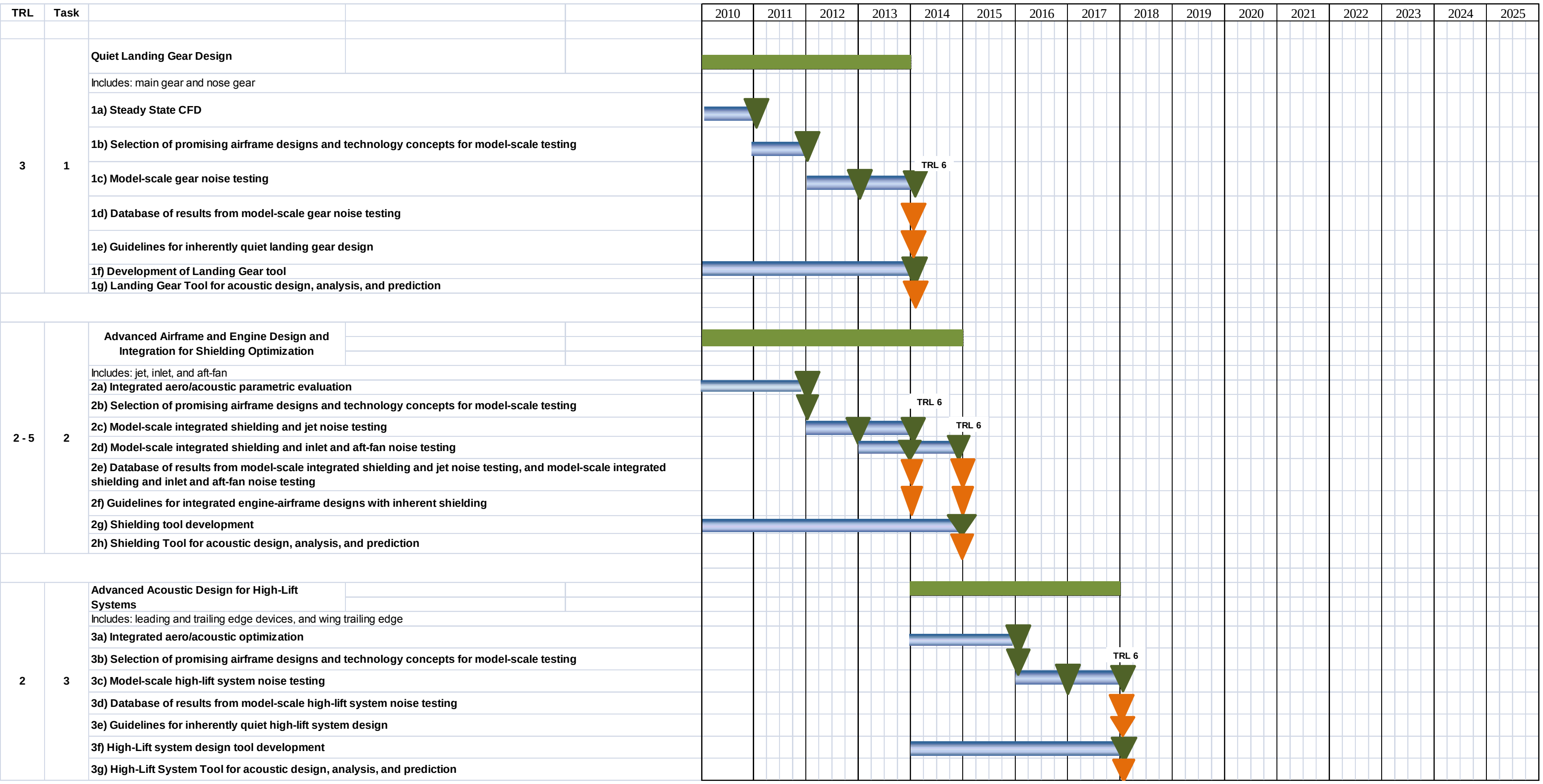
Dependency:

Airplane design and development (cross-effect and reaction to engine design, high-lift design and airplane performance)
Facilities for model-scale testing
Platform (testbed) for full-scale flight testing
CFD resources

Success Criteria:

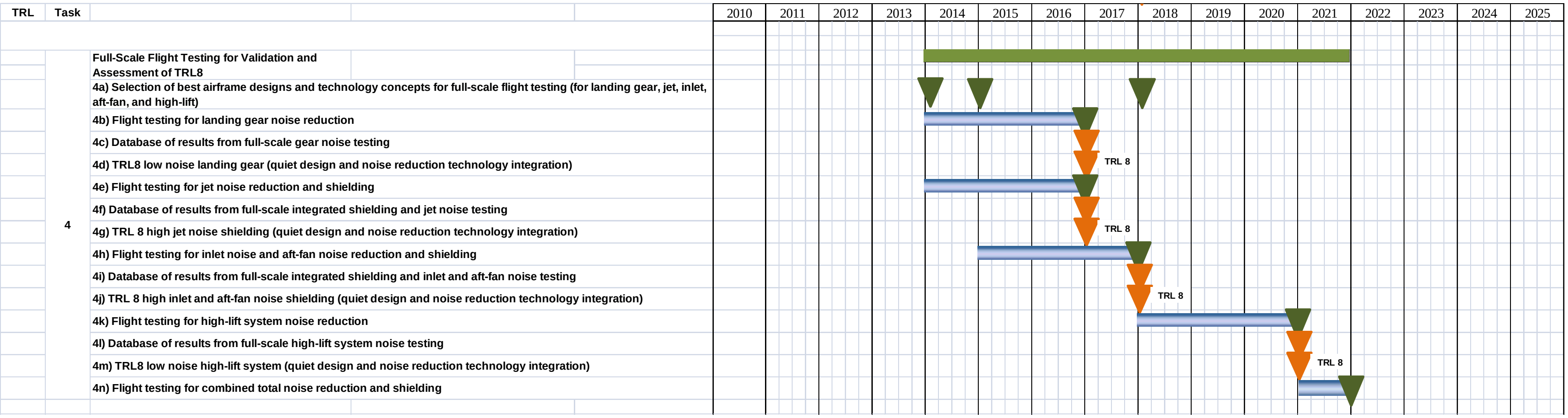
Table 7.8 – Airframe Acoustic Technologies Success Criteria

Task Name	Success Criteria	Alternate Steps if Unsuccessful
Quiet Landing Gear Design	5 dB reduction in gear noise	More testing with alternate concepts or use of lowest attained reduction level
	Landing Gear design tool	Alternate approach/methodology or use of existing gear noise prediction tools
Advanced Airframe and Engine Design and Integration for Shielding Optimization	5 dB reduction in jet and aft-fan noise	More testing with alternate concepts or use of lowest attained reduction level
	15-20 dB cumulative shielding benefit (sum of jet, inlet, and aft-fan shielding)	More testing with alternate concepts or use of highest attained shielding benefit
	Shielding design tool	Alternate approach/methodology or use of existing shielding prediction tools
Advanced Acoustic Design for High-Lift Systems	8-10 dB combined reduction	Use of lowest existing high-lift noise levels
	High-Lift System design tool	Use of existing noise prediction tools
Full-Scale Flight Testing for Validation and Assessment of TRL8	Agreement between model-scale and full-scale results; realizing most of the expected benefits	Adjustment/extrapolation of existing data
		Conservative use of model-scale benefits



TRL	Task	
3	1	**Quiet Landing Gear Design**
		Includes: main gear and nose gear
		1a) Steady State CFD
		1b) Selection of promising airframe designs and technology concepts for model-scale testing
		1c) Model-scale gear noise testing
		1d) Database of results from model-scale gear noise testing
		1e) Guidelines for inherently quiet landing gear design
		1f) Development of Landing Gear tool
		1g) Landing Gear Tool for acoustic design, analysis, and prediction
2 - 5	2	**Advanced Airframe and Engine Design and Integration for Shielding Optimization**
		Includes: jet, inlet, and aft-fan
		2a) Integrated aero/acoustic parametric evaluation
		2b) Selection of promising airframe designs and technology concepts for model-scale testing
		2c) Model-scale integrated shielding and jet noise testing
		2d) Model-scale integrated shielding and inlet and aft-fan noise testing
		2e) Database of results from model-scale integrated shielding and jet noise testing, and model-scale integrated shielding and inlet and aft-fan noise testing
		2f) Guidelines for integrated engine-airframe designs with inherent shielding
		2g) Shielding tool development
		2h) Shielding Tool for acoustic design, analysis, and prediction
2	3	**Advanced Acoustic Design for High-Lift Systems**
		Includes: leading and trailing edge devices, and wing trailing edge
		3a) Integrated aero/acoustic optimization
		3b) Selection of promising airframe designs and technology concepts for model-scale testing
		3c) Model-scale high-lift system noise testing
		3d) Database of results from model-scale high-lift system noise testing
		3e) Guidelines for inherently quiet high-lift system design
		3f) High-Lift system design tool development
		3g) High-Lift System Tool for acoustic design, analysis, and prediction

Figure 7.37 – Airframe Acoustic Technology Roadmap (part 1 of 2)



TRL	Task	
	4	Full-Scale Flight Testing for Validation and Assessment of TRL8
		4a) Selection of best airframe designs and technology concepts for full-scale flight testing (for landing gear, jet, inlet, aft-fan, and high-lift)
		4b) Flight testing for landing gear noise reduction
		4c) Database of results from full-scale gear noise testing
		4d) TRL8 low noise landing gear (quiet design and noise reduction technology integration)
		4e) Flight testing for jet noise reduction and shielding
		4f) Database of results from full-scale integrated shielding and jet noise testing
		4g) TRL 8 high jet noise shielding (quiet design and noise reduction technology integration)
		4h) Flight testing for inlet noise and aft-fan noise reduction and shielding
		4i) Database of results from full-scale integrated shielding and inlet and aft-fan noise testing
		4j) TRL 8 high inlet and aft-fan noise shielding (quiet design and noise reduction technology integration)
		4k) Flight testing for high-lift system noise reduction
		4l) Database of results from full-scale high-lift system noise testing
		4m) TRL8 low noise high-lift system (quiet design and noise reduction technology integration)
		4n) Flight testing for combined total noise reduction and shielding

Figure 7.38 – Airframe Acoustic Technology Roadmap (part 2 of 2)

7.3.5 – Engine Acoustic Technologies

Goals and Objectives:

Develop new and innovative designs and methods to reduce propulsion system noise

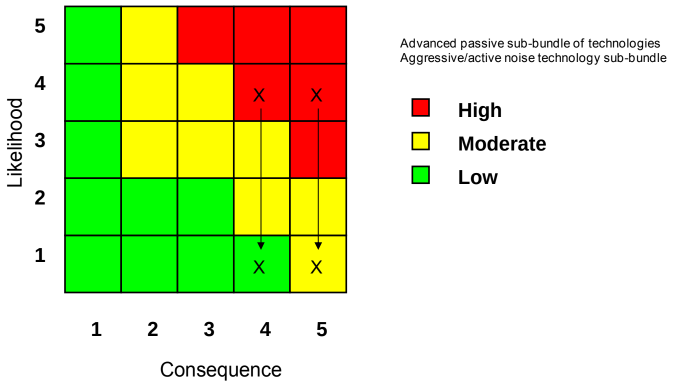
Performance Area and Impact:

Engine Acoustic Properties

Technical Description:

Two pronged approach to develop a suite of near-term, mostly passive technologies and far-term aggressive suppression technologies

Risk Assessment:



Passive Technologies: 4 x 4
Active Technologies: 4 x 5

Current TRL:

Engine Acoustic Tech. 3

Major Milestones:

Overall program: program provides an "onramp" for demo engine test of technology concepts every 2 years

Ongoing design studies / data reduction / methods improvement throughout program

Phase I - advanced/passive noise treatments full scale tests (typically 2 design/build/test iterations), best funding fit with N+2

Phase II - advanced/active noise treatments subscale/rig design/build/test cycles (3), plus full scale design/build/test cycles (2), best funding fir with N+3

Early thrusts of N+3 acoustic work: 1) sustained work on high-performance bulk absorbers, 2) open rotor noise reduction, Basic physics of fluidics and flow control

Mid-phase thrusts expanded to include Unconventional UHB, soft/active elements, and non-axisymmetric exhausts

Far term focus on low noise combustor, shape memory alloy

Dependency:

Need dedicated engine asset(s) to use as testbed
Variable fan nozzle is not shown (appears on advanced engine tech roadmap)

Notes:

10-yr sustained development of bulk and tailored absorbers
Development program utilizes multiple builds of an engine test asset
Hold pace of 1 engine build and test every 2 years
Early program focused on full scale demos of incremental/moderate risk concepts
Early program focused on subscale/rig demos of aggressive and high risk concepts
Later program focused on full scale demo of aggressive/high risk projects
Each technology gets 2 build/test cycles (can adjust as needed based on results: most promising concepts-->More builds, less promising-->fewer builds)
Continuous effort to incorporate results into methods and design practices
Variable fan nozzle is not shown (appears on advanced engine tech roadmap)

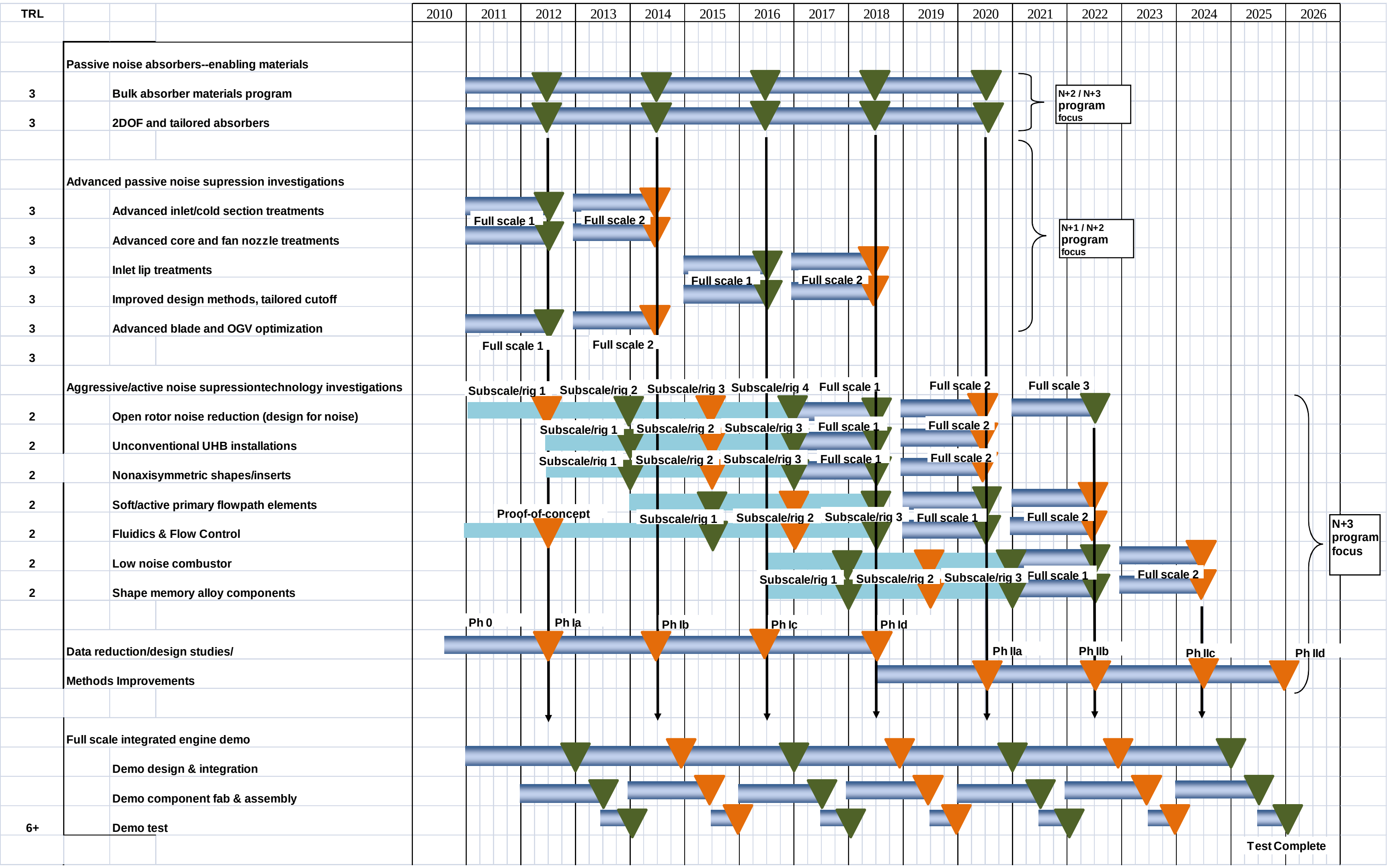


Figure 7.39 – Engine Acoustic Technology Roadmap*

* The roadmap schedule shown is notional, suitable for overall program planning purposes only, with no implied guarantee or commitment on the part of GE Aviation

7.3.6 – Advanced Subsystems

Goals and Objectives:

Significantly improve weight and reliability of aircraft subsystems

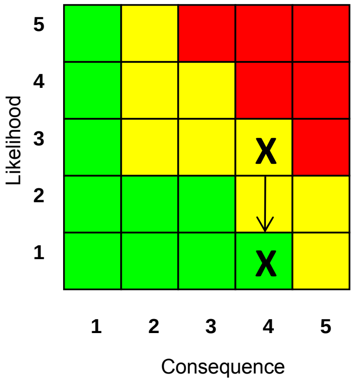
Performance Area and Impact:

Reduced airplane weight, improved system reliability

Technical Description:

Adaptive Power Management
Diesel APU
EMA Actuators
Fiberoptic Control Architecture
Lightweight Thermal Technology
Integrated Computing Networks

Risk Assessment:



Current TRL:

2 to 4

Major Milestones:

Diesel APU certification	2017
Fiberoptic control system certification	2017
Integrated computing network 3.0 certification	2018
Adaptive power management system certification	2019
Lightweight thermal technology certification	2020
EMA Actuators Flight Demo	2021
Integrated computing network 4.0 certification	2026

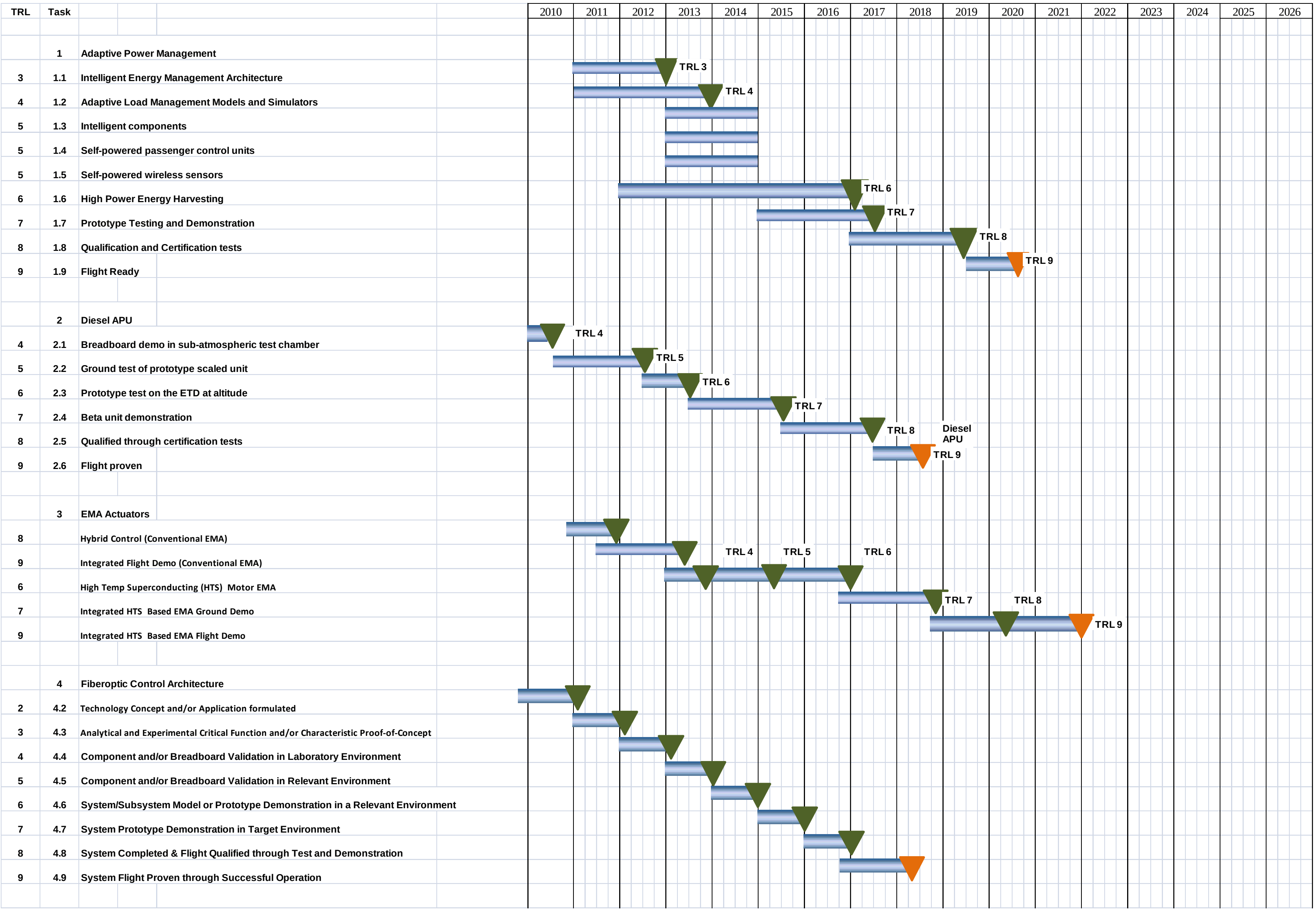
Dependency:

Integrated Airplane Systems Architecture

Success Criteria:

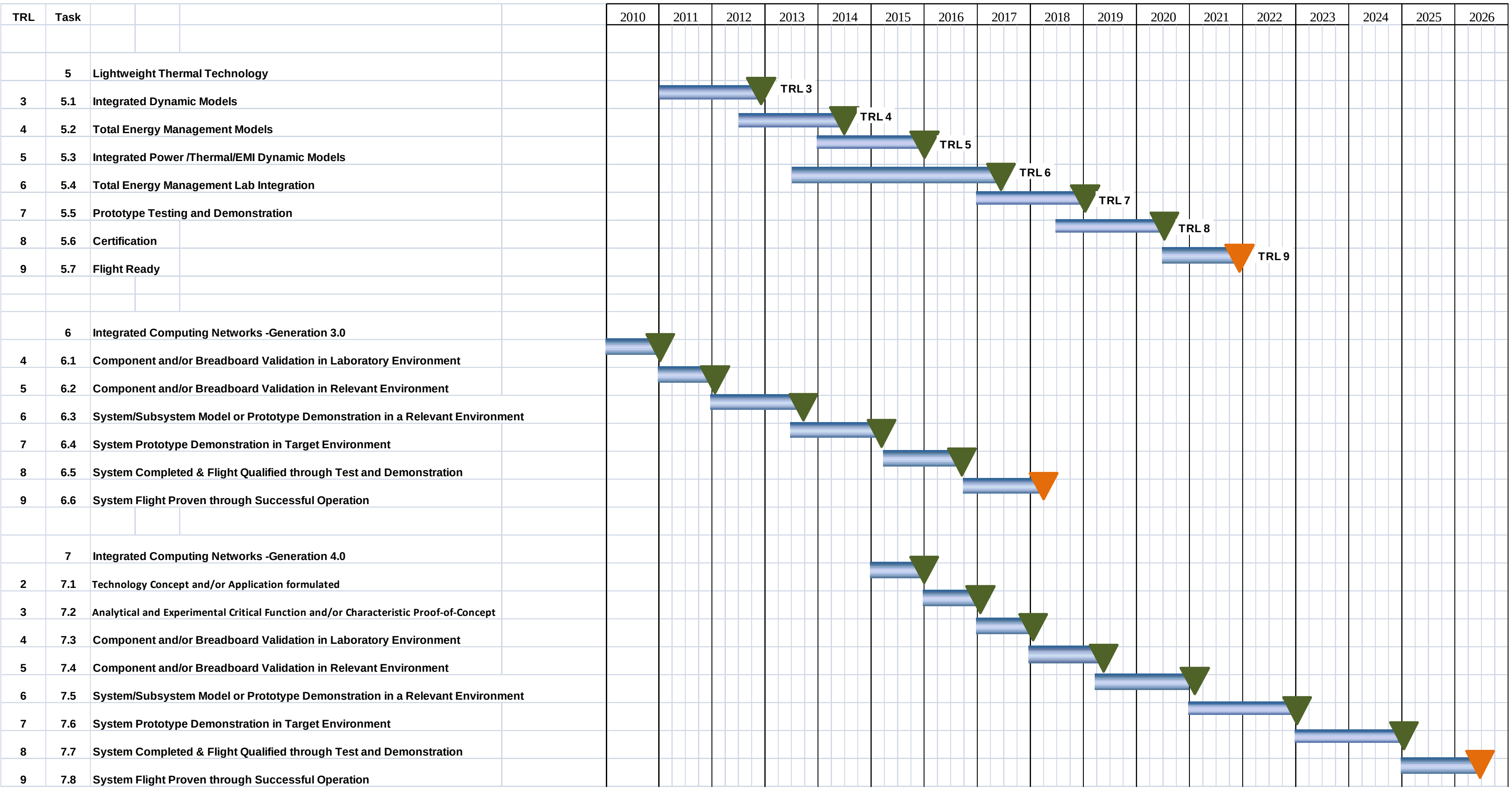
Table 7.9 – Advanced Subsystems Success Criteria

Task Number	Task Name	Success Criteria	Alternate Steps if Unsuccessful
1	**Adaptive Power Management**	Certification	Revert to current SOA
2	**Diesel APU**	Certification	Revert to advanced turboshaft APU
3	**EMA Actuators**	Certification	Revert to current SOA
4	**Fiberoptic Control Architecture**	Certification	Revert to current SOA
5	**Lightweight Thermal Technology**	Certification	Revert to current SOA
6	**Integrated Computing Networks - Generation 3.0**	Certification	Revert to current SOA
7	**Integrated Computing Networks - Generation 4.0**	Certification	Revert to generation 3.0 architecture



TRL	Task	
	1	Adaptive Power Management
3	1.1	Intelligent Energy Management Architecture
4	1.2	Adaptive Load Management Models and Simulators
5	1.3	Intelligent components
5	1.4	Self-powered passenger control units
5	1.5	Self-powered wireless sensors
6	1.6	High Power Energy Harvesting
7	1.7	Prototype Testing and Demonstration
8	1.8	Qualification and Certification tests
9	1.9	Flight Ready
	2	Diesel APU
4	2.1	Breadboard demo in sub-atmospheric test chamber
5	2.2	Ground test of prototype scaled unit
6	2.3	Prototype test on the ETD at altitude
7	2.4	Beta unit demonstration
8	2.5	Qualified through certification tests
9	2.6	Flight proven
	3	EMA Actuators
8		Hybrid Control (Conventional EMA)
9		Integrated Flight Demo (Conventional EMA)
6		High Temp Superconducting (HTS) Motor EMA
7		Integrated HTS Based EMA Ground Demo
9		Integrated HTS Based EMA Flight Demo
	4	Fiberoptic Control Architecture
2	4.2	Technology Concept and/or Application formulated
3	4.3	Analytical and Experimental Critical Function and/or Characteristic Proof-of-Concept
4	4.4	Component and/or Breadboard Validation in Laboratory Environment
5	4.5	Component and/or Breadboard Validation in Relevant Environment
6	4.6	System/Subsystem Model or Prototype Demonstration in a Relevant Environment
7	4.7	System Prototype Demonstration in Target Environment
8	4.8	System Completed & Flight Qualified through Test and Demonstration
9	4.9	System Flight Proven through Successful Operation

Figure 7.40 – Advanced Subsystems Roadmap (part 1 of 2)



TRL	Task	
	5	Lightweight Thermal Technology
3	5.1	Integrated Dynamic Models
4	5.2	Total Energy Management Models
5	5.3	Integrated Power /Thermal/EMI Dynamic Models
6	5.4	Total Energy Management Lab Integration
7	5.5	Prototype Testing and Demonstration
8	5.6	Certification
9	5.7	Flight Ready
	6	Integrated Computing Networks -Generation 3.0
4	6.1	Component and/or Breadboard Validation in Laboratory Environment
5	6.2	Component and/or Breadboard Validation in Relevant Environment
6	6.3	System/Subsystem Model or Prototype Demonstration in a Relevant Environment
7	6.4	System Prototype Demonstration in Target Environment
8	6.5	System Completed & Flight Qualified through Test and Demonstration
9	6.6	System Flight Proven through Successful Operation
	7	Integrated Computing Networks -Generation 4.0
2	7.1	Technology Concept and/or Application formulated
3	7.2	Analytical and Experimental Critical Function and/or Characteristic Proof-of-Concept
4	7.3	Component and/or Breadboard Validation in Laboratory Environment
5	7.4	Component and/or Breadboard Validation in Relevant Environment
6	7.5	System/Subsystem Model or Prototype Demonstration in a Relevant Environment
7	7.6	System Prototype Demonstration in Target Environment
8	7.7	System Completed & Flight Qualified through Test and Demonstration
9	7.8	System Flight Proven through Successful Operation

Figure 7.41 – Advanced Subsystems Roadmap (part 2 of 2)

7.3.7 – Structural Materials

Goals and Objectives:

Implement advanced materials with greatly improved properties are needed to support the N+3 SUGAR configurations. Improved specific strength and specific stiffness are needed to enable very thin, very high aspect ratio wings.

Performance Area and Impact:

Primary, structural weight (OWE). Secondary, systems components weights (OEW)

Secondary, support operations of advanced aerodynamics and control technologies to reduce drag and reduce noise

Technical Description:

Ultra-High-Modulus, Ultra-High-Strength Fibers - Carbon or other fibers that provide significant increase in specific strength or specific stiffness for improvement in both strength driven structure such as fuselage and lower wing surfaces, and stiffness driven structures such as wing upper surface. Thin wing loads, including dynamic loads such as gust and maneuver loads, and aeroelastic considerations will dictate to what extent improved strength is needed vs. improved stiffness

Metal-Matrix Composites - titanium matrix composites to provide lower weight for very high strength applications such as landing gear

Very Tough Composites - Resin systems with greatly reduced susceptibility to impact damage and reduced curing temperatures to support lower cost

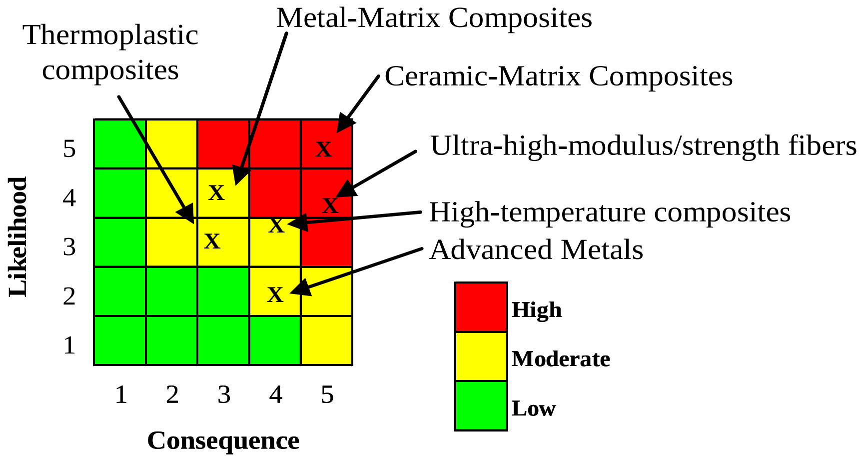
Thermoplastic Composites - thermoplastic resin systems support low cost manufacturing

High-Temperature Polymer Composites - Composite matrix systems capable of sustained operation at temperatures above 350F for use near engine and exhaust

Layer-by-Layer/Multifunctional nanocomposites for structures with integrated sensors and electronics to support structural health management and loads monitoring/active control

Ceramics/CMC Durable ceramic and ceramic matrix composites for elevated temperature load bearing structure

Risk Assessment:



Current TRL:

2 to 5

Major Milestones:

Identify target applications/requirements for enhanced materials
Identify new material chemistries for development
Develop and refine processing methods
Scale-up for manufacturing

Dependency:

None

Success Criteria:

Table 7.10 – Structural Materials Success Criteria

Task Number	Task Name	Success Criteria	Alternate Steps if Unsuccessful
1	**Ultra High Modulus Ultra High Strength Fibers**	Very high aspect ratio wing designs not driven by sizing for aeroelasticity and gust/maneuver loads	Active control of aeroelastic response and loads alleviation
2	**Metal Matrix Composites**	Lightweight landing gear structures	Conventional materials, e.g., stainless steel
3	**Very Tough Composites**	Composite structure weight not driven by fracture toughness	Structural health management/prognosis to reduce fracture critical structural weight
4	**Thermoplastic Composites**	Sufficient strength for use in loaded secondary structures	Continued use of thermoset composites
5	**High Temperature Polymer Composites**	Use in engine nacelles	Titanium or high temperature aluminum depending on application
6	**Layer-by Layer-Multifunctional Nanocomposites**	Lightweight broad area sensing and distributed processing	Higher weight sensors and electronics
7	**Ceramics/Ceramic Matrix Composites**	Use in engines and nacelles	High temperature metals

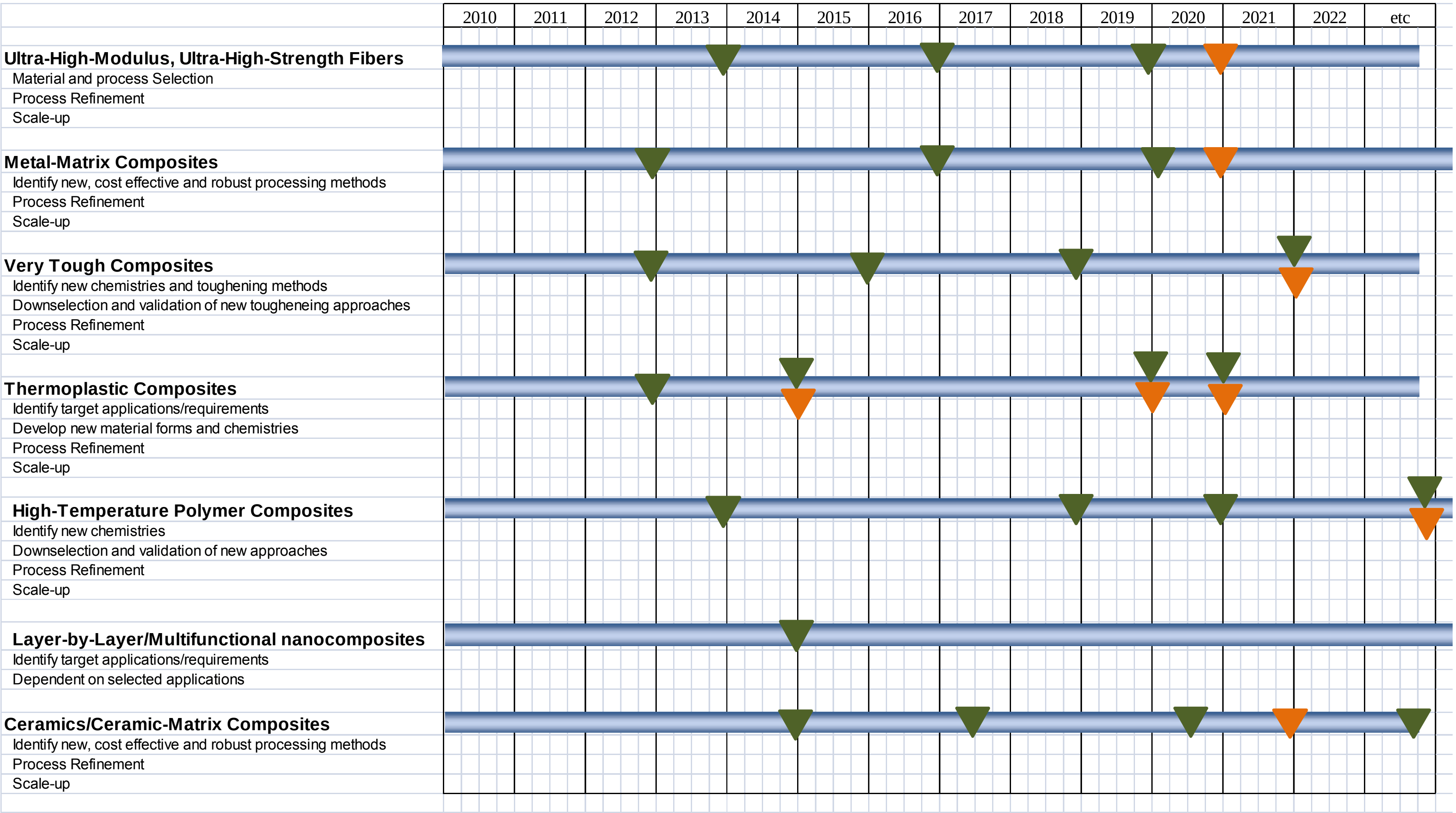


Figure 7.42 – Structural Materials Roadmap

7.3.8 – Structural Concepts Roadmap

Goals and Objectives:

Implement advanced structural technologies currently under development enabling design, fabrication and operation of advanced high performance structural systems without the conservatism inherent in current structures.

Structural designs will include integrated systems functionality which will benefit both airplane systems operations as well lighter weight structures.

Performance Area and Impact:

Primary, structural weight (OWE). Secondary, systems components weights (OEW)

Secondary, support operations of advanced aerodynamics and control technologies to reduce drag and reduce noise

Technical Description:

Reliability based design (RBD) and certification – quantify and actively manage structural design conservatism minimize excess weight while increasing airplane structural reliability

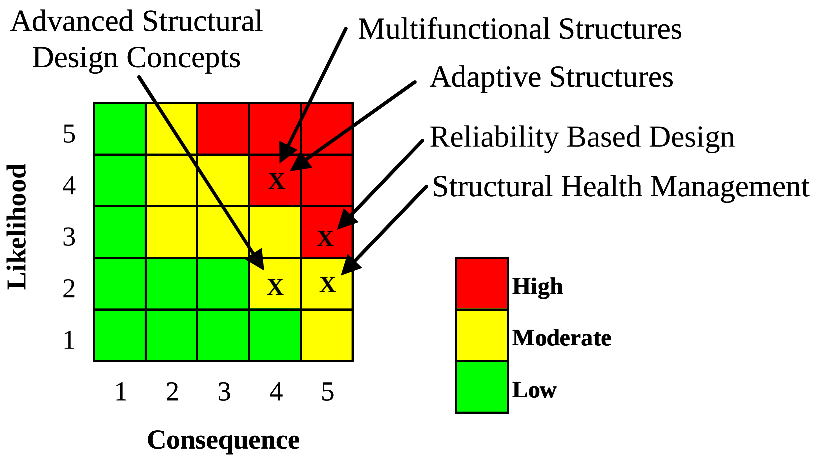
Structural Health Management (SHM) – know and manage the current state of the structures health throughout its life cycle

Advanced design concepts – design optimized structures using new design tools, advanced materials, fabrication and maintenance concepts

Multifunctional structures (MFS) – integrate system functionality into structures to reduce overall airplane weight and increase operational reliability through distributed redundancy

Adaptive structures – highly distributed actuation and sensing will enable airplanes to conformally change shape during flight to optimize L/D across a broad

Risk Assessment:



Current TRL:

2 to 5

Major Milestones:

Define objective function forms for each of the selected technologies

Develop a complete objective function form integrating all the selected technologies

Perform multidisciplinary optimization that maximizes airplane level performance for one or more N+3 configurations

Dependency:

None

Success Criteria:

Table 7.11 – Structural Concepts Success Criteria

Task Number	Task Name	Success Criteria	Alternate Steps if Unsuccessful
1	**RBD Analysis and Certification**	Use of probabilistic design methods for balanced design conservatism	Use of probabilistic design methods for secondary structure
2	**Structural Health Management**	Broad area monitoring of structure	Loads monitoring and structural hot spot detection (minimal weight improvement)
3	**Advanced Structural Design Concepts**	New structural concepts enable reduced weight	Conventional design
4	**Multifunctional Structures**	Structure with highly integrated systems functionality	Limited integration of wiring and thermal paths
5	**Adaptive Structures**	Reduced weight and complexity of conformal control surfaces and high lift systems	Reduce weight and complexity of rigid control and high lift surfaces

Figure 7.43 – Structural Concepts Roadmap

7.3.9 – Advanced Engine Technologies

Goals and Objectives:

Develop enabling materials and methods for improved component performance

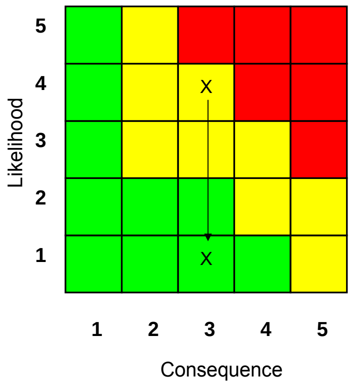
Performance Area and Impact:

Noise, Fuel burn, Emissions

Technical Description:

Develop propulsion enabling materials, cooling technology and component technology to support continued advancements in gas turbine efficiency, weight, and power

Risk Assessment:



Current TRL:

2 to 5

Major Milestones:

Subscale alloy process development
Full scale alloy development
Final alloy ready for engine use
Man tech milestones--TBD
Test of gen 1, 2, 3 CMC components
Tests of seals and bearings components
Tests of variable fan nozzle concepts
Tests of modulated cooling concepts
Tests of advanced Active Clearance Control concepts
Low emissions combustor cup, sector, full annular rig, and demo engine tests
Overall program: program provides an "onramp" for demo engine test of technology concepts every 2 years

Dependency:

Need suitable mule engine(s) to use as dedicated engine test asset
Need a contingency plan for acquiring a backup asset should a catastrophic test failure occur

Notes:

Program centered around multiple fast-paced builds of dedicated engine test vehicle
3 parallel materials development programs - 10 yr sustained
2 parallel man. Tech programs - 10 year sustained
Base engine is off-the-shelf
Yields TRL6 by 2025
Program for continuous improvement of low-emissions combustion technology

PMC = polymer matrix composites
CMC = ceramic matrix composites

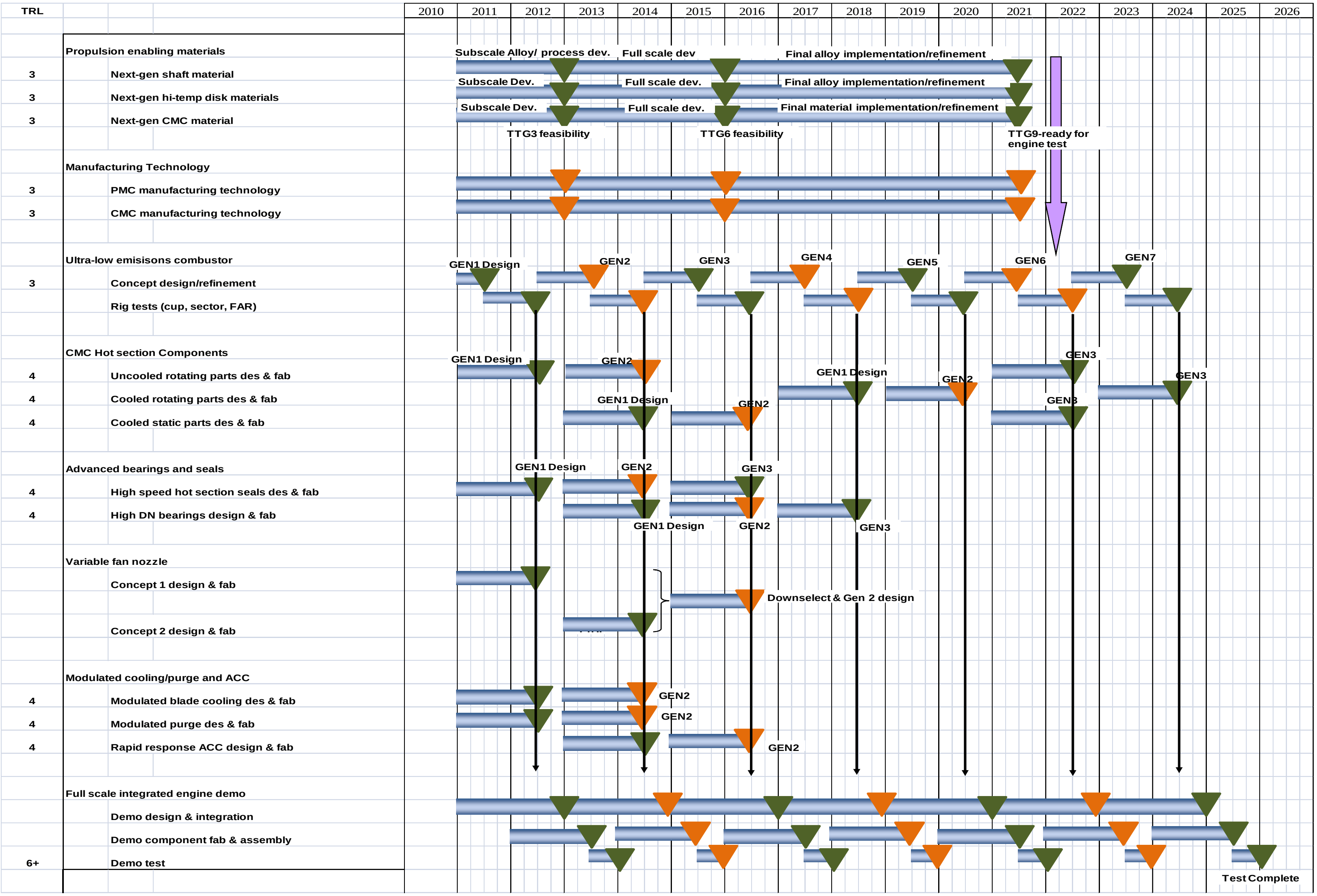


Figure 7.44 – Advanced Engine Technologies Roadmap*

* The roadmap schedule shown is notional, suitable for overall program planning purposes only, with no implied guarantee or commitment on the part of GE Aviation

7.3.10 – Hybrid Engine Technologies

Goals and Objectives:

Develop high performance, flight weight, and prime-reliable electric power components suitable for flight propulsion applications.

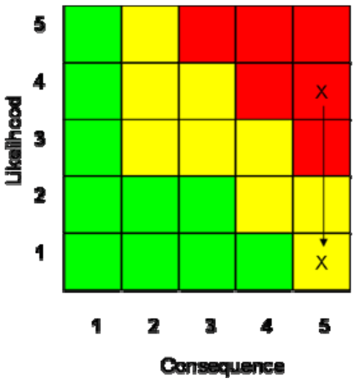
Performance Area and Impact:

Noise, Fuel burn, Emissions

Technical Description:

Develop high power, light weight motors, controllers, radiators and surface coolers, variable core nozzle

Risk Assessment:



Current TRL:

3

Major Milestones:

3 motor design, build, test, report-out cycles
3 surface cooler/radiator design, build, test, report out cycles
3 motor controller/power electronics design, build, test, report out cycles
Sustained program for lightweight high voltage conductors and insulators, with off ramps every ~18 months
Lightweight variable core exhaust nozzle design, build, test
Integration into full scale demo engine
Demo engine test

Dependency:

Need suitable off-the-shelf engine asset to support test

Notes:

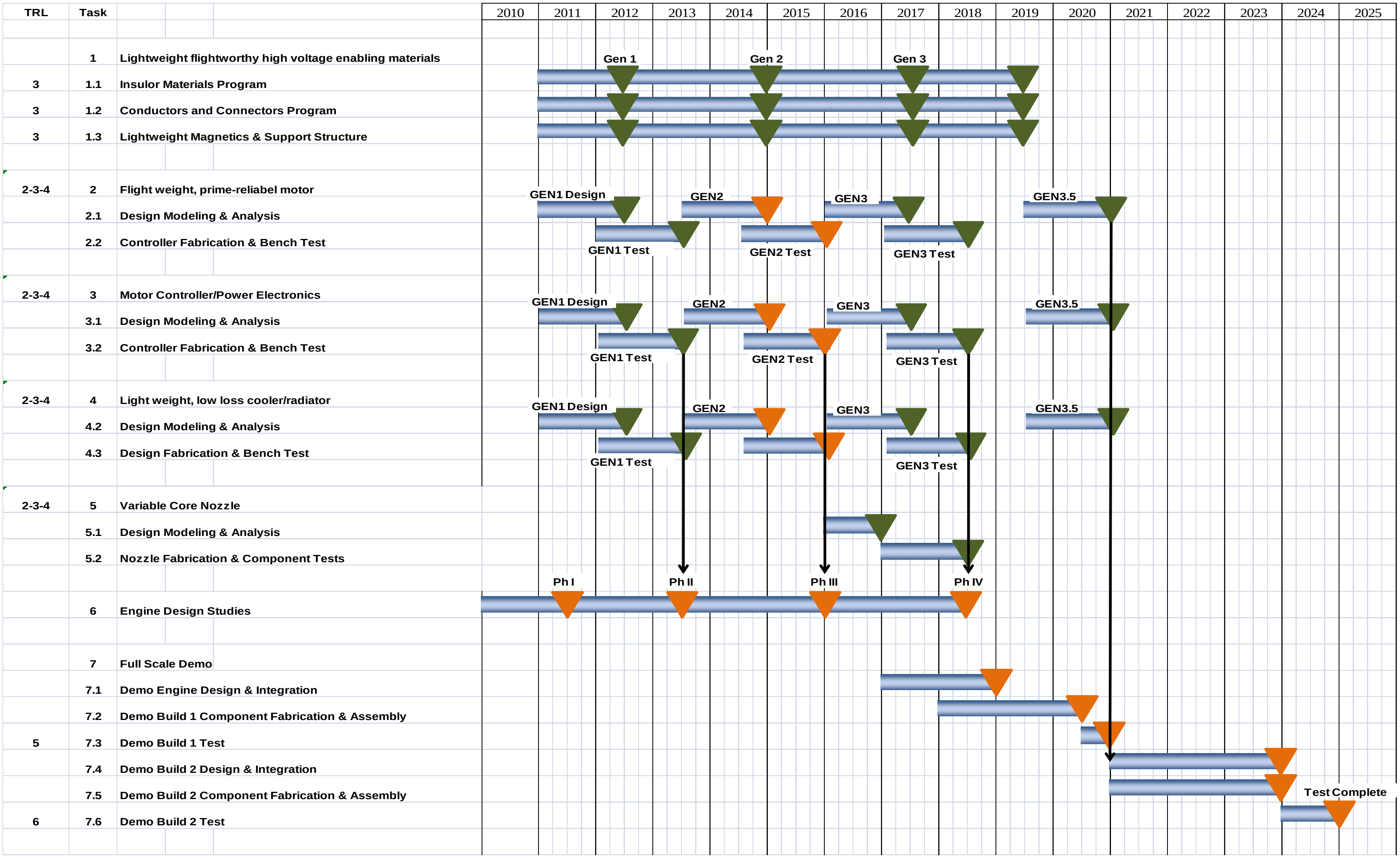
Sustained base technology program for flight-worthy conductors and insulators

2 builds for demo engine
Base engine is off-the-shelf
Yields TRL6 by 2025

3.5 design/build/test cycles for motor, motor controller, and associated cooling system hardware yields TRL3+ by 2018

Base engine is off-the-shelf
Yields TRL6 by 2025

Assumes battery technology development program separate from this plan
Ongoing engine design refinement studies



TRL	Task	
	1	Lightweight flightworthy high voltage enabling materials
3	1.1	Insulor Materials Program
3	1.2	Conductors and Connectors Program
3	1.3	Lightweight Magnetics & Support Structure
2-3-4	2	Flight weight, prime-reliabel motor
	2.1	Design Modeling & Analysis
	2.2	Controller Fabrication & Bench Test
2-3-4	3	Motor Controller/Power Electronics
	3.1	Design Modeling & Analysis
	3.2	Controller Fabrication & Bench Test
2-3-4	4	Light weight, low loss cooler/radiator
	4.2	Design Modeling & Analysis
	4.3	Design Fabrication & Bench Test
2-3-4	5	Variable Core Nozzle
	5.1	Design Modeling & Analysis
	5.2	Nozzle Fabrication & Component Tests
	6	Engine Design Studies
	7	Full Scale Demo
	7.1	Demo Engine Design & Integration
	7.2	Demo Build 1 Component Fabrication & Assembly
5	7.3	Demo Build 1 Test
	7.4	Demo Build 2 Design & Integration
	7.5	Demo Build 2 Component Fabrication & Assembly
6	7.6	Demo Build 2 Test

Figure 7.45 – Hybrid Engine Technologies Roadmap*

* The roadmap schedule shown is notional, suitable for overall program planning purposes only, with no implied guarantee or commitment on the part of GE Aviation

7.3.11 – High Span Strut Braced Wing Technology Integration

Goals and Objectives:

Develop and integrate technologies required to enable a high speed strut-braced wing.

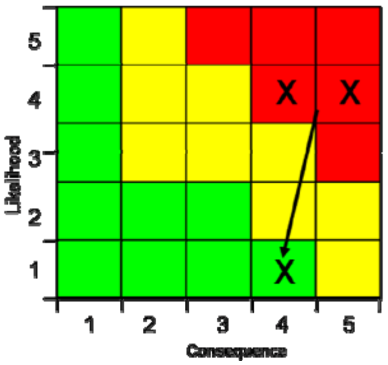
Performance Area and Impact:

Enable integration of high span strut braced wing allowing very high aspect ratio wings for low induced drag and natural laminar flow

Technical Description:

Ultra-High-Modulus, Ultra-High-Strength Fibers
Low interference drag struts
Low interference drag nacelles for a highly integrated configuration
Active/Passive aeroelastic response for load control
Advanced high cruise CL supercritical wing design
Layer-by-Layer/Multifunctional nanocomposites
Natural laminar flow wing design

Risk Assessment:



Current IRL:

2 to 4

Major Milestones:

Ultra High Modulus fibers production ready	2020
Integration of low interference drag struts on high span wing configurations. Improvement in interference drag is significant. Identity system benefits for go-no-go.	2020
Integration of low interference drag nacelles on high span wing configurations. Improvement in interference drag is significant. Identity system benefits for go-no-go.	2020
Collaborate integration of active/passive aeroelastic response for load control. Identity system benefits for go-no-go.	2020
Layer-by-Layer/Multifunctional nanocomposites production ready	2025
Natural laminar flow wing design without HLFC systems to achieve a viable configuration. Roadmap will address passive/active systems to achieve Aerodynamic goals. Identity system benefits for go-no-go.	2020

Dependency:

Items are interdependent to achieve viable high aspect ratio strut-braced wing design.

Success Criteria:

Table 7.12 – High Span Strut Braced Wing Technology Integration Success Criteria

Task Number	Task Name	Success Criteria	Alternate Steps if Unsuccessful
1	**Natural Laminar Flow**	NLF laminar design matches Active LFC	Achieve 50% of an Active LFC laminar Run
2	**Low Interference Drag Struts**	Integrate strut into wing-body for only strut parasite drag	Establish low interference levels
3	**Advanced Supercritical Wing Design**	Target 3% airplane drag improvement while attaining high design lift coefficient	Achieve 50% of target drag improvement
4	**Low Interference Drag Nacelles**	Integrate nacelle/pylon to wing body for only nacelle/pylon parasite drag	Establish low interference levels
5	**Active/Passive Aeroelastic Load Control**	Span load traded for Aerodynamics and structural efficiencies to improve overall mission performance	Achieve improvement for one discipline
6	**Multifunctional Nanocomposites**	Lightweight broad area sensing and distributed processing	Higher weight sensors and electronics
7	**Ultra High Modulus and Strength Fibers**	Very high aspect ratio wing designs not driven by sizing for aeroelasticity and gust/maneuver loads	Active control of aeroelastic response and loads alleviation
8	**Vehicle Technology Integration**	Integrated vehicle design with advanced technology suite	Integrated vehicle design with all achieved technology advancements

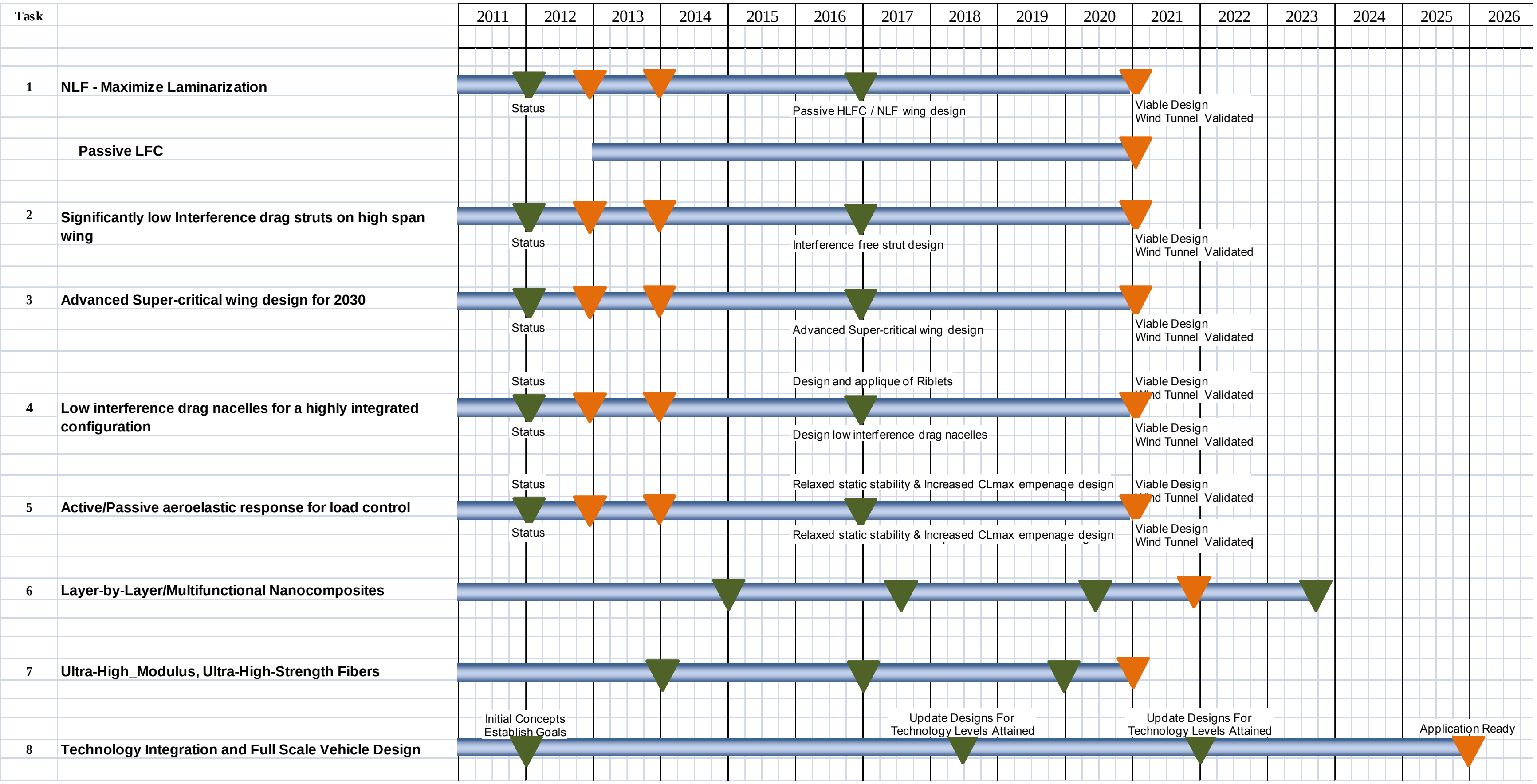


Figure 7.46 – High Span Strut Braced Wing Technology Integration Roadmap

8.0 – Summary, Conclusions, and Recommendations

8.1 – Summary

This Final Report summarizes the work accomplished by the Boeing Subsonic Ultra Green Aircraft Research (SUGAR) team in Phase 1, which includes the time period of October 2008 through March 2010. Work completed includes the development of a comprehensive future scenario for world-wide commercial aviation, the consideration and selection of baseline and advanced configurations for study, the generation of technology suites for each configuration, detailed performance analysis of the baseline, reference, and advanced configurations, noise and emissions of all concepts, and the development of technology risks and roadmaps.

The future scenario is based on a 20-year current market outlook process that Boeing has used for the last 40 years. The future scenario was used to establish baseline, reference, and advanced aircraft in three size classes (regional, medium, and large) for the 2008-2055 timeframe. Also derived from the future scenario were the payload, speed, design range, and average range for each of the size classes. For this study, it was decided to concentrate design and analysis resources on a medium size aircraft carrying 154 passengers to a maximum range of 3500 nm.

A concept selection workshop was held at Georgia Tech to discuss and select advanced concept configurations and enabling propulsion technologies. From the workshop and post-workshop discussions, the following five configurations were selected for detailed analysis:

1. SUGAR Free – Current technology, similar to 737 class aircraft. Used as Baseline for performance comparisons.
2. Refined SUGAR – Basic conventional configuration with estimated 2030-2035 N+3 technologies, including improved NEXTGEN air traffic control mission efficiency. Includes “gFan” turbofan engine from GE.
3. SUGAR High – High span strut-braced wing configuration with advanced 2030-2035 N+3 technologies. Assumes significant technology development beyond the technologies in the Refined SUGAR concept. “gFan+” turbofan and open fan propulsion options supplied by GE.
4. SUGAR Volt – Builds off of SUGAR High configuration to add electric propulsion technologies. Initially considered a variety of electric-propulsion architectures (Battery electric only, fuel-cell gas turbine hybrid, battery electric gas turbine hybrid), but Boeing point-of-departure sizing analysis and GE analysis led to selection of battery gas turbine hybrid propulsion architecture. “hFan” turbofan-electric hybrid engine data developed by GE.
5. SUGAR Ray – A HWB configuration that uses a similar suite of advanced technologies as the SUGAR High. Primary design emphasis is on reducing aircraft noise, while maintaining performance similar to the SUGAR High.

Technology and system experts were engaged to establish technology suites for each of the five configurations. Technologies were selected in four categories: Aero, Structural, Subsystem, and Propulsion. Refined SUGAR technologies assume a “business as usual” technology development between now and 2030-2035. SUGAR High, SUGAR Volt, and SUGAR Ray assume significant additional focused development of technologies for these aircraft.

To begin the analysis and sizing process, a point-of-departure sizing analysis was conducted. This conceptual analysis provided initial sizing information to start the more detailed design and analysis process. These results established “goal” performance levels for the configurations and their technologies. For the SUGAR Volt, the point-of-departure analysis included a trade study to establish required battery technology levels and to compare various electric propulsion architectures. Ultimately a battery electric, gas turbine hybrid propulsion architecture was selected. These results were presented at the 6-month review, and for the average 900 nm mission, showed approximately a 50% reduction in fuel burn for the Refined SUGAR, a 58% reduction for the SUGAR High, and up to a 90% reduction in fuel used for the SUGAR Volt.

Detailed analysis and sizing began when the point-of-departure results were used to draw each configuration. From this geometry model, aerodynamics and mass properties analyses were conducted on the as-drawn configuration. The point-of-departure results were also used to develop an initial size for the engines. Then a mission performance analysis was used to resize the as-drawn aircraft to meet all constraints. In some cases, constraints were adjusted as part of a requirements analysis trade study. Detailed analysis and sizing was completed for all configurations.

> The Refined SUGAR results indicate a 44% reduction in fuel burn compared to the SUGAR Free baseline on a 900nm mission. Opportunities have been identified for up to a 54% fuel burn reduction by using the gFan+ engine and a higher span wing. NOx emissions were reduced to 42% of CAEP 6 levels by using an advanced combustor. CO_2 emissions can be reduced by 72% by adding biofuels to the other technologies. Noise is reduced by 16 db. Design takeoff distances of 8200 ft can be achieved at full weight or reduced to 5500 ft or less for the average mission fuel load.
>
> The SUGAR High results indicate a 39% reduction in fuel burn compared to the SUGAR Free baseline on a 900nm mission. Opportunities for wing weight reduction and aerodynamic improvements have been identified for up to a 58% fuel burn reduction. NOx emissions were reduced to 28% of CAEP 6 levels by using an advanced combustor. CO_2 emissions can be reduced by 69% by adding biofuels to the other technologies. Noise is reduced by 22 db. Design takeoff distances of 8200 ft can be achieved at full weight or reduced to 6000 ft or less for the average mission fuel load.
>
> The SUGAR Volt results indicate a 63% reduction in fuel burn compared to the SUGAR Free baseline on a 900nm mission. Opportunities have been identified for up to a 90% fuel burn reduction through greater electric usage. If total energy usage (fuel plus electricity) is considered, a 56% reduction is achieved. NOx emissions were reduced to 21% of CAEP 6 levels by using an advanced combustor with a potential for even greater reductions (to 11%) by optimizing electric motor usage. CO_2 emissions can be reduced by 81% by adding biofuels to the other technologies. Noise is reduced by at least 22 db, with more reduction available by optimizing the electric motor usage and trajectory during takeoff and climb-out. Design takeoff distances of 8200 ft can be achieved at full weight or reduced to 4000-5200 ft for the average mission takeoff weight.
>
> The SUGAR Ray results indicate a 43% reduction in fuel burn compared to the SUGAR Free baseline on a 900nm mission. NOx emissions were reduced to 28% of CAEP 6 levels. CO_2 emissions can be reduced by 75% by adding biofuels to the other technologies. Due to additional airframe shielding benefits, noise is reduced by 37 db.

The team conducted a Technology Workshop in November 2009. At this workshop, the team accelerated the final technology roadmap prioritization and risk assessment. The risk associated with the technology suites for each configuration has been assessed and the relationship between each technology (or technology group) and each NASA goal has been quantified. Development roadmaps for each technology (or technology group) have been established.

A wide range of technologies contribute to substantial fuel burn reduction. Biofuels are a large contributor to reducing greenhouse gas emissions. Advanced combustor technology is key to reducing NOx emissions. Reducing aircraft noise requires an array of engine and airframe noise technologies.

Finally, the results of the configuration assessment and technology analysis processes were used to develop recommendations for Phase 2 work.

8.2 – Conclusions

1. Fuel Burn – The NASA fuel burn goal of a 70% reduction is very aggressive. A combination of air traffic management, airframe, and propulsion improvements were shown to achieve a 44-58% reduction in fuel burn for conventional propulsion. The addition of hybrid electric propulsion to the technology suite has the potential for fuel burn reductions of 70-90%. If electric energy is considered in a modified goal of "energy usage", then a 56% or greater reduction in energy use is possible.
2. Greenhouse Gases – Although NASA did not establish a goal for greenhouse gas emissions, Boeing considered the goal of reducing life cycle CO_2 emissions. The fuel burn reductions identified above directly reduce CO_2 emissions as well. Sustainable biofuels can be used to reduce CO_2 emissions by 72% for conventional propulsion and even more with hybrid electric propulsion using "green" electrical power to charge the battery system.
3. NOx Emissions – Landing and takeoff NOx emissions can be at or near the NASA goal of a 75% reduction from CAEP 6 using advanced combustor technology. The use of electric power in the hybrid electric propulsion concept offers the opportunity for even lower emissions.
4. Noise – The original Phase I noise reduction goal to provide a 55 DNL contour at the airport boundary is difficult to achieve. An investigation of airport characteristics shows that a 1.8 nm boundary distance is representative. At this distance a 45 dB reduction relative to the SUGAR Free is needed to provide the 55 DNL contour. However, the best performing configuration, SUGAR Ray, achieved only a 37 dB noise reduction and needs a larger 2.5 nm boundary to contain the 55 DNL contour. To further reduce the airport boundary distance, or meet the updated 71 dB reduction NASA goal, requires significant additional reduction in aircraft noise.
5. Field Length – Takeoff distances are designed to be approximately 8,200 ft at Maximum Takeoff Weight (MTOW). For the average 900 nm range with reduced takeoff weight, distances of approximately 5,000 ft are achieved. The use of hybrid electric propulsion allows additional application of power for takeoff, possibly lowering the takeoff distance even more. This was achieved without adding aggressive high lift technologies. For the study, it was assumed that a takeoff distance of approximately 5,000 ft for the average range mission is sufficient for operation at an adequate number of airports to support

necessary operations. We chose not to expend limited study resources to further investigate configurations and technologies needed to achieve shorter takeoff distances.

6. Advanced Configurations – The SUGAR High configuration has potential to beat the conventional configuration (Refined SUGAR) with regard to fuel burn, but the present uncertainty in the wing weight and high cruise lift coefficient prevents a definitive conclusion at this time. The SUGAR Ray HWB configuration is clearly the quietest.
7. Technologies – A wide portfolio of technologies is needed to achieve the NASA N+3 goals. Significant improvements in air traffic management, and aerodynamic, structural, system, and propulsion technologies are needed to address fuel burn goals. Biofuels are needed to further reduce greenhouse gas emissions. Advanced combustor technology is necessary to meet NOx goals. Even more aggressive engine and airframe noise reduction technologies than applied in this study are needed. The hybrid electric engine technology is a clear winner, as it has the potential to improve performance relative to all of the NASA goals.

8.3 – Recommendations

Based on the Phase 1 configuration assessment and technology analysis results, we recommend the following for Phase 2 activities (in approximate order of priority):

1. Additional design and analysis of hybrid electric gas turbine propulsion architectures and the integration of the concept into other configurations (like the Refined SUGAR or SUGAR Ray). A noise analysis for the hybrid electric propulsion system needs to be conducted to determine potential noise benefits for operating on partial or full electric power.
2. A comprehensive study of high aspect ratio strut/truss braced wings, accounting for coupled aerodynamics, structures, materials, propulsion, and control. Making this wing aerodynamically effective while controlling weight is key to enabling this high L/D configuration. A detailed finite element model is needed, and an aeroelastic test is necessary to validate the structural analysis and to determine the weight of the wing. The high cruise lift coefficient required at Mach 0.70 for high aspect ratio wings requires additional analysis, optimization, and experimental validation.
3. Additional noise technologies need to be identified and validated to achieve the updated NASA -71 db noise goal. This could include use of trajectory optimization, greater use of electric propulsion, turboprops, and low noise propellers. Airframe and tail shielding should continue to be investigated in HWB and conventional configurations.
4. A follow-on to this study to consider the synergistic benefits of methane and/or hydrogen fuel (high heating value, thermal management, fuel cells, and superconducting electric propulsion).
5. A follow-on to this study to include the large aircraft size class. It is anticipated that some technologies will become more important as the length of the cruise segment is increased.
6. An aircraft power system study to determine the best architecture for aircraft power, including diesel and conventional APUs, fuel-cells, batteries, and both engine power take-off and bleed air. This study should include traditional, more-electric and all-electric aircraft system architectures, per aircraft size class.

7. A follow-on to this study to include the regional jet size class. Special emphasis should be placed on low noise propulsion, field length, and possible use of electric or hybrid electric propulsion.

Additionally, work should continue to investigate and validate the performance for the HWB configuration. It is anticipated that the HWB configuration will be emphasized in the N+2 Environmentally Responsible Aviation (ERA) program, as well as other ongoing NASA, Air Force, and Boeing funded projects. This other work can be effectively leveraged, and the HWB concept should continue to be carried in the N+3 program, as most N+3 technologies can be applied to improve the HWB concept as well.

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14. ABSTRACT

This Final Report summarizes the work accomplished by the Boeing Subsonic Ultra Green Aircraft Research (SUGAR) team in Phase 1, which includes the time period of October 2008 through March 2010. The team consisted of Boeing Research and Technology, Boeing Commercial Airplanes, General Electric, and Georgia Tech. The team completed the development of a comprehensive future scenario for world-wide commercial aviation, selected baseline and advanced configurations for detailed study, generated technology suites for each configuration, conducted detailed performance analysis, calculated noise and emissions, assessed technology risks, and developed technology roadmaps. Five concepts were evaluated in detail: 2008 baseline, N+3 reference, N+3 high span strut braced wing, N+3 gas turbine battery electric concept, and N+3 hybrid wing body. A wide portfolio of technologies was identified to address the NASA N+3 goals. Significant improvements in air traffic management, aerodynamics, materials and structures, aircraft systems, propulsion, and acoustics are needed. Recommendations for Phase 2 concept and technology projects have been identified.

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