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Environmentally Responsible Aviation (ERA) Project - N+2 Advanced Vehicle Concepts Study and Conceptual Design of Subscale Test Vehicle (STV) Final Report

John T. Bonet, Harvey G. Schellenger, Blaine K. Rawdon, Kevin R. Elmer, Sean R. Wakayama, Derrell L. Brown, Yueping Guo
Boeing Research & Technology, Huntington Beach, California
Dryden Flight Research Center, Edwards, California

December 2011

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List of Abbreviations

ABACUS	A structural analysis
AC	Alternating Current
ADVENT	Adaptive Versatile Engine Technology
AFRL	Air Force Research Laboratory
AGL	Above Ground Level (altitude)
ALDC	Aircraft Level Design Criteria
Alpha	Angle of Attack
APU	Auxiliary Power Unit
AR	Aspect ratio
ARwet	wetted Aspect Ratio
ARC	Ames Research Center
ARMD	Aeronautics Research Mission Directorate
ASP	Airspace Systems Program
AT&W	Advanced Tube and Wing
ATC	Air Traffic Control
ATD	Advanced Technology Demonstration
ATF	Advanced Turbo Fan
ATL	Acoustic Testing Laboratory
ATP	Aeronautics Test Program, Authority to Proceed
AVCS	Advanced Vehicle Concepts Study
AVIATR	Air Vehicle Integration and Technology Research
AvSP	NASA Aviation Safety Program
AVTIP	Air Vehicle Technology Integration Program
BCA	Boeing Commercial Airplanes
BDS	Boeing Defense, Space & Security
b eff	effective span
b overall	overall span
b ref	reference span
BR&T	Boeing Research & Technology
BTU	British Thermal Units
BVID	Below-Visual Impact Damage
BWB	Blended Wing Body
CAD	Computer Aided Design
CAEP	Committee on Aviation Environmental Protection
CAIV	Cost As Independent Variable
CAPRI	Controlled Atmospheric Pressure Resin Infusion
CASES	Computer-Aided Sizing and Evaluation System
CD	Coefficient of Drag
CDR	Critical Design Review

CF	Carbon Fiber
CFD	Computational Fluid Dynamics
CFRP	Carbon Fiber Reinforced Polymers
CG	Center of Gravity
CL	Coefficient of Lift
CLEEN	Continuous Lower Energy, Emissions and Noise
CLG	Center landing Gear
C mac	chord length, mean aerodynamic chord
CO	Contracting Officer
CO2	Carbon Dioxide
CoDR	Concept Design Review
CoLTS	Combined Loads Test System
ConOps	CONcept of OPerationS
CONUS	CONtinental United States
COTR	Contracting Officer's Technical Represent
COTS	Commercial Off-The-Shelf
cp	center of pressure
CPU	Central Processing Unit
CR	NASA Contractor Report
CTE	Coefficient of Thermal Expansion
DA	Determinant Assembly
dB	Decibel
DFRC	Dryden Flight Research Center
DI	Destructive Inspection
DNL	Day Night Level
DOC	Direct Operating Cost
DOD	Department of Defense
DRFM	Design Reference Flight Mission
DTOGW	Design TakeOff Gross Weight
e	Spanwise Efficiency Factor
ECS	Environmental Control System
EHA	Electro Hydrostatic Actuator
EIS	Entry into Service
EMA	Electromechanical Actuator
EMD	Engineering and Manufacturing Development
EO&T	Engineering, Operations & Technology
EPNL	Effective Perceived Noise Level
ERA	Environmentally Responsible Aviation
ETOPS	Extended-Range Twin-Engine Operations
F	Flat plate drag area
FAA	Federal Aviation Administration

FAR	Federal Aviation Regulations
FC	Flight Controls
FCC	Flight Control Computer
FEM	Finite Element Model
FMEA	Failure Mode and Effects Analysis
FMS	Flight Management System
FN	thrust, net
FOD	Foreign Object Damage
FPR	Fan Pressure Ratio
FQ	Flying Qualities
FSD	Full Scale Development
ft	feet
FTDS	Flight Test Data System
FY	Fiscal Year
GFE	Government furnished equipment
GN&C	Guidance, Navigation & Control
GRC	Glenn Research Center
GTF	Geared Turbo Fan
GVT	Ground Vibration Testing
HEETE	Highly Efficient Embedded Turbine Engine
HLFC	Hybrid Laminar Flow Control
Hp	Horsepower
HPC	High Pressure Compressor
HPT	High Pressure Turbine
HQ	Handling Qualities
HRP	Heat-Resistant Phenolic resin
ICA	Initial Cruise Altitude
ICAO	International Civil Aviation Organization
IKC	Interface Key Characteristics
IML	Inner Mold Line
IOC	Initial Operational Capability
IPT	Integrated Product Team
IRAD	Internal Research and Development
IWWF	Inter-Woven Wire Fabric
keas	knots, equivalent airspeed
KPP	Key Performance Parameter
ktas	knots, true air speed
L/D	Lift to Drag ratio
LaRC	Langley Research Center
lb	pound
lbf	pound force

lbm	pound mass
LCN	Load Classification Number
LE	Leading Edge
LHV	Lower Heating Value
LQR	Linear Quadratic Regulator
LSAF	Low Speed Aero-acoustic Facility
LTO	Landing-Takeoff
M	Mach number
M&S	Modeling & Simulation
MAC	Mean Aerodynamic Chord
MDO	Multi-Disciplinary Optimization
MLG	Main Landing Gear
M_{MO}	Max Operating Mach Number
MMPDS	Metallic Materials Properties Development and Standardization
MOU	Memorandum of Understanding
MSC-MARC	A structural analysis
MSL	Mean Sea Level (altitude)
MTOGW	Maximum Takeoff Gross Weight
MZFW	Maximum Zero Fuel Weight
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
nd	non-dimensional
NDI	Non-Destructive Inspection
NextGen	Next Generation Air Transportation System
NG	Next Generation Air Transportation System
nm	nautical miles
NOI	Notice of Intent
NOx	Nitrogen Oxide
NRA	NASA Research Announcement
NSPIRES	NASA Solicitation and Proposal Integrated Review and Evaluation System
NTF	National Transonic Facility
nz	normal acceleration
OAPR	Overall Pressure Ratio
ODC	Other Direct Cost
OEW	Operational Empty Weight
OML	Outer Mold Line
OOA	Out Of Autoclave
OP	Operational Mission rules
OPD	Optimized Profile Descents
OPR	Overall Pressure Ratio

OR	Open Rotor
OTS	Off-The-Shelf
P&W	Pratt & Whitney
PAA	Propulsion Airframe Aero-acoustics
PAI	Propulsion Airframe Integration
PD	Preliminary Design
PDR	Preliminary Design Review
PM	Particulate Matter
POC	Point of Contact
PRSEUS	Pultruded Rod Stitched Efficient Unitized Structure
PSC	Preferred System Concept
R&D	Research & Development
R-R NA	Rolls-Royce North America
RANS	Reynolds Averaged Navier-Stokes
RASER	Revolutionary AeroSpace Engine Research
RASR	Revolutionary Aerospace Engine Research
RAT	Ram Air Turbine
RCEE	Revolutionary Configurations for Energy Efficiency
RFI	Request For Information
ROM	Rough Order of Magnitude
RRNA	Rolls-Royce North America
S&C	Stability & Control
S&T	Science & Technology
SC	Stability & Control
SCAP	Shared Capability Assets Program
SCAS	Stability Control Augmentation System
SDR	System Design Review
SEMP	Systems Engineering Master Plan
SFC	Specific Fuel Consumption
SFW	Subsonic Fixed Wing
SGTF	Study Geared Turbo Fan
Sim	Simulation
SME	Subject Matter Expert
SOB	Side of Body
SOW	Statement of Work
SPF	Super Plastic Formed
SRI	Stitched Resin Infused
SRL	System Readiness Level
SRR	System Requirements Review
STV	Subscale Test Vehicle, Subscale Testbed Vehicle
SUGAR	Subsonic Ultra-Green Aircraft Research

Sv	Vertical Tail Area
T&W	Tube & Wing
T41	Takeoff turbine rotor inlet temperature
t/c	thickness to chord ratio
tau	Engine fraction of full thrust (for a given condition)
TBD	To Be Determined
TE	Trailing Edge
TEMP	Test and Evaluation Master Plan
TMP	Technology Maturation Plans
TOGW	TakeOff Gross Weight
TPM	Technical Performance Measure
TPS	Turbine Powered Simulator
TRL	Technology Readiness Level
UAS	Unmanned Aircraft System
UAV	Unmanned Air Vehicle
UHBPR	Ultra-High ByPass Ratio
ULD	Unit Load Devices
V	Velocity
V&V	Verification & Validation
VCAS	Vertical Control Augmentation System
VDD	Vehicle Description Document
VFR	Visual Flight Rules
Vh	Horizontal Tail Volume
Vmcg	minimum control speed on the ground
VMS	Vertical Motion Simulator
VMS	Vehicle Management System
Vv	Vertical Tail Volume
VV&A	Verification, Validation and Accreditation
WATR	Western Aeronautical Test Range
WB	Wing-Body
WBNV	Wing-Body-Nacelle-Vertical
WBS	Work Breakdown Structure

1 Introduction

NASA has set demanding goals for technology developments to meet national needs to improve fuel efficiency concurrent with improving the environment to enable air transportation growth. Figure 1 shows NASA's subsonic transport system metrics. The results of Boeing ERA N+2 Advanced Vehicle Concept Study show that the Blended Wing Body (BWB) vehicle, with ultra high bypass propulsion systems have the potential to meet the combined NASA ERA N+2 goals.

NASA's Subsonic Transport System Level Metrics

CORNERS OF THE TRADE SPACE	N+1 = 2015*** Technology Benefits Relative To a Single Aisle Reference Configuration	N+2 = 2020*** Technology Benefits Relative To a Large Twin Aisle Reference Configuration	N+3 = 2025*** Technology Benefits
Noise (cum below Stage 4)	-32 dB	-42 dB	-71 dB
LTO NO_x Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%**	-50%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metro-plex* concepts

***Technology Readiness Level for key technologies = 4-6
** RECENTLY UPDATED. Additional gains may be possible through operational improvements
* Concepts that enable optimal use of runways at multiple airports within the metropolitan area

ERA Approach

- *Focused on N+2 Timeframe – Fuel Burn, Noise, and NO_x System-level Metrics*
- *Focused on Advanced Multi-Discipline Based Concepts and Technologies*
- *Focused on Highly Integrated Engine/Airframe Configurations for Dramatic Improvements*

Figure 1 NASA Subsonic Transport System Level Metrics

This study had 3 main activities. 1) The development of an advanced vehicle concepts that can meet the NASA system level metrics. 2) Identification of key enabling technologies and the development of technology roadmaps and maturation plans. 3) The development of a subscale test vehicle that can demonstrate and mature the key enabling technologies needed to meet the NASA system level metrics.

Boeing has developed a future scenario of how the concept aircraft will operate within the NextGen airspace in 2025 and beyond. Boeing has developed two Preferred System Concepts (PSC), (passenger vehicle and cargo vehicle) with capabilities that meet or exceed the stated mission requirements and the ERA N+2 fuel burn, noise and emissions goals. In selecting the PSC, Boeing evaluated several different configurations and propulsion systems.

A conventional advanced aircraft design process is used with increased level of detail and fidelity. Major steps in the study are: Requirements development; Creation of baseline 1998-technology airplanes; Generation of three substantially different 2025-technology airplanes configurations, that are evaluated with three alternative propulsion system types; Refinement of design to minimize fuel consumption; Evaluation of key designs in terms of NASA's system level metrics; Definition of the 2025 operating context in terms of air traffic control and fleet mix; Selection of the "Preferred System Concept" as a basis for a subscale test vehicle.

The PSC community noise was assessed for both single events and cumulative airport operations that included airport baseline & forecast models, PSC performance & noise models, and various PSC market penetration levels.

Key mission requirements are a 224 passenger (50,000 lb) design payload, 8000 nm range and Mach 0.85 cruise speed. Cargo versions of some passenger airplanes are examined. The cargo version has a 100,000 lb design payload, Mach 0.85 cruise and a range of approximately 6000 nm.

Three representative 2025 configurations are defined, these are: a conventional 2025 tube-and-wing configuration; an advanced, double-deck, mid-engine, tube-and wing configuration; and a blended-wing-body configuration.

Three types of advanced engines are used on the 2025 airplanes: an advanced three-spool turbofan, a geared turbofan and an open rotor engine.

In addition to advanced engines, 2025-technology airplanes feature advanced composite airframes, laminar flow control, and reduced noise airframe features.

The effect of operating rules on airplane fuel consumption, operating empty weight and direct operating cost is evaluated.

The PSC aircraft conceived in this study will require a significant amount of technology development. With its BWB configuration, the PSC is dependent on technology development needed to enable the BWB configuration technology. The PSC employs additional technologies that enhance its performance. Development of the complete set of BWB-enabling and BWB-enhancing technologies is expected to provide the PSC with the capability of achieving the Environmentally Responsible Aviation (ERA) goals.

Technology maturation plans are developed in this study with the goal of demonstrating technology readiness sufficient to authorize starting Engineering and Manufacturing Development (EMD) or the equivalent commercial aircraft development process for a production PSC. A Technology Readiness Level (TRL) of 6 was targeted for completion through the technology demonstrator program for noted critical technologies.

The Subscale Test-bed Vehicle (STV) is a scaled demonstrator of the PSC that provides the means for performing the TRL 6 demonstrations. The STV is integral to technology maturation to the point of being the focus of all the near-term technology development activities. The STV will have a representative shape to test and validate aerodynamic and acoustic features of the PSC. It will be large enough to validate BWB-unique structural concepts (such as the flat-sided pressure vessel). This size will also facilitate maturation of Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) composite structure technology (which will bring weight and cost benefits to the production PSC). The STV will accommodate geared turbofan engines, providing a means to test propulsion technology and address concerns with propulsion-airframe integration. After numerous technical concerns with the basic BWB configuration are addressed through flight test, the STV will provide a platform for validating additional enhancing technologies, such as laminar flow.

Technology maturation plans are presented and include key performance parameters and technical performance measures. The plans describe the risks that will be reduced with technology development and the expected progression of technical maturity.

A flight demonstration vehicle is necessary to test critical technologies in relevant environments that cannot be recreated via ground-based testing including flyover noise, dynamics, and integrated structural scale up. Toward this end, Boeing developed a conceptual design of a STV that would transition the enabling technologies to TRL 6 and validate that the full-size PSC will meet NASA performance and environmental goals. In addition, the STV is designed with long life and modularity to be a flexible test-bed for incorporating future technologies, plus performing flight campaigns to integrate Unmanned Aircraft Systems (UAS) in the National Airspace System.

The STV conceptual design is based on a 65-percent scale version of the PSC. That size was selected because it best meets Boeing and NASA requirements and objectives while trying to minimize cost. Several factors led to the relatively large scale selected such as achievement of dynamic scaling and Mach scaling, Strouhal scaling with atmospheric attenuation for acoustics, a reasonably sized flight deck for long-term flight operations and a good fit for the planned 26,000 lb-class advanced engines.

2 Preferred System Concept (PSC) and NextGen

2.1 Summary

This section describes work performed for Task 2 of the ERA study. The primary objective of Task 2 is to develop a 2025-technology airplane that best meets NASA's challenging goals for fuel consumption, noise and landing and takeoff emissions. The resulting Preferred System Concept (PSC) provides a basis for a subscale research vehicle as described in the Task 5 report. The NASA goals were achieved.

A conventional advanced aircraft design process is used with an increased level of detail and fidelity. Major steps in the study are:

- Requirements development.
- Creation of baseline 1998-technology airplanes as a reference for NASA's performance goals.
- Generation of three substantially different 2025-technology airplanes configurations. These are evaluated with three alternative propulsion system types.
- Refinement of each design to minimize fuel consumption.
- Evaluation of key designs in terms of NASA's goals.
- Definition of the 2025 operating context in terms of air traffic control and fleet mix.
- Selection of the "Preferred System Concept" as a basis for a subscale test vehicle.

Key mission requirements are a 224 passenger (50,000 lb) design payload, 8000 nm range and Mach 0.85 cruise speed. A cargo version of some passenger airplanes is examined. The cargo version has a 100,000 lb design payload, Mach 0.85 cruise and a fallout range of approximately 6000 nm.

NASA provided three challenging goals:

- Reduce fuel consumption by 50% relative to the 1998 baseline airplane.
- Reduce noise to a cumulative noise margin of 42 dB relative to Stage 4 noise standards.
- A 75% reduction of landing and takeoff emissions relative to CAEP/6 standards.

A baseline 1998 configuration and three alternative 2025 configurations are developed. Two 1998 engine types and three 2025 engine types are examined on these configurations. In addition to advanced engines, 2025-technology airplanes feature advanced composite airframes, hybrid laminar flow control on the wing and tails, natural laminar flow on the nacelles, and riblet surface texture on all turbulent exterior surfaces. Four representative configurations are shown in Figure 2. From the left, these are:

- A conventional 1998 "tube-and-wing" configuration.
- A conventional 2025 tube-and-wing configuration.
- An advanced, double-deck, mid-engine, tube-and wing configuration. This configuration provides advantages in fuselage wetted area and acoustic shielding of the engines.
- A blended-wing-body configuration. This configuration provides increased aerodynamic efficiency and acoustic shielding.

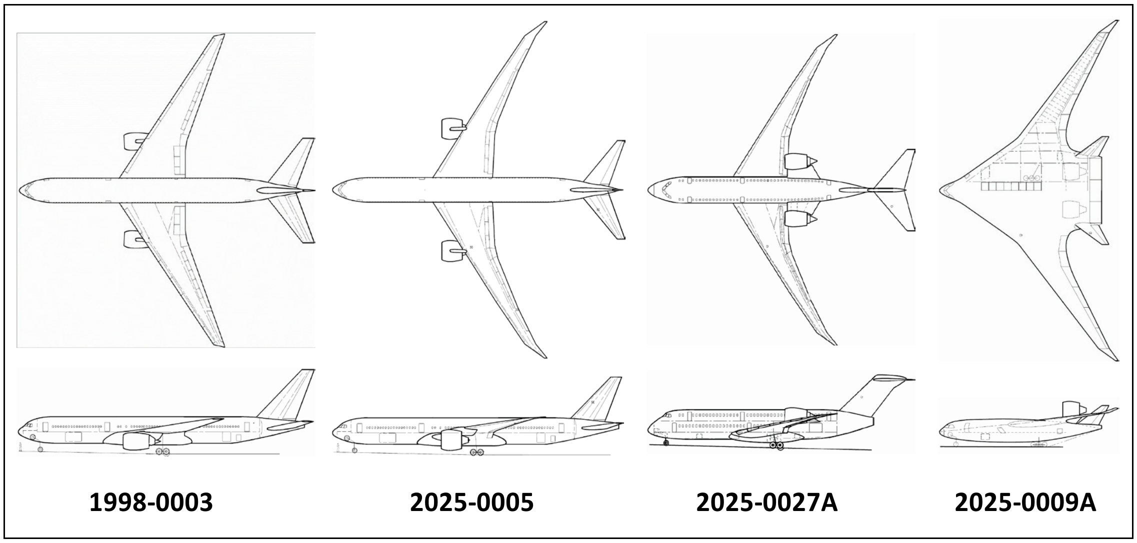


Figure 2. Four Representative Airplane Configurations

Conventional turbofan engines are used on the 1998 baseline aircraft. Three types of engines are used on the 2025 airplanes:

- An advanced three-spool turbofan. This type is the lightest but is least efficient and creates more noise.
- A geared turbofan. This type is heavier, more efficient and quieter than the advanced turbofan.
- An open rotor engine. Exposed, counter-rotating rotors are heavier and more efficient than the geared turbofan but are noisier.

Relative propulsion system fuel efficiency and weight are drivers on airplane performance. Propulsion system weight varies slightly according to the airplane configuration on which it is mounted due to differing pylon weights.

A total of 15 airplanes are formally examined in the study – each a different combination of configuration, engine type and mission (passenger or freighter). Each tube-and-wing airplane is refined in terms of wing area, tail area and engine thrust to achieve minimum fuel consumption. Each blended-wing-body design is refined in engine thrust. Three additional blended wing body designs with increased wingspan are evaluated less formally to explore the impact of span on the design.

Results of the refined airplanes are compared with NASA's fuel consumption goals in Figure 3. An enlargement of this plot showing just the 2025-technology airplanes is provided in Figure 4. These plots show that all 2025-technology airplanes reduce fuel consumption by more than 42%; all blended-wing-body designs meet NASA's 50% goal. These plots also show that 2025-technology airplanes provide substantial reductions in operating empty weight (OEW) and direct operating cost (DOC).

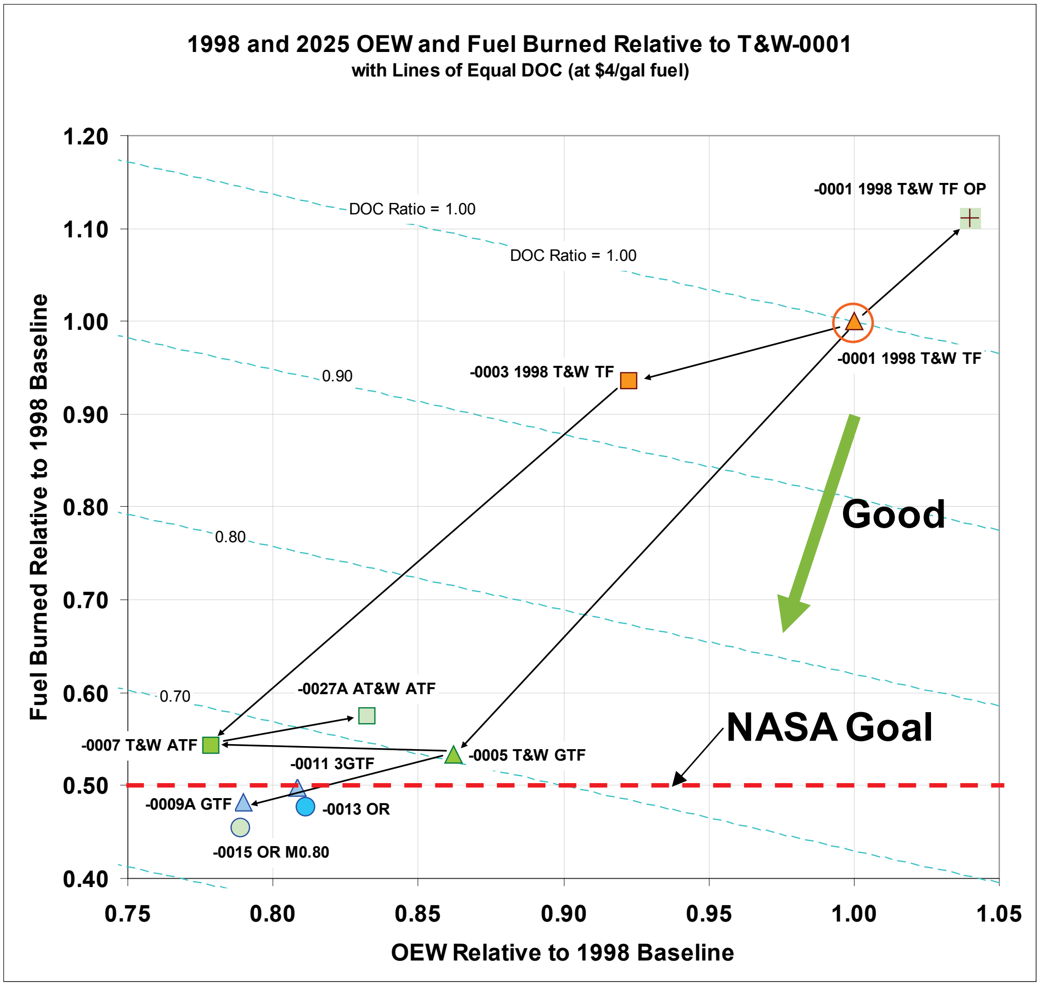


Figure 3. Overview – Relative Fuel Burned and OEW

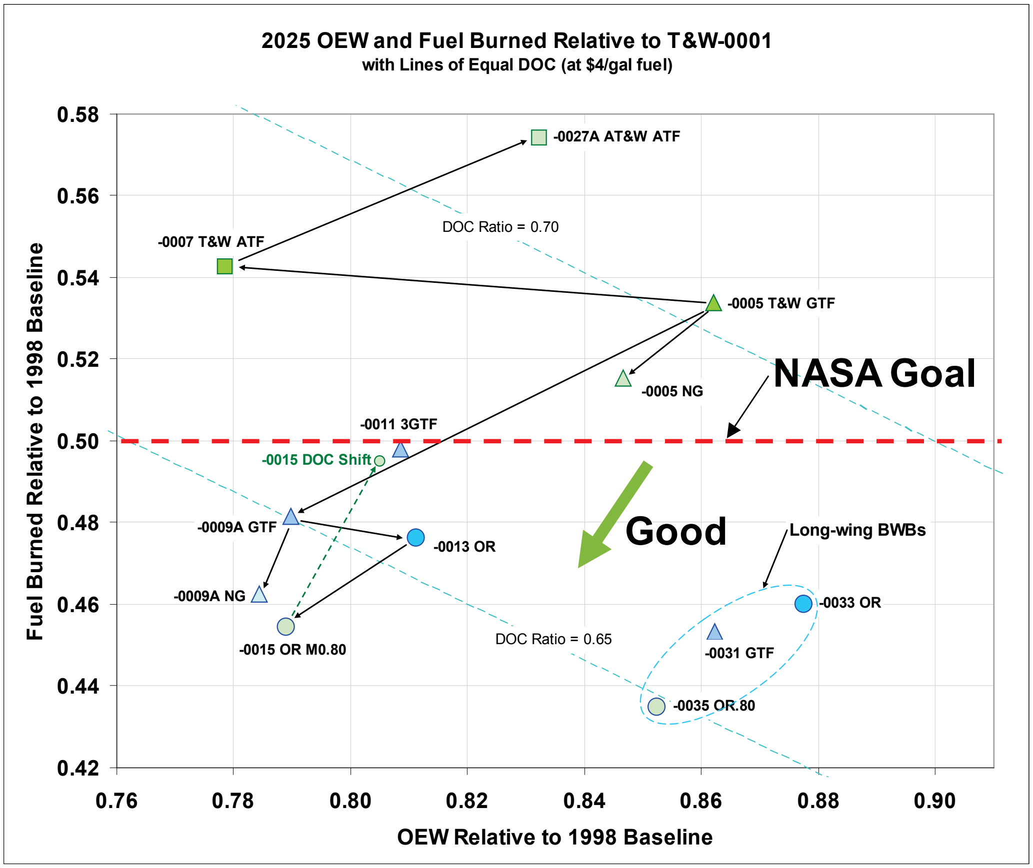


Figure 4. Relative Fuel Burned and OEW for 2025 Passenger Airplanes

Following refinement of the airplane designs for minimum fuel consumption, acoustic analysis of selected designs is performed. Results of cumulative margins to Stage 4 are shown in Figure 5. The blended-wing-body configuration with geared turbofan engine (-0009) is the quietest combination examined. However, without additional acoustic treatment, no configuration meets NASA's noise goal. A trade study, described in Section 2.9, determines further noise reduction potential for each source noise to achieve the NASA goal. For BWB-0009A, a 3 dB slat noise reduction and 5 dB landing gear noise reduction can achieve the NASA goal.

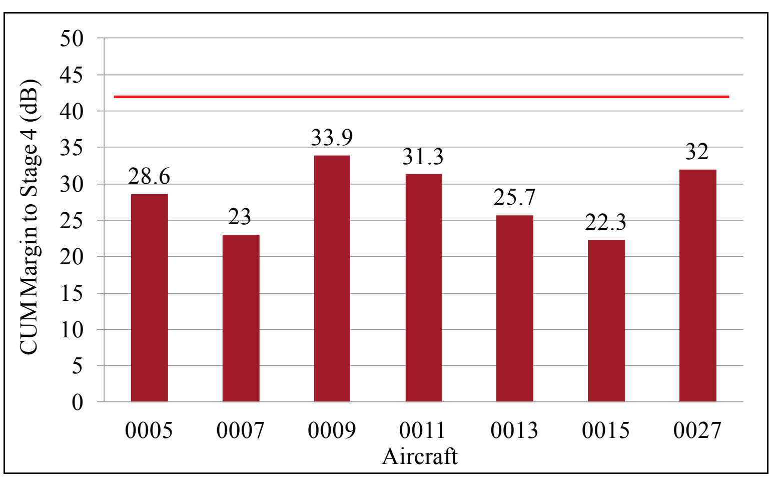


Figure 5. Cumulative Margin to Stage 4 for Selected Airplanes

Analysis of future aircraft operations, emissions and airport noise contours is described in Section 2.11 “NextGen”. This analysis finds that a reduction of 15-20% in contour areas can be achieved by replacing all twin aisle aircraft in 2030 with PSC aircraft with additional slat and gear noise reduction. The contour areas can be reduced by 30-40% by replacing all twin aisle aircraft in 2030 with PSCs, and by applying PSC technologies to all single aisle aircraft in 2030. In this scenario, the 75 CNEL noise contour is contained within the airport boundary, as illustrated in red in Figure 6. The trade study also finds that additional noise reduction can be obtained with low noise operations.

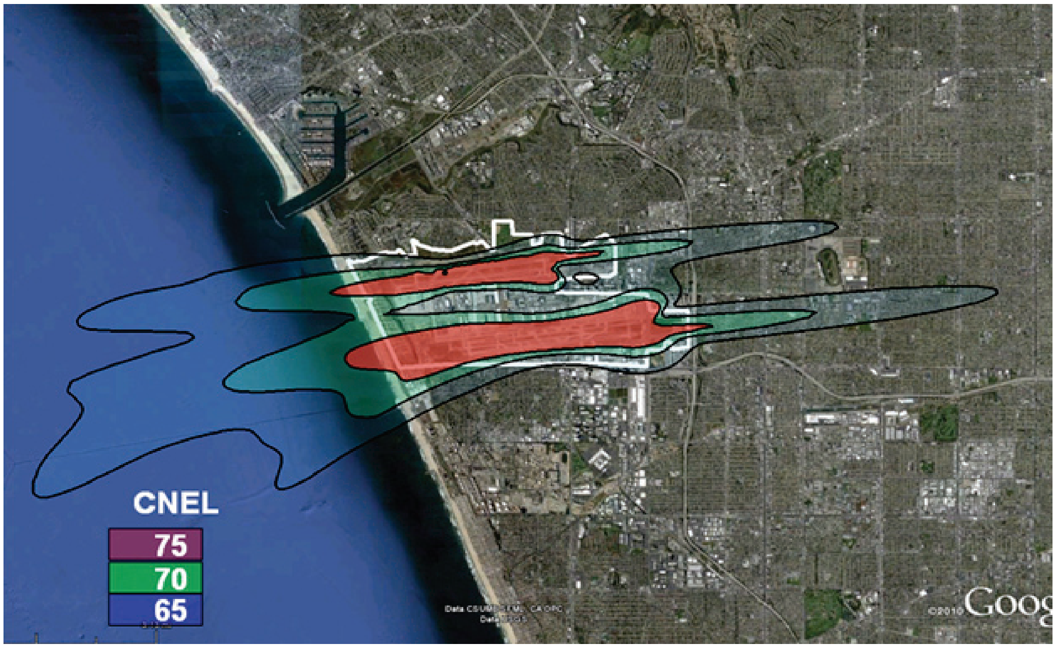


Figure 6. 2030 Noise Contours with PSC Aircraft & PSC Technology

Characteristic engine data pertaining to landing and takeoff emissions are provided by engine manufacturers. As shown in Figure 7, two of the three 2025 engines meet NASA’s goal to fall 75% below the CAEP/6 limit. The advanced turbofan narrowly misses this goal.

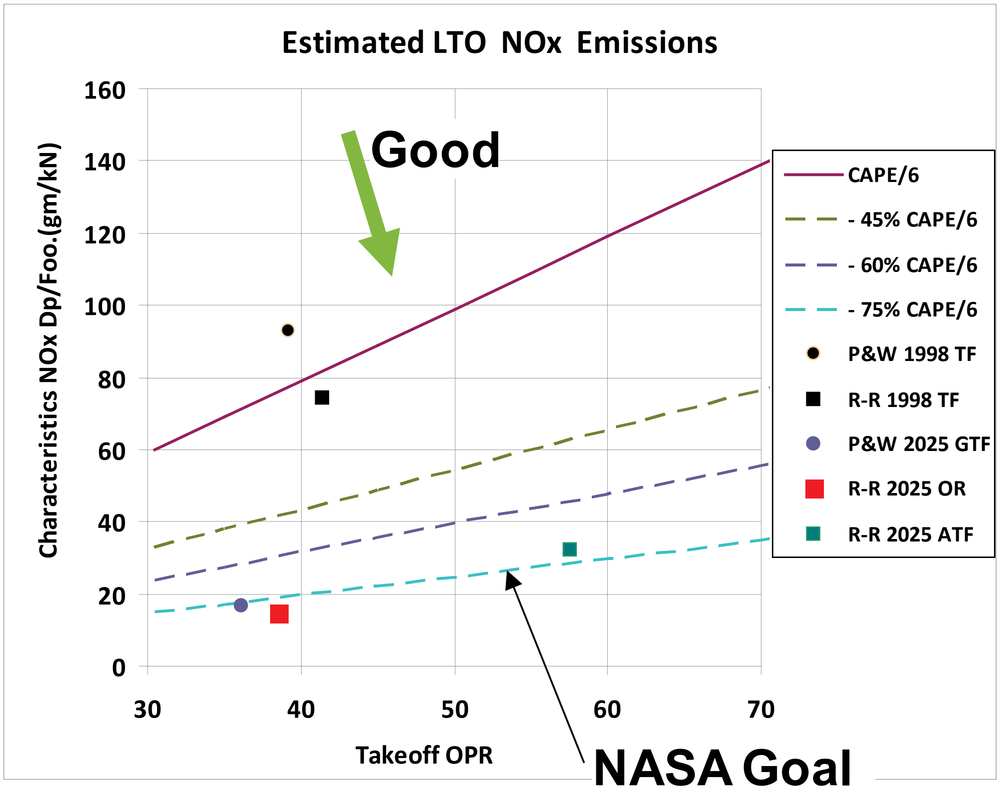


Figure 7. LTO NO_x Emissions versus Overall Pressure Ratio

The effect of operating rules on airplane fuel consumption is evaluated. Three sets of rules are devised:

- Operational Mission: this is an approximation of rules applied in 1998.
- NASA Reference Mission: this is a more efficient version of the Operational Mission.
- NextGen Mission: this is a highly-efficient rule set envisioned for 2025.

The effect of these rules on airplane fuel consumption, operating empty weight and direct operating cost is evaluated. Results are shown in Figure 8. Relative to Operational Mission rules, the NASA Reference Mission saves 10.7% fuel. Relative to NASA Reference Mission rules, NextGen saves 3.6% - 3.9% fuel. Changing from Operational rules to NextGen rules saves 13.9% to 14.2% fuel for 2025-technology airplanes. Improvements in fuel consumption are mirrored by reductions in operating empty weight and direct operating cost.

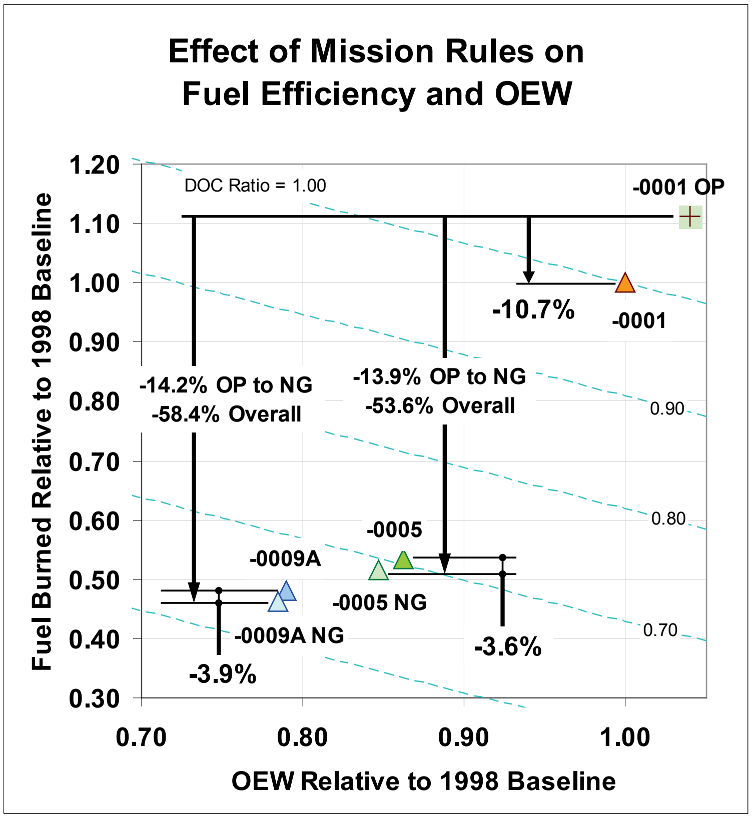


Figure 8. Effect of Mission Rules on Fuel Burned and OEW

Based on fuel consumption, noise and landing and takeoff emissions, the 2025 BWB-0009A configuration is selected as the preferred system concept. As shown graphically in Figure 9, this airplane provides an excellent combination of fuel economy and low noise. Its geared turbofan engines exceed NASA's stringent goal for emissions. This airplane, slightly resized and operated according to NextGen rules, provides an additional 3.9% fuel burn reduction. With the noise reduction features mentioned above, the airplane also meets NASA's noise goals as shown by the upper-right airplane, BWB-0009A NG AAT.

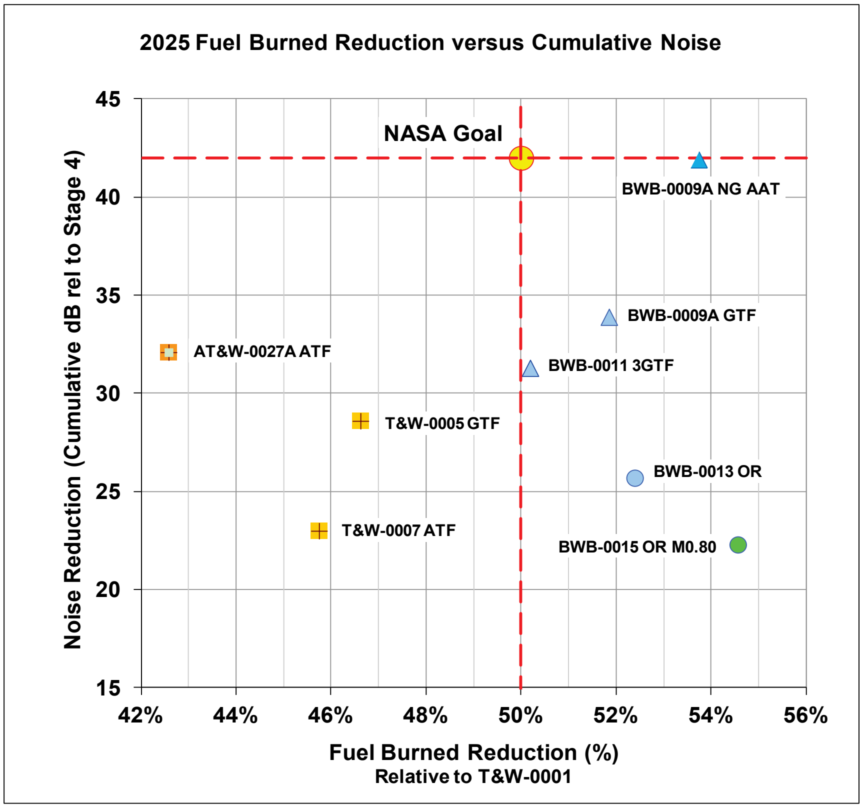


Figure 9. Noise and Relative Fuel Burned Reduction

To conclude, the blended wing body with geared turbofan engines exceeds NASA's goals for fuel consumption and emissions and can meet its noise goal with advanced treatments. A line drawing of this airplane is shown in Figure 10.

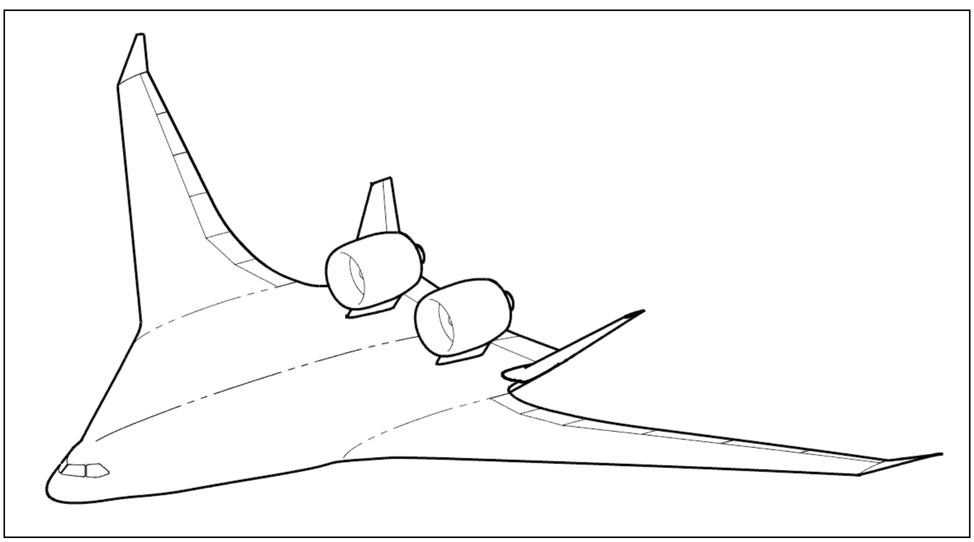


Figure 10. Trimetric View of BWB-0009A NG

2.2 Requirements, Measures of Merit and Technologies

Requirements define what each airplane has to do and how it must do it. Two sets of consistent requirements are applied to the studied airplane designs. Key requirements include type of mission, payload, range and speed.

Two mission types are studied – passenger airliners and freighters. These have different requirements including payload and range. The freighter requirements permit the freighter to be a practical derivative version of the passenger airplane. This is a common relationship in commercial practice. There is potential for additional performance if the derivative requirement is relaxed, especially for the freighter. This potential is not examined in this study.

The detailed requirements are intended to simulate modern commercial airliner and freighter practice. This decision is based on the assumption that airplane operations will be largely the same in 2025 as they are currently. As a result, the 2025 airplanes are fully capable of operating efficiently without evolution of the operational context.

2.2.1 Requirements

2.2.1.1 Passenger

The passenger airplane requirements lead to a medium capacity, long range airliner similar to the Boeing 767 or 787 models. In addition to the specific requirements outlined in Table 1, the designs meet FAR Part 25 regulations and other conventional requirements that comprise the Aircraft Level Design Criteria (ALDC). An additional requirement is that the airplanes are fueled with Jet-A hydrocarbon fuel with a heating value of 18,580 British Thermal Units (BTU) per pound.

Table 1. Passenger Airplane Requirements

		Passenger
Payload:		
Passengers	-	~224
Design Payload	lb	50,000
Maximum Payload	lb	90,000
Interior	-	3-class
Interior Rules	-	medium-long range
Economy Class Seatpan	in	18
Economy Class Armrests	in	2
Economy Class Aisle	in	18
Business Class Seatpan	in	20
Business Class Armrest	in	3
Business Class Aisle	in	19 - 20
First Class Seatpan	in	22
First Class Armrest	in	3
First Class Aisle	in	22
Overhead Stowage	-	1 - 9x14x22" bag/pax
Cargo Volume (not counting overhead)	ft^3	850
Performance:		
Range with Design Payload	nm	8000
Range with Maximum Payload	nm	Fallout
Ferry range	nm	Fallout
ETOPS	minutes	270 at EIS
Minimum Cruise Speed	Mach	0.85
Distance to Climb	nm	≤ 200 to 35,000 ft
Initial Cruise Altitude	ft	35,000
Critical Field Length (SL, 86°F @ MTOGW)	ft	10,500
Landing Field Length (SL Std @ MLW)	ft	5,200
Max Landing Weight (MLW)	lb	MZFW + Reserve Fuel
Max Approach Speed at MLW	kt	150
Maximum Sinkrate @ Landing	ft/sec	10
Airport Compatibility:		
Runway Load Classification Number		<= Boeing 777
Wingspan Constraint (tradeable)	meters	65 meters

The passenger airplane has a primary or "design" mission that defines most of the airplane's characteristics. A secondary mission with a heavier "maximum" payload is also defined with some requirements relaxed or left open.

Passenger count is specified for the design mission. This is the approximate number of passengers that the airplane must carry in a three-class, long range interior. This interior classification specifies a subset of requirements including seat width and pitch, lavatory and galley requirements, pilot and crew rest area requirements and so on. The passenger count is used as a target for the interior designer to design the most compact fuselage that holds a number close to 224 passengers. The passenger count increment from a single seat row is approximately eight, so achieving a seat count within roughly four of the 224 target is acceptable.

Despite the potentially variable seat count between airplanes, each airplane has a specified design payload of 50,000 lb. Fixing the design payload between airplanes provides a fair basis for comparison and reduces pressure on the interior designer to squeeze in as many seats as possible. The 50,000 lb design payload includes passengers and their bags but does not include the tare weight of the cargo containers and pallets (also known as "Unit Load Devices" or "ULD").

Long-range, three-class airliners are sometimes used at shorter range with higher density seating arrangements. A maximum payload weight of 90,000 lb is selected as representative of higher density arrangements.

Seat and aisle dimensions are chosen as representative of long-range, three-class interiors.

Overhead bag storage space is sufficient for one "roller bag" per passenger. The lower hold cargo volume requirement provides 3.8 ft^3 per passenger, sufficient to provide for about 27 pounds of cargo per passenger at a typical density of 7 lb/ft^3.

Range with the design payload is 8000 nautical miles (nm). To reach the maximum payload, the airplane must offload 40,000 lb of fuel. As a result, the maximum payload range is shorter. The change in range depends on the airplane's fuel efficiency. Very efficient airplanes go far on 40,000 lb of fuel, so their range with maximum payload will be less than those airplanes that are less efficient.

Ferry range is the distance the airplane will fly with zero payload and maximum fuel. Maximum fuel is limited either by the airplane's maximum takeoff gross weight (MTOGW) or by its fuel capacity, whichever is less.

Extended-range, twin-engine operations (ETOPS) range with one engine inoperative is set at 270 minutes. This period permits nearly unrestricted overwater operations and is consistent with current practice.

The minimum cruise speed is set at Mach 0.85. At Mach 0.85, airspeed varies with altitude between the minimum initial cruise altitude of 35,000 ft and 36,089 ft. At 35,000 ft it is 489.9 kt and at 36,089 ft and higher it is a constant 487.6 kt. Because increased Mach numbers generally lead to less efficient airplanes, the "minimum" Mach number is used by all of the airplanes – no airplane performed better at greater speed.

A requirement to reach a minimum cruise altitude of 35,000 ft in less than 200 nm from takeoff is a practical requirement set by a desire to simplify air traffic control. A rapid climb to cruise altitude reduces conflict with lower, climbing and descending airplanes.

Takeoff and landing field lengths are set to be consistent with current practice for medium-size, long range airliners. For conventional airplane configurations, the much-shorter landing field length is not a challenging requirement. For BWB configurations, the landing field length is challenging – as a result we treat landing field length as a target value rather than as a sizing constraint.

Maximum landing weight (MLW) is set as maximum zero fuel weight (MZFW) plus reserve fuel. MZFW is the weight of the empty airplane plus maximum payload. For the design mission with a 40,000 lb lighter payload, the airplane lands at a considerably lighter weight than MLW. In practice, landing field length with the design payload is shorter than that with MZFW plus reserves.

Maximum landing approach speed is set to a value consistent with current practice for airliners. Maximum sinkrate (vertical speed) at touchdown is set to the value used in current practice.

The runway load classification number (LCN) is a measure of the load imposed by the airplane's landing gear on the runway and taxiway surfaces. In practice, this value is used to determine the size, number and arrangement of the landing gears according to the airplane's maximum weight. The referenced LCN of the Boeing 777 is among the higher values of current transports – this permits compact and efficient landing gear.

The target for maximum wingspan is 65 meters (213.3 ft). This marks the upper span limit for Group V (FAA) and Code E (ICAO) airports.[1,2] Because longer spans may enable reduced fuel consumption, this limit is considered a tradeable target rather than a hard limit.

2.2.1.2 Freighter

Freighter requirements and constraints are devised so a realistic commercial freighter can be derived from the passenger version of the airplane. These lead to freighters similar in capacity and mission to the 767-300F.

Freighter design constraints stipulate that certain characteristics of the freighter are the same as the airliner from which it is derived. These include MTOGW, engine type and thrust, and the entire outer mold line (shape and dimensions). This insures the freighter's performance is generally the same as the passenger version. Other characteristics may be changed in creating the derivative freighter. Chief among these is the airplane's structure, operating empty weight (OEW) and MZFW. It is common practice in the design of derivative freighters to provide local structural reinforcements to enable an increased MZFW. Such reinforcements pay for themselves with increased freighter productivity and value.

Specific design requirements are shown in Table 2. The designs also conform to FAR 25 and the ALDC.

Table 2. Freighter Requirements

		Freighter
Payload:		
Design Payload	lb	100,000 incl tare
Maximum Payload	lb	150,000 incl tare
Total Cargo Volume	ft3	Fallout from Pax A/C
Performance:		
Range with Design Payload	nm	Fallout
Range with Maximum Payload	nm	Fallout
Ferry range	nm	Fallout
ETOPS	minutes	270 at EIS
Minimum Cruise Speed	Mach	0.85
Distance to Climb	nm	≤ 200 to 35,000 ft
Initial Cruise Altitude	ft	35,000
Critical Field Length (SL, 86°F @ MTOGW)	ft	10,500
Landing Field Length (SL Std @ MLW)	ft	5,200
Max Landing Weight (MLW)	lb	MZFW + Reserve Fuel
Max Approach Speed at MLW	kt	155
Maximum Sinkrate @ Landing	ft/sec	10
Airport Compatibility:		
Runway Load Classification Number	-	<= Boeing 777
Wingspan Constraint (tradeable)	meters	65 meters

In commercial practice, the design of a new airliner is sometimes compromised slightly to improve the performance of the derivative freighter. This compromise typically arises in the detailed design of the cross section, perhaps to accommodate or tightly wrap a popular ULD shape. Such considerations are beyond the scope of this advanced design study. Instead, the airliner cross section and internal volume are intended to provide the most efficient packaging of the passengers and their cargo. The resulting cargo volume falls out from the passenger fuselage dimensions.

The design payload corresponds to typical commercial freight payload densities. For the conventional configurations, 100,000 lb corresponds to a cargo density of 5.68 lb/ft^3 including cargo ULD tare weight. For the BWB configurations the density is 7.39 lb/ft^3. The maximum payload results in typical high density payloads – 8.52 lb/ft^3 for the conventional configurations and 11.08 lb/ft^3 for the BWB.

Range with design, maximum and zero payload is not specified. These ranges are determined by the maximum fuel with each payload and the airplane's fuel efficiency. These vary from airplane to airplane so ranges are not fixed.

Other performance requirements match those of the passenger airplanes described in Section 2.2.1.1 with the exception of maximum landing approach speed. This value is increased five knots to 155 kt, reflecting the increased MZFW of the freighters. Such increases are common in commercial practice.

Airport compatibility requirements are also the same as for the passenger airplanes. This is not a constraint since the freighters' dimensions and MTOGW are unchanged.

2.2.2 Operating Rules

In the design process, each airplane is "flown" through an entire mission to determine its optimum characteristics and resulting performance. The operating rules for the mission influence the results. Operating rules address such aspects of the mission as taxi time, climb profile, cruise altitude, descent profile, routing and fuel reserves.

Three sets of operating rules are used in the study. The primary set, called "NASA Reference" (or "Reference") is used for all of the airplanes. The effect of two other sets is explored on a few of the airplanes. One is a set that accurately reflects operational state of the art in 1998 called "Operational" (or "OP" for short). The other is a potential set for 2025 called "NextGen" (NG) – this is the most efficient of the three sets. The Operational rules are derived from a prior study.[3]

2.2.2.1 NASA Reference Mission

The Reference mission is defined in two phases. The first is the mission itself; the second is the reserve mission. A graphic showing the mission is shown in Figure 11 and is described in the following paragraphs.

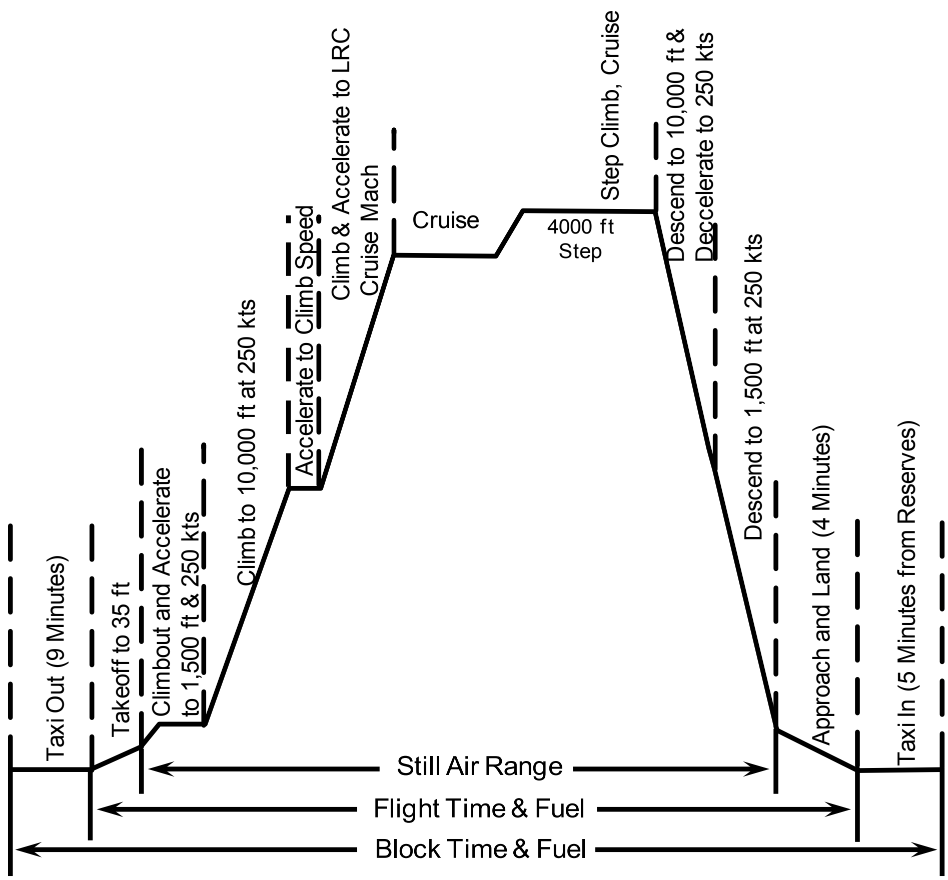


Figure 11. NASA Reference Mission (without Reserves)

The Reference mission is described as a sequentially series of steps. Airspeeds are specified as true airspeeds; altitudes are above mean sea level (MSL) unless otherwise noted. The steps are itemized in the following list:

- Taxi out (9 minutes). This is the specified time between engine start at the gate to the beginning of the takeoff roll. The beginning of this phase marks the beginning of block time and block fuel. The end of this phase marks the beginning of flight time and flight fuel.
- Takeoff to 35 ft above ground lever (AGL) altitude. The end of this phase when the airplane reaches 35 ft altitude marks the beginning of still air range.
- Climbout and accelerate to 1500 ft AGL and 250 kt. In this phase the airplane climbs to 1500 ft and holds this altitude as it accelerates to a specified 250 kt.
- Climb to 10,000 ft at 250 knots. Below 10,000 ft, airspeed is limited to 250 kt.
- At 10,000 ft, accelerate to optimal climb speed and climb to initial cruise altitude.
- At initial cruise altitude, adjust speed to cruise Mach number and maintain a constant altitude until a step-climb is initiated to climb to a higher altitude. Initial cruise altitude for the ERA Task 2 mission is 35,000 ft. Steps to higher altitudes must be 4000 ft so permissible altitudes are 35,000, 39,000 and 43,000 ft. Greater altitudes are not permitted due to concerns regarding depressurization and emergency descent.
- A step climb is initiated at the point the airplane would be more efficient at the next greater altitude. The climb is made at full power but no climb rate is specified.
- At the end of the cruise phase a descent is made to 10,000 ft while gradually decelerating to 250 kt.

- At 10,000 ft, a descent to 1500 ft AGL is made at a constant 250 kt. The end of this phase marks the end of the still air range.
- A four-minute approach to landing and landing rollout is made. The end of this phase marks the end of the flight time and flight fuel.
- The landing is followed by a 5-minute taxi back to the gate. Fuel for this taxi is taken from the reserves since the reserve mission will not be flown following a successful landing. The end of the taxi phase marks the end of block time and block fuel.

The reserves portion of the mission is shown in Figure 12. The reserves address at least three issues: unplanned extra fuel consumption due to unexpected headwinds or rerouting; the need to reach an alternate airport where, for instance, weather may be better; and the need to hold for landing clearance. The phases that make up the reserve portion of the mission are described below.

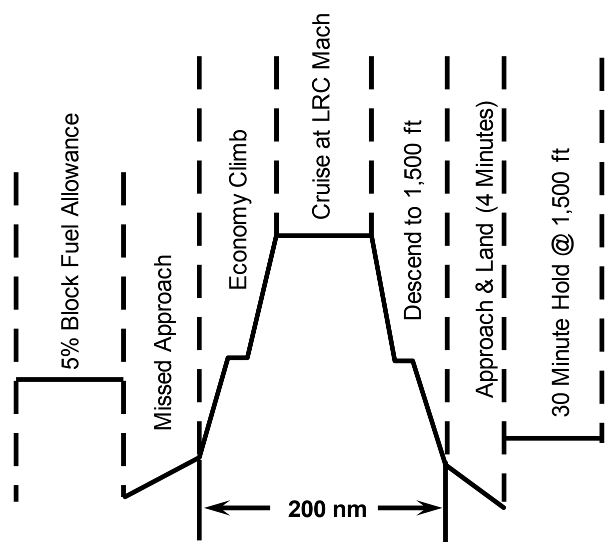


Figure 12. NASA Reference Mission Reserves

Phases of the reserve mission are:

- A 5% block fuel allowance accounts for perhaps unexpected headwinds or rerouting.
- Missed approach. The reserve mission starts with a missed approach at the end of the basic mission.
- Economy climb. The airplane is climbed following the same general profile as in the basic mission include speed limits below 10,000 ft. The beginning of this phase marks the start of the 200 nm diversion distance.
- Cruise. The airplane is cruised at the long range cruise Mach number at the altitude that provides the least fuel burn over the diversion distance.
- Descent to 1500 ft AGL. This follows the same general profile as in the basic mission. The end of this phase marks the end of the 200 nm diversion distance.
- Approach and landing. Four minutes is allotted for this.
- 30 minute hold at 1500 ft AGL. This is provided in case weather is bad even at the alternate airport or perhaps the airport is crowded due to bad weather elsewhere.

2.2.2.2 Operational Mission

This mission represents Boeing's most realistic estimate of 1998 operating rules. These are significantly less efficient than the Reference mission described above, primarily from the extra 5% mission range ascribed to non-optimum track. The basic mission portion is diagramed in Figure 13.

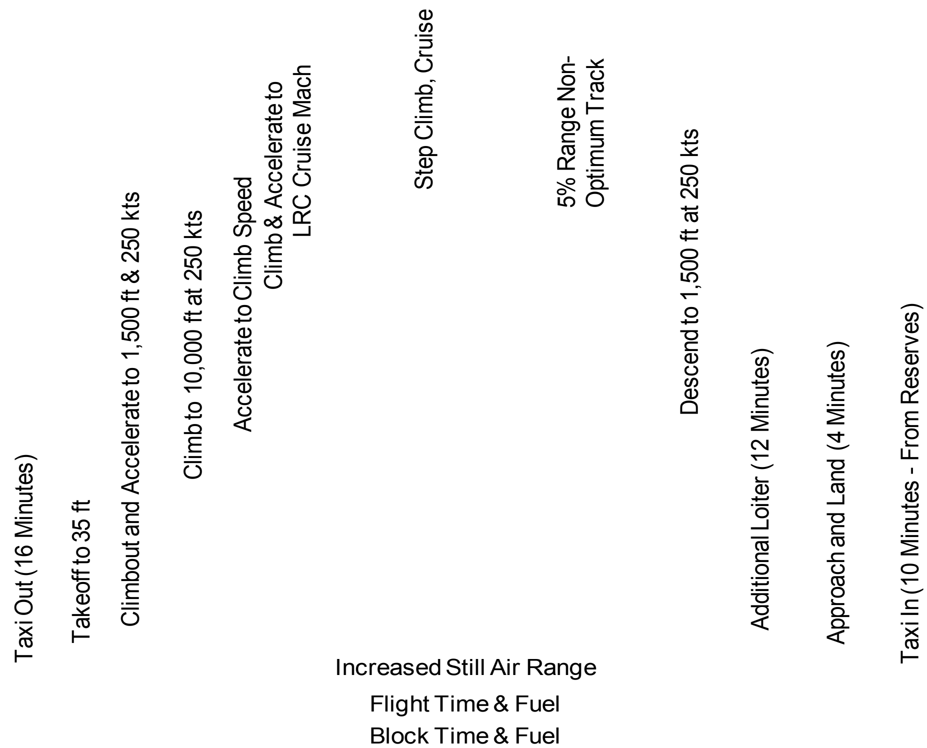


Figure 13. Operational Mission Profile (without Reserves)

Comparison of the Operational mission in Figure 13 with those of the Reference mission in Figure 11 shows only a few key differences. These are:

- Taxi out time is lengthened to 16 minutes from nine minutes.
- Still air range is increased by 5% to account for non-optimum track.
- A 12-minute loiter phase is added between descent and approach to land.
- Taxi in after the landing is lengthened to 10 minutes from five minutes.

The reserve portion of the Operational mission is shown in Figure 14. It is identical to the reserve portion of the Reference mission.

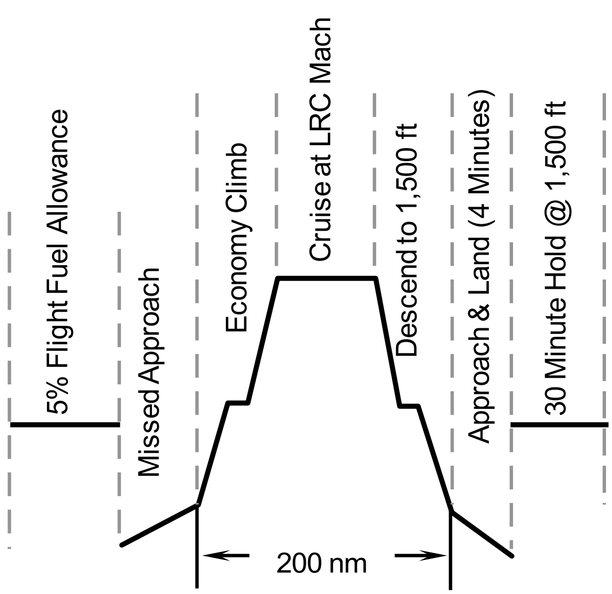


Figure 14. Operational Mission Reserves

2.2.2.3 NextGen Mission

The NextGen mission represents an advanced set of operating rules based on precise knowledge and prediction of aircraft flight paths. This permits airplanes to operate with fewer constraints to speed, altitude and hold times. A diagram of the basic NextGen mission is show in Figure 15.

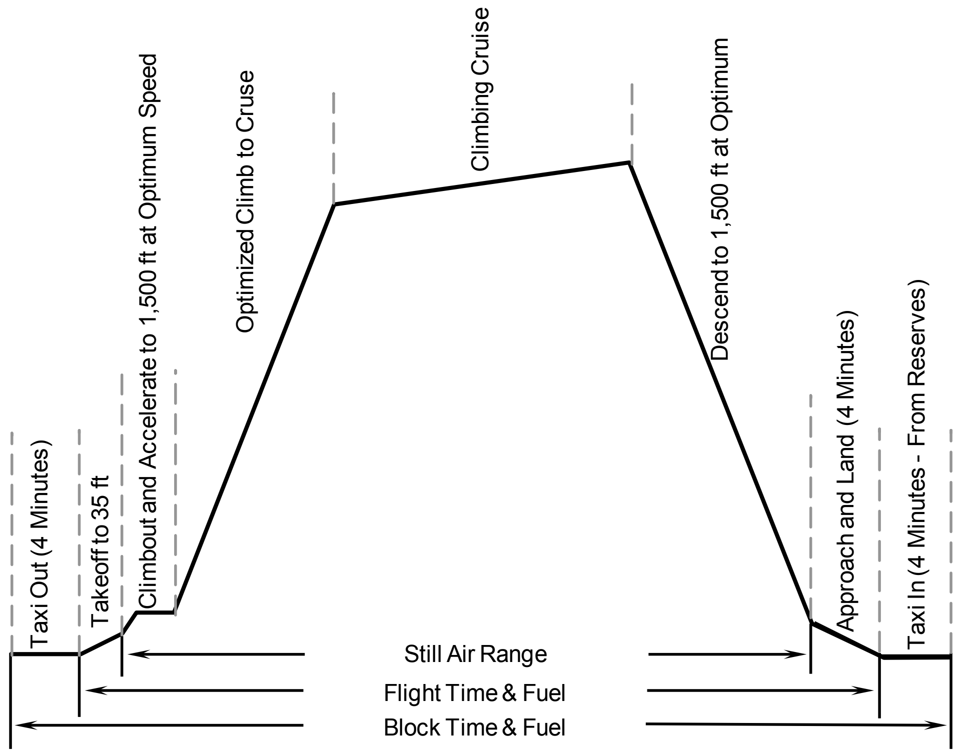


Figure 15. NextGen Mission (without Reserves)

Comparison of the NextGen mission shown in Figure 15 with those of the Reference mission in Figure 11 show a few key differences. These are:

- Taxi out time reduced to four minutes from nine minutes.
- The climb profile from 1500 ft AGL to cruise altitude is no longer constrained with respect to speed. As a result, the study airplanes climb directly to cruise altitudes at speeds considerably greater than the Reference mission's 250 kt limit below 10,000 ft. Figure 16 shows NextGen climb and descent airspeeds versus altitude for two representative 2025 airplanes. The -0007 is a conventional configuration; the -0009A is a BWB. In the plot, the airplanes climb to the right and descend to the left.

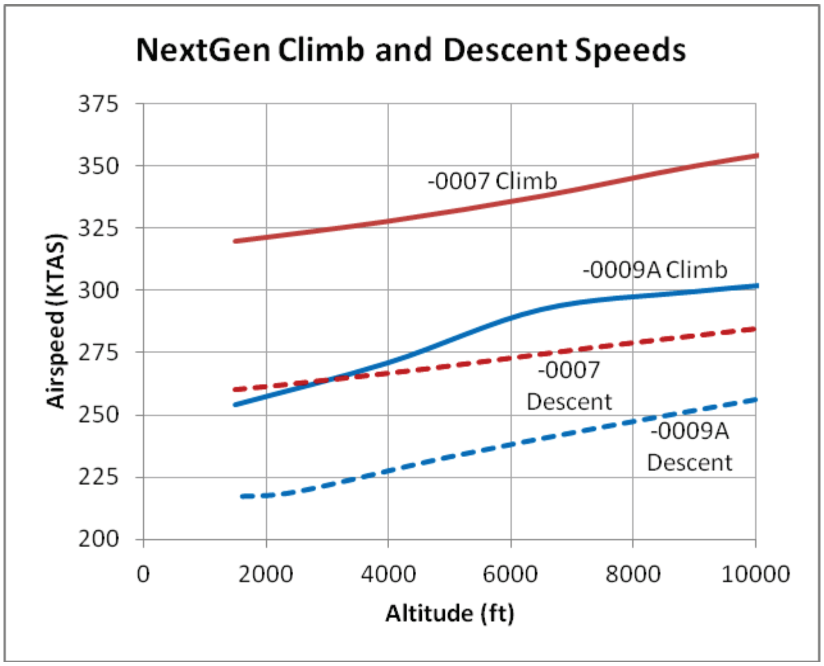


Figure 16. NextGen Climb and Descent Speeds

- The cruise phase is unconstrained with respect to altitude. Rather than cruise at specific 4000-ft altitude levels, the airplanes may fly at any altitude and may climb gradually as fuel consumption lightens the airplane - the most efficient altitude is used throughout the cruise. Two caveats: 1) The study airplanes are still constrained to begin cruise at greater than or equal to 35,000 ft. 2) The study airplanes are constrained to a maximum altitude of 45,000 ft due to depressurization considerations.
- The descent profile, like the climb profile, is no longer constrained with respect to speed. Following the cruise, the airplanes are lighter so the descents are slower than the climbs as shown in Figure 16.

There are several important changes from the Reference mission reserve to the reserve portion of the NextGen mission as illustrated in Figure 17. These are noted below.

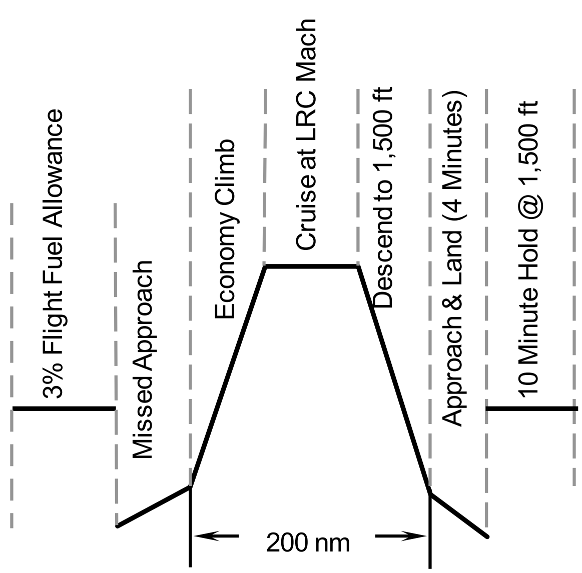


Figure 17. NextGen Mission Reserves

- The fuel reserve has been changed from 5% of the block fuel to 3% of the flight fuel. The flight fuel is somewhat less than the block fuel so represents slightly more than a 40% reduction in reserve fuel.
- The climb to and descent from the cruise segment is done without speed constraints as for the main NextGen mission.
- The hold time is reduced from 30 minutes to 10 minutes.

2.2.3 Measures of Merit

The study airplanes are modeled, operated according to the mission rules, and evaluated. Each tube-and-wing design is then evolved in terms of wing and tail area and engine thrust to minimize block fuel burned. BWB designs are evolved using only adjustments to engine thrust. Following this evolution, the airplanes are evaluated according to their noise and landing and takeoff emissions characteristics. Additional practical considerations enter into selecting a Preferred System Concept (PSC). These include airport compatibility and direct operating cost (DOC).

2.2.3.1 Fuel Consumption

Fuel consumption is recorded as block fuel burned. Mission segments included in block fuel are illustrated in Figure 11. Since all of the passenger airplanes have the same design payload and range, fuel consumption can be compared directly according to block fuel burned. It may also be compared as the ratio of payload times range divided by fuel burn in units of ton-nautical miles per pound of block fuel burned.

Each freighter airplane has a different design range. Fuel consumption is compared by ton-nm/lb fuel and not by simple block fuel burned. This provides a fairer comparison of fuel efficiency.

NASA provided the fuel consumption goal for the PSC to reduce block fuel burned by 50% relative to the 1998 baseline aircraft.

2.2.3.2 Noise

The noise metric for each airplane is based on the regulatory standard for airport noise.[4]**Error! Reference source not found.** Noise internal to the airplane (as heard by the passengers) is not a consideration in this study.

Noise levels are estimated for seven representative airplanes in the study. For these, absolute estimates of approach, cutback and sideline noise are made. The cumulative level is used to calculate the margin to Stage 4 noise standards.

NASA's goal for cumulative noise is a 42 dB margin to Stage 4.

2.2.3.3 Landing and Takeoff NO_x

Landing and takeoff oxides of nitrogen (NO and NO_2, known collectively as NO_x) are included as a measure of merit. The International Civil Aviation Organization's (ICAO) Committee on Aviation Environmental Protection (CAEP) has prepared limits for NO_x emissions for a reference landing and takeoff (LTO) cycle below 3000 ft altitude. One version of these limits is known as CAEP/6. Emissions of the study airplanes relative to the CAEP/6 standard is a measure of merit.

NASA's goal for LTO NO_x is a 75% reduction from CAEP/6 levels.

2.2.3.4 Other Considerations

In addition to measures of merit suggested by NASA, the study considered airport compatibility and direct operating cost.

2.2.3.4.1 Airport Compatibility

Airport compatibility is addressed in the design requirements discussed in Section 2.2.1. Aspects include wingspan and load classification number. Because wingspan was set as a tradeable requirement, some study airplanes explore the benefit of extra span. One subjective measure of merit is the benefit of additional wingspan to fuel consumption, noise and LTO NOx relative to the impact on airport compatibility.

2.2.3.4.2 Direct Operating Cost

Direct operating cost (DOC) is estimated for the study airplanes and is used subjectively in comparing airplanes and selecting the PSC. DOC is the sum of operating, ownership and indirect costs for an efficiently operated airplane.

It is possible to create a very sophisticated model to estimate DOC. Such a model considers many subtleties and would be proprietary. For the purpose of this study, the DOC model is extremely simple so that only the most important variables contribute. The model considers airplane productivity, ownership, fuel, pilots, cabin attendants and maintenance.

2.2.4 Technologies

This study determines efficiency, noise and emission benefits provided by advanced technologies relative to 1998-level technologies. These technologies are defined in some detail in Volume 2 of this report – "Technology Maturation Plan" and are summarized below in Table 3. These technologies are consistently applied to all study airplanes according to technology date and configuration type. One exception is for the 2025 advanced conventional configuration (AT&W-0027) – this particular design explores the effect of increased aerodynamic technology levels. A consistent-level technology version of this airplane, the AT&W-0027A, is also studied.

Table 3. Configuration Technologies

	1998	2025 Conventional	2025 BWB
High Speed Aerodynamics	Supercritical Airfoils	Hybrid Laminar Flow Riblets High Aspect Ratio	Hybrid Laminar Flow Riblets High Aspect Ratio
Low Speed Aerodynamics	Slotted Flap Slat	Slotted Flap Low Noise Krueger Flap	Plain Flap Low Noise Krueger Flap
Propulsion	High-Bypass Turbofan	Geared Turbofan Open Rotor	Geared Turbofan Open Rotor
Fuselage Structure	Aluminum	Composite (PRSEUS)	Composite (PRSEUS)
Wing Structure	Aluminum	Composite	Composite
Empennage Structure	Composite	Composite	Composite
Systems		(Electric Controls) Advanced APU	(Electric Controls) Advanced APU
Acoustics		Leading Edge Acoustic Treatment Landing Gear Acoustic Treatment Engine Acoustic Treatment	Shielding Leading Edge Acoustic Treatment Landing Gear Acoustic Treatment Engine Acoustic Treatment

2.3 Summary of All Configurations

Three different configurations are studied. One is the conventional transport airplane configuration, often referred to in this study as “Tube-and-Wing” (T&W). These serve as baselines for comparisons. The second is an advanced conventional configuration, referred to as “Advanced Tube-and-Wing” (AT&W). This is investigated to see if it provides a favorable balance of fuel burn and noise. The third is the Blended-Wing-Body (BWB) configuration.

The conventional configuration is studied at two technology levels: 1998 and 2025; all others are studied with 2025 technologies only. Considering this division, there are four basic families of airplanes in the study. Three freighter derivatives are examined: 1998 T&W, 2025 T&W and 2025 BWB.

2.3.1 1998 Conventional Configuration

The 1998 conventional configuration is intended to be representative of 1998 technology level passenger and freighter aircraft. The descriptions below apply to all 1998 T&W airplanes. Individual airplane sizing and performance is described in Section 2.5. A general arrangement drawing and layout of passenger accommodations of T&W-0001 is shown in Figure 18.

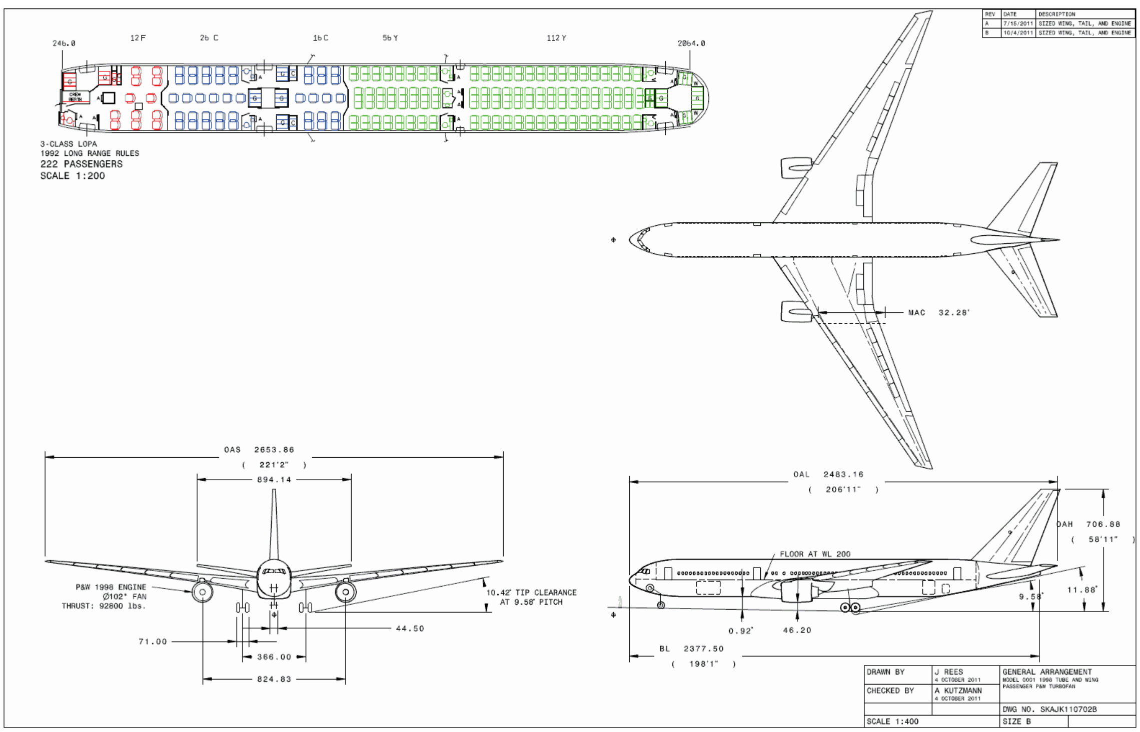


Figure 18. 1998 T&W-0001 General Arrangement Drawing

2.3.1.1 Configuration Description

2.3.1.1.1 Design Features

The 1998 T&W is a cantilever wing monoplane with a horizontal and vertical stabilizer mounted on the aft fuselage, twin podded turbofan engines mounted to the wing with pylons, tricycle landing gear, and a forward crew compartment with conventional controls and transparencies. The design is created in a passenger and freighter version with common fuselage geometry.

2.3.1.1.2 Aerodynamics

Aerodynamic features include a swept wing. The gross wing aspect ratio is approximately 8.4. The wing airfoil sections are supercritical with divergent trailing edges. There are no provisions for laminar flow and riblets are not used.

The fuselage length to diameter ratio is 11.42. This ratio is the overall length of the fuselage divided by the diameter of a circle with the same area as the fuselage cross section.

2.3.1.1.3 Flying Controls and High Lift Systems

Flying controls for roll are inboard and outboard ailerons plus asymmetrical spoiler deflection. Pitch control is provided by elevators mounted on the horizontal stabilizer. Pitch trim is provided by variable incidence of the horizontal stabilizer. Yaw control is provided by a rudder mounted to the fixed vertical stabilizer. Lift and drag modulation is provided by symmetrical deployment of the wing spoilers.

Lift is augmented at low speed by full-span leading edge slats and slotted trailing edge flaps. The leading edge slats have three positions; retracted for high speed, partially extended and sealed for takeoff, and fully extended and open for landing. Trailing edge flaps are divided into inboard and outboard segments. These are separated by an inboard, high-speed aileron aligned with the engine efflux.

2.3.1.1.4 Structure

Most primary airframe structure is semi-monocoque aluminum alloy connected by mechanical fasteners.

The pressurized, slightly double-bubble fuselage consists of an outer skin stabilized by longitudinal stringers and lateral-vertical frames. Some frames are reinforced to accept concentrated loads from the wing, tail and nose landing gear.

Primary wing structure is a two-spar box formed by front and rear web and upper and lower skins stiffened by longitudinal stringers. Skins are stabilized by regularly spaced wing ribs. Some ribs are reinforced to accept concentrated loads from flap brackets, engine pylons and main landing gear. Secondary wing structure is a mix of aluminum alloy and carbon-epoxy laminates. Ahead of the front spar the structure is aluminum. Flaps, ailerons and spoilers are carbon-epoxy laminates.

Structure of the horizontal and vertical stabilizers is similar to that of the wing except the structural box is carbon-epoxy.

2.3.1.1.5 Landing Gear

The landing gear is arranged in a tricycle configuration with two main gear struts and a single nose gear. Tire size, count and arrangement are set to meet the LCN requirement described in Section 2.2.1.

In the extended position, main gear tires are located to enable takeoff rotation and provide sufficient nose wheel steering authority over the airplane's center of gravity (CG) range. Main gear struts are mounted to the aft wing spar and retract inboard and upwards so that the main gear is housed within the lower fuselage and wing-body fairing just behind the rear wing spar carry-through. Each main gear strut has four tires arranged in a two-by-two configuration. Suspension is provided by an integrated oleo strut.

The nose gear is mounted to the lower forward fuselage and retracts forward and up into the lower forward fuselage. It has two tires mounted side-by-side. Suspension is provided by an integrated oleo strut.

Hydraulically actuated, carbon-carbon fiber multi-disk brakes are provided in each of the eight main gear wheels. The nose gear has no braking.

2.3.1.1.6 Propulsion

Propulsion is provided by two axial flow gas turbine engines driving a moderate pressure ratio single-stage ducted fan (turbofan). The turbofan engines represent 1998 state of the art and incorporate wide cord fan blades. Both Pratt & Whitney and Rolls-Royce 1998 baseline engines represent their production engines of the era, the PW4090 and Trent 800, each powering versions of the Boeing 777. Separate flow short duct nacelles with integral translating sleeve cascade thrust reversers are used on both engines.

The propulsion system is under-wing pylon mounted, fueled with Jet A with a fuel heating value of 18,580 BTU/lbm. Bleed air and shaft power is extracted from each engine to provide the aircraft with electrical, hydraulic and pneumatic power.

Fixed cycle data packs are provided by P&W and R-R with simple scaling factors for fan diameter, weight and length to allow thrust sizing of the engine to meet airplane requirements.

Takeoff thrust lapse, top-of-climb thrust, cruise SFC, engine weight and nacelle drag are different between the P&W and R-R engines for the 1998 baseline.

It is an important feature of this study that there is no iterative adjustment of the engine cycle characteristics to match airplane characteristics. With the exception of "rubberized" sizing of the engines, the engines are used as delivered by the engine manufacturers.

2.3.1.1.7 Accommodation

All versions of the 1998 and 2025 T&W airplanes have the same fuselage dimensions and accommodations. Of course, passenger and freighter versions provide different accommodations. Both airplanes share a crew compartment with provisions for two pilots and an observer's jump seat.

Passenger

Accommodations are shown in Figure 19, Figure 20, Figure 21 and Figure 22. These are described below each figure.

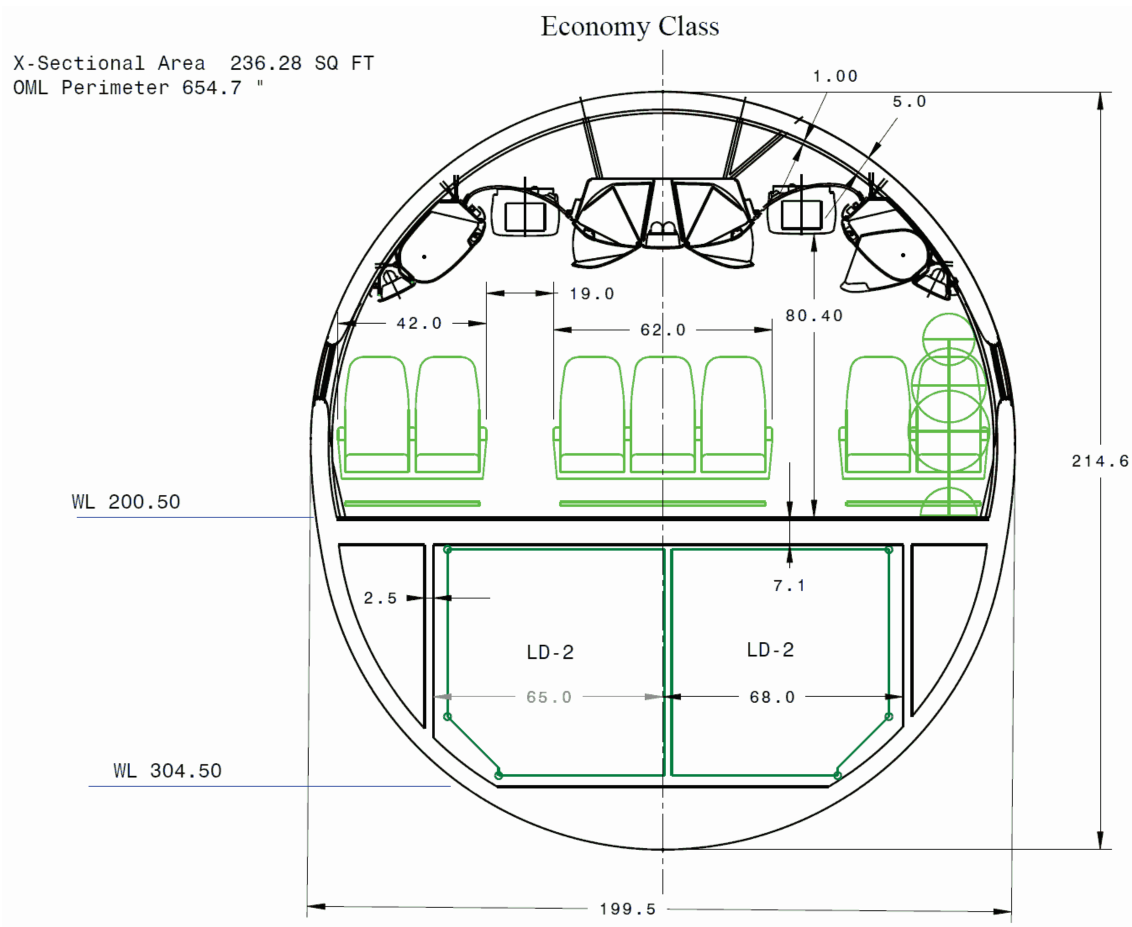


Figure 19. Economy Class Cabin Cross Section

Economy class seating is provided in a twin-aisle 2-3-2 arrangement on the main deck. Four overhead storage bins are provided.

Two rows of LD-2 cargo containers are accommodated on the lower deck throughout the length of the airplane except where interrupted by nose or main landing gear, the wing box and aft fuselage taper.

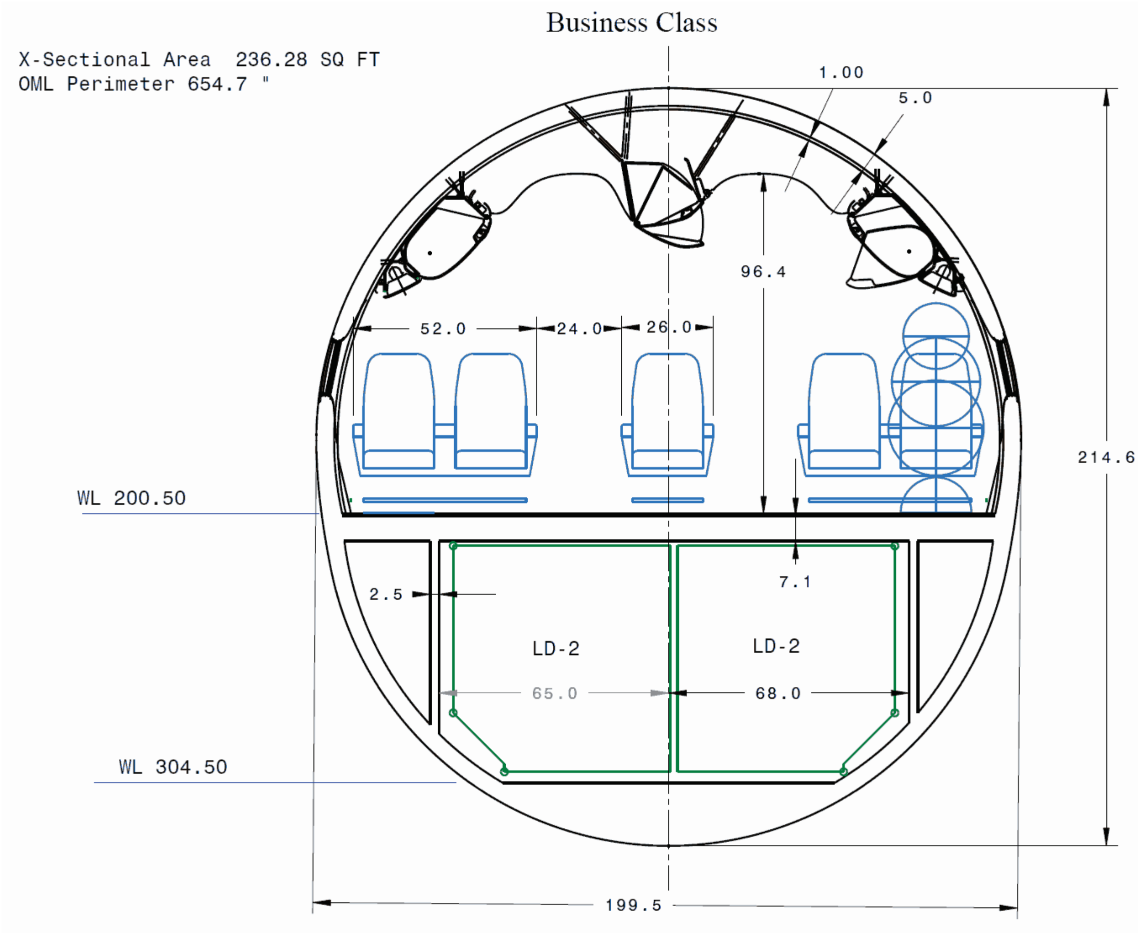


Figure 20. Business Class Cabin Cross Section

Business class seating is a twin-aisle 2-1-2 arrangement on the main deck. Three overhead storage bins are provided.

The business class seating arrangement meets the strict design requirements described in Section 2.2.1. With a minor reduction of seat and aisle width, an extra row of seats may be included, converting the arrangement to 2-2-2. The economic benefits of this arrangement (20% extra business class seats or a reduction in fuselage length, weight and drag) are likely to outweigh the small reduction in passenger comfort. In practice, this denser arrangement would probably be selected by most airlines.

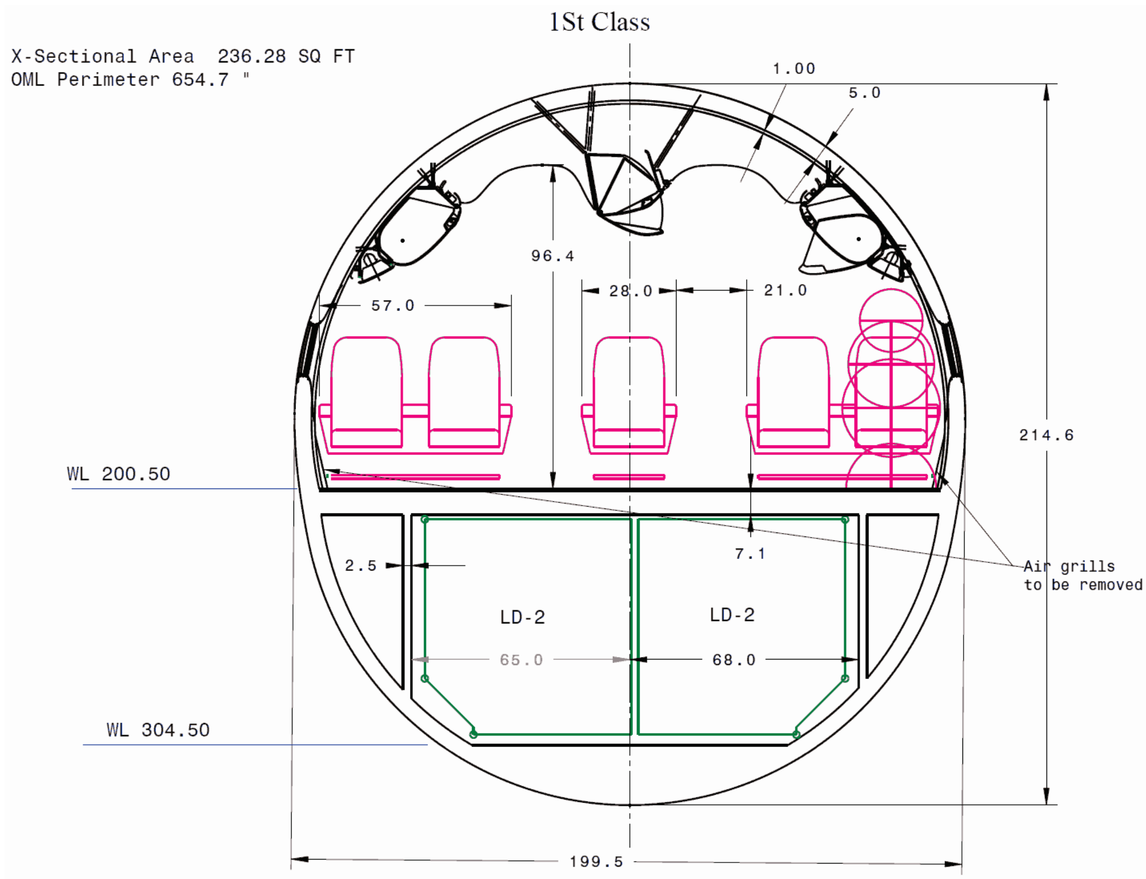


Figure 21. First Class Cabin Cross Section

First class seating is provided in a twin-aisle, 2-1-2 arrangement on the main deck. While this arrangement is the same as in business class, slightly wider seats are provided. Overhead bins are the same as in business class.

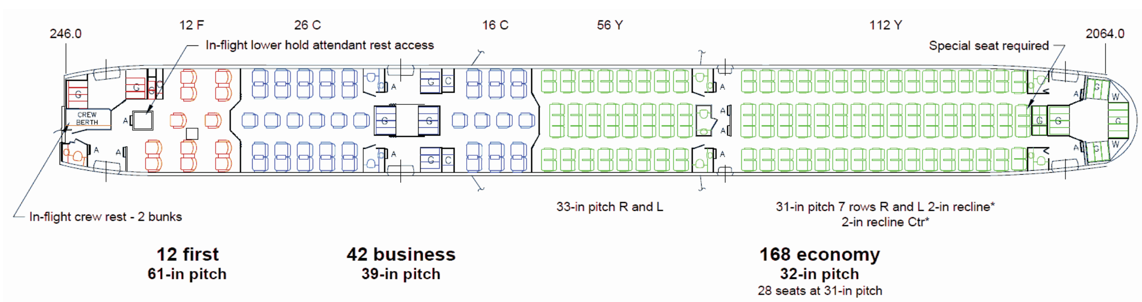


Figure 22. Layout of Passenger Accommodations

Figure 22 shows the overall layout of passenger accommodations on the main deck. In addition to the seating and overhead bins described in the cross section drawings, other features are shown. Four doors are provided on each side of the cabin to provide for emergency egress, passenger loading and cabin servicing. Galleys, indicated by the letter "G", are located in the nose, middle of business class and very aft cabin. An aspect of the galley arrangement is their alignment with starboard doors, easing galley servicing. Lavatories, indicated by a toilet and sink symbol are located at the front of the first class cabin and in the middle of the business and economy class cabins. A double bunk-bed is provided for pilots on the main deck just behind the crew compartment. Access to a lower hold attendant rest area is provided near the front of the first class cabin. Cabin attendant seats are provided immediately adjacent to seven of the eight doors, and nearby to the eighth door. Windows are provided for outboard passengers between nearly every fuselage frame – approximately 20 inches on center.

Freighter

The freighter version replaces the main deck passenger accommodations with cargo in unit load devices (ULD) in the form of netted pallets or enclosed containers. The lower deck is unchanged from the passenger version. The plan view is shown in Figure 23.

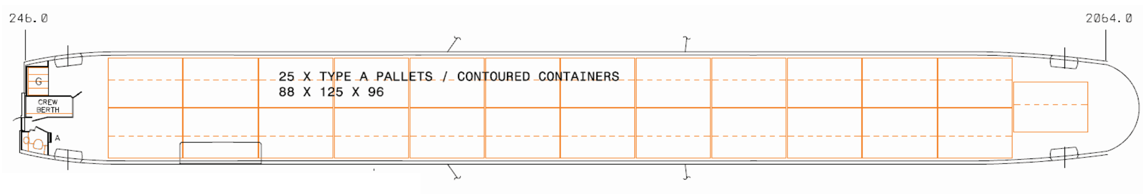


Figure 23. Freighter Main Deck Cargo Arrangement

The forward and aft pairs of passenger doors are retained from the passenger version; the four central doors are eliminated. A 137” wide x 75” high main cargo door is added to the port side of the forward fuselage.

The forward lavatory and the forward portion of the first class galley are retained from the passenger version as are the crew rest bunks.

2.3.1.1.8   Systems and Avionics

Systems are consistent with 1998 practice. The engines produce electric and hydraulic power and heated bleed air. Flight control surfaces are hydraulically powered and electrically signaled. Brakes are hydraulically operated. The wing leading edge anti-ice system is powered by hot engine bleed air. Emergency power is provided by a ram-air turbine (RAT).

2.3.1.1.9   Acoustic Features

The acoustic features of 1998 aircraft are the low bypass ratio engines and the conventional high lift design that is needed for the T&W aircraft. The former makes the engine noise dominant at sideline and cutback conditions and the latter contributes a significant amount of noise at approach conditions. For the engine noise, liner treatments are usually applied for both the inlet and the exhaust duct, typically with the inlet liner targeting the first few tones and the exhaust duct liner for broadband noise.

2.3.2   2025 Conventional Configurations

The descriptions below apply to the 2025 T&W airplanes. Individual airplane sizing and performance is described in Section 2.5. A general arrangement drawing and layout of passenger accommodations of T&W-0005 is shown in Figure 24.

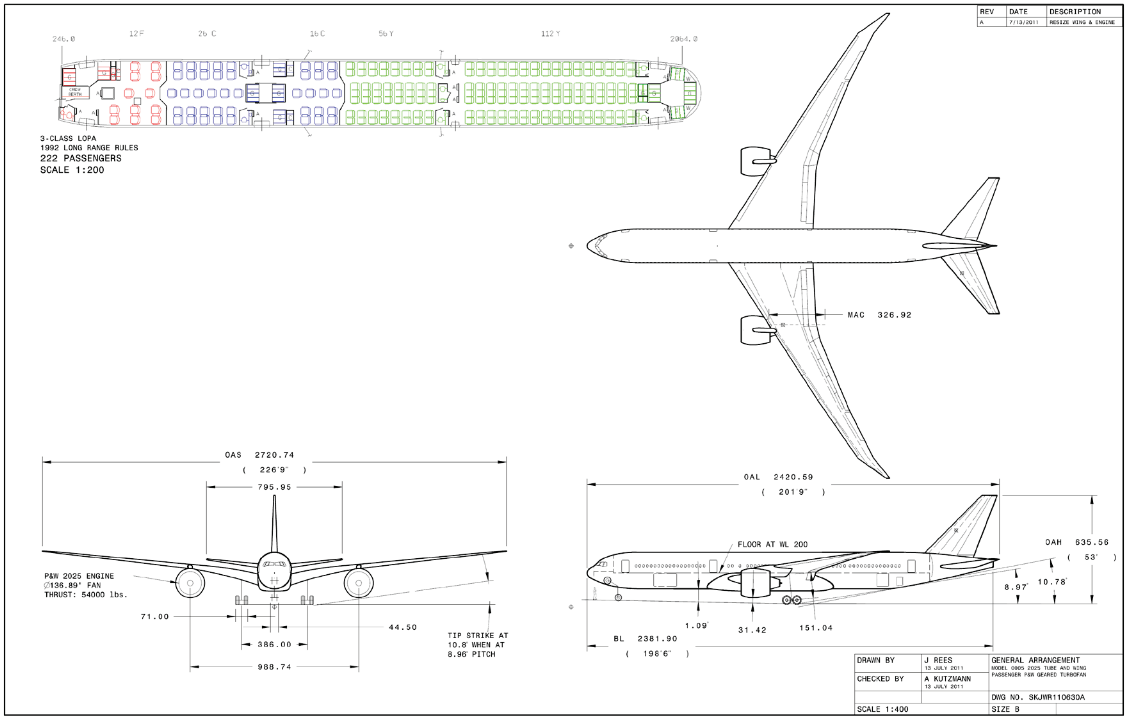


Figure 24. 2025 T&W-0005 General Arrangement Drawing

2.3.2.1 Configuration Description

2.3.2.1.1 Design Features

The 2025 T&W is a cantilever wing monoplane with a horizontal and vertical stabilizer mounted on the aft fuselage; twin podded engines mounted to the wing with pylons; tricycle landing gear; and a forward crew compartment with conventional controls and transparencies. Two distinct engine types are examined – a geared turbofan and a three-spool advanced turbofan. Figure 24 shows a geared turbofan.

The design is created in a passenger and freighter version with common fuselage geometry.

2.3.2.1.2 Aerodynamics

Aerodynamic features include a swept wing. The wing planform has several breaks intended to balance aerodynamic and structural considerations. A raked tip extends the 1-g effective wingspan and reduces bending moment under higher-g conditions. The gross wing aspect ratio is approximately 11.0.

The wing airfoil sections are supercritical with divergent trailing edges tailored to sustain laminar flow on the upper surface to just short of the shock. Laminar flow on the upper surface is initiated with a hybrid laminar flow control system (HLFC). This system ducts air to a passive suction device from perforated skins on the forward portion of the airfoil ahead of the front spar.[5]

Forward portions of the horizontal and vertical stabilizers also have HLFC.

Riblet surface texture is applied to the fuselage and turbulent portions of the wing and tails. This texture provides a parasite drag reduction.

The fuselage length to diameter ratio is 11.42 – the same as the 1998 T&W fuselage.

2.3.2.1.3 Flying Controls and High Lift Systems

Flying controls for roll are inboard and outboard ailerons plus asymmetrical spoiler deflection. Pitch control is provided by elevators mounted on the horizontal stabilizer. Pitch trim is provided by variable incidence of the horizontal stabilizer. Yaw control is provided by a rudder mounted to the fixed vertical stabilizer. Lift and drag modulation is provided by symmetrical deployment of the wing spoilers.

Lift is augmented at low speed by full-span leading edge Krueger flaps and slotted trailing edge flaps. The leading edge Krueger flaps have three positions: retracted for high speed; partially extended and sealed for takeoff; fully extended and open for landing. Trailing edge flaps are divided into inboard and outboard segments. These are separated by an inboard, high-speed aileron aligned with the engine efflux.

2.3.2.1.4 Structure

Most primary airframe structure is semi-monocoque carbon-epoxy composite. Much of the airframe is co-cured in large assemblies. Components within these co-cured assemblies are connected in part by through-the-thickness stitching. Assemblies are then connected by mechanical fasteners. Stitching provides damage arrestment and enables increased stress allowable and reduced minimum gauges.[6]

The pressurized, slightly double-bubble fuselage consists of an outer skin stabilized by longitudinal stringers and lateral-vertical frames. Some frames are reinforced to accept concentrated loads from the wing, tail and nose landing gear.

Primary wing structure is a two-spar box formed by front and rear web and upper and lower skins stiffened by longitudinal stringers. Skins are stabilized by regularly-spaced wing ribs. Some ribs are reinforced to accept concentrated loads from flap brackets, engine pylons and main landing gear. Secondary wing structure is a mix of aluminum alloy and carbon-epoxy laminates. Ahead of the front spar, much of the structure is aluminum. Flaps, ailerons and spoilers are carbon-epoxy laminates.

Structure of the horizontal and vertical stabilizers is similar to that of the wing.

2.3.2.1.5 Landing Gear

The landing gear is the same as the 1998 T&W design as described in Section 2.3.1.1.5.

2.3.2.1.6 Propulsion

Propulsion is provided by two turbofan engines. Two engine architectures are examined; the P&W geared turbofan and the R-R direct drive turbofan.

The P&W advanced engine concept configuration is defined as a Geared Turbofan (GTF) propulsion system. These are scaled from a known advanced cycle (SGTF 1781). The engines are scaled to thrust requirements to power three different 2025 configurations. These are the Advanced 2025 tube-and-wing and two 2025 BWB designs; one with twin GTFs and a second with triple GTFs.

For all the advanced engine configurations the technology level is assessed for a 2020 Technology Readiness Level (TRL) of 6 / EIS 2025 and performance is updated to the levels expected with this level of technology insertion.

The RRNA 2025 ATF engine and technologies are based on existing Rolls-Royce programs funded outside of ERA.

Both the P&W GTF and RRNA ATF engines use separate flow short duct nacelles with integral translating sleeve cascade thrust reversers. Both are mounted on under-wing pylons and are fueled with Jet A with a fuel heating value of 18,580 BTU/lbm. Bleed air and shaft power is extracted from each engine to provide the aircraft with electrical, hydraulic and pneumatic power.

Fixed cycle data packs are provided by P&W and RRNA with simple scaling factors for fan diameter, weight and length to allow thrust sizing of the engine to meet airplane requirements.

2.3.2.1.7 Accommodation

All versions of the 1998 and 2025 T&W airplanes provide the same fuselage dimensions and accommodations. For details of the 2025 T&W accommodations, see Section 2.3.1.1.7.

2.3.2.1.8 Acoustic Features

The acoustic features of the 2025 conventional T&W aircraft are dominated by the high bypass ratio engines, which reduces the engine noise source amplitude significantly from the levels of the 1998 engines. Because of the high bypass ratio, the engine noise is dominated by the tones from the fan and its interactions with the stators.

2.3.3 Advanced Conventional Configuration

A single advanced conventional configuration is created in a passenger version. This is called the AT&W-0027A. Sizing and performance are described in Section 2.7.1.5. A general arrangement drawing is shown in Figure 25.

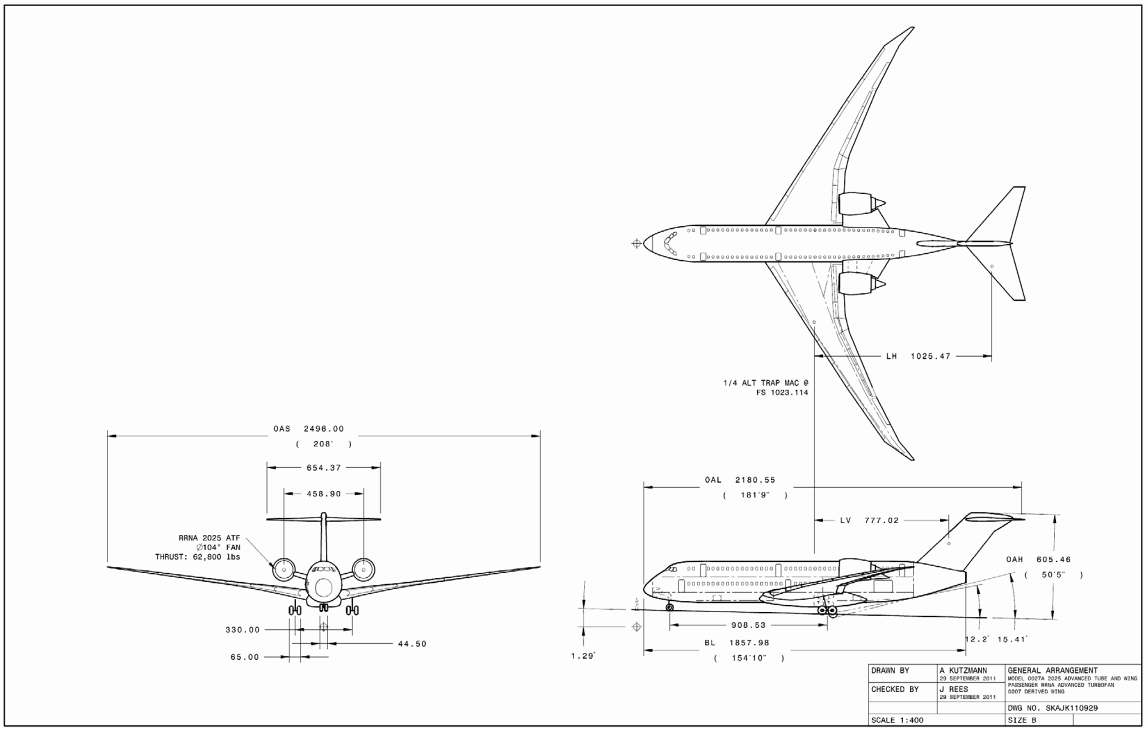


Figure 25. 2025 AT&W-0027A General Arrangement Drawing

2.3.3.1.1 Configuration Description

2.3.3.1.2 Design Features.

The 2025 AT&W-0027A is a cantilever wing monoplane with a T-tail mounted on the aft fuselage; double-deck passenger cabin; twin podded engines on horizontal, fuselage-mounted pylons with the engine inlet lip just forward of the wing trailing edge; tricycle landing gear; and a forward crew compartment with conventional controls and transparencies.

2.3.3.1.3 Aerodynamics

The wing geometry is scaled from the wings on the 2025 conventional configurations described in Section 2.3.2.1.2. Aerodynamic features of the wing are common with those of the conventional 2025 T&W designs as described in Section 2.3.2.1.2

Hybrid laminar flow control is provided for the horizontal and vertical.

Riblet surface texture is applied to the fuselage and turbulent portions of the wing and tails. This texture provides a parasite drag reduction.

The fuselage length to diameter ratio is 8.29.

2.3.3.1.4 Flying Controls and High Lift Systems

Flying controls for roll are inboard and outboard ailerons plus asymmetrical spoiler deflection. Pitch control is provided by elevators mounted on the horizontal stabilizer. Pitch trim is provided by variable incidence of the horizontal stabilizer. Yaw control is provided by a rudder mounted to the fixed vertical stabilizer. Lift and drag modulation is provided by symmetrical deployment of the wing spoilers.

Lift is augmented at low speed by full-span leading edge Krueger flaps and slotted trailing edge flaps. The leading edge Krueger flaps have three positions: retracted for high speed; partially extended and sealed for takeoff; fully extended and open for landing. Trailing edge flaps are divided into inboard and outboard segments. These are separated by an inboard, high-speed aileron that may be deflected to coordinate with the flaps.

2.3.3.1.5 Structure

The airframe structure is generally the same as for the 2025 conventional configuration as described in Section 2.3.2.1.4. The fuselage is a double-bubble design supporting the upper deck at the bubble node.

2.3.3.1.6 Landing Gear

The main landing gear is the same as that of the 2025 conventional configuration as described in Section 2.3.2.1.5. One important difference is that the depth of the lower cargo hold is too shallow to fully contain the retracted nose gear. As a result, the nose gear well extends into the forward lower cabin, forming a "dog house".

2.3.3.1.7 Propulsion

Propulsion is provided by twin RRNA advanced turbofan engines. Data for these engines were provided by R-R.

2.3.3.1.8 Accommodations

Accommodations for the AT&W-0027A are provided on three decks. The upper deck accommodates passengers in a single-aisle cabin as well as the forward crew compartment. The main (middle) deck provides passenger accommodations in the forward portion and a cargo volume in the aft portion. The main deck passenger cabin is wider than the upper cabin and has two aisles. The lower compartment is for bulk cargo only.

A cross section through economy class (upper deck) and business class (lower deck) is shown in Figure 26. A layout of passenger accommodations is shown in Figure 27.

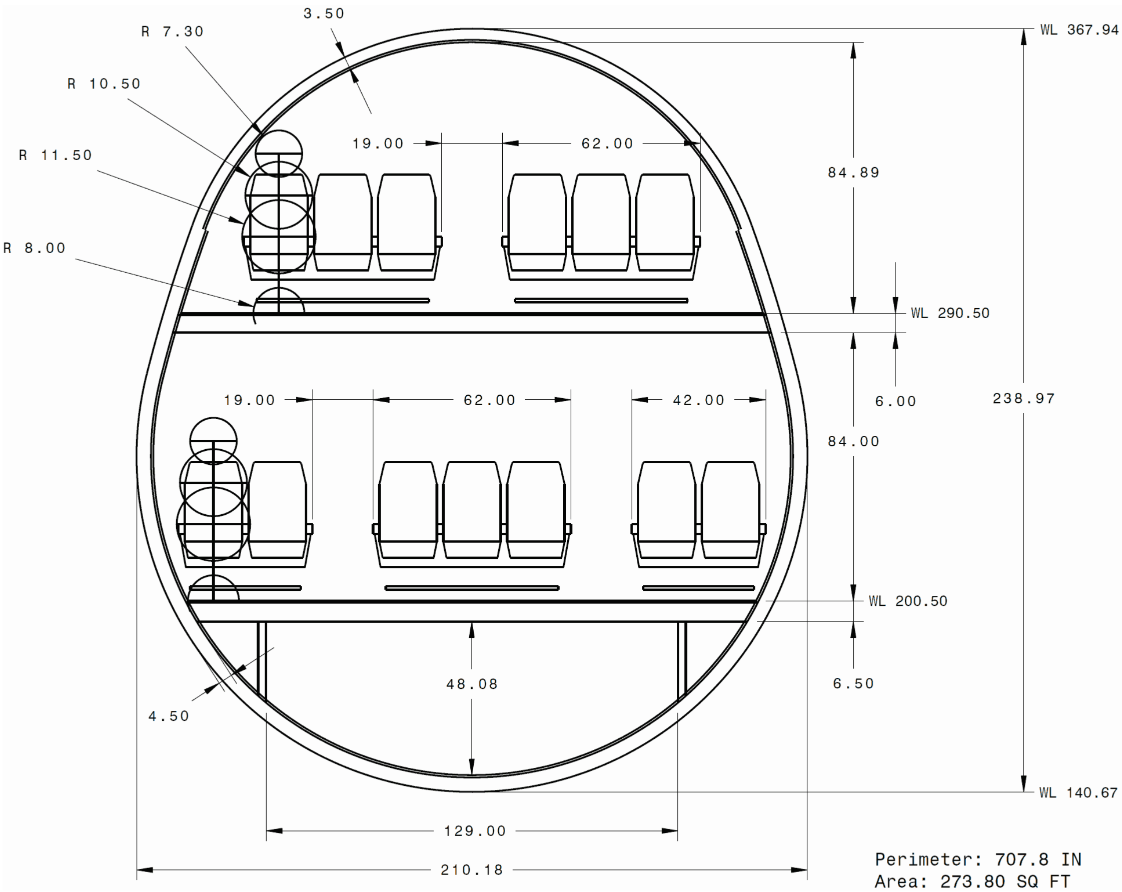


Figure 26. 2025 AT&W-0027A Cross Section

Figure 26 shows a typical cross section with economy class seating on the upper and main decks. Structurally, the cross section is a double-bubble with a faired cusp. Upper cabin dimensions are set by head clearance as determined by the passenger envelope "snowman". A minimum aisle height of 84" is observed on the upper and lower decks. Lower cabin width is set by foot clearance of the snowman.

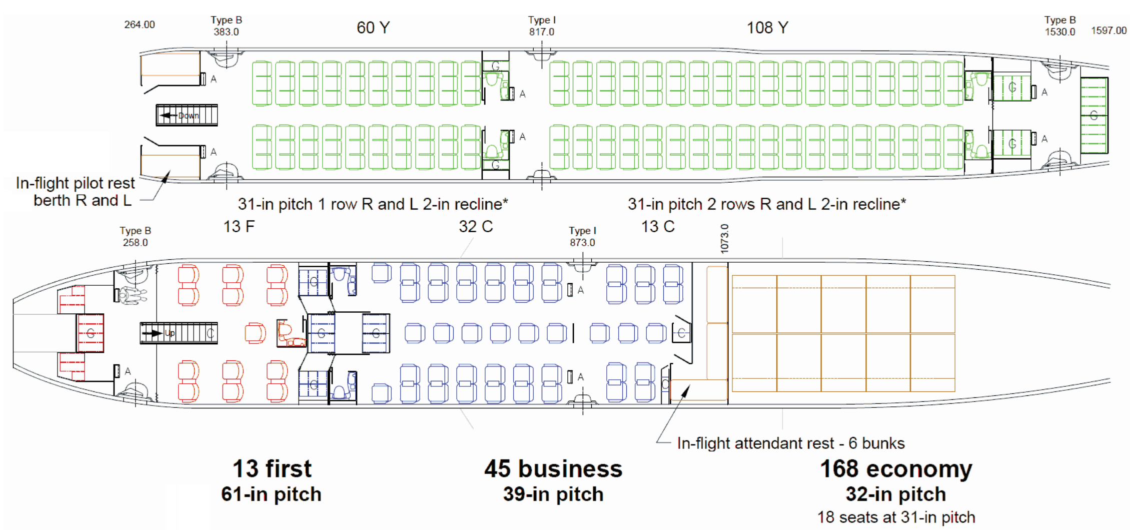


Figure 27. 2025 AT&W-0027A Layout of Passenger Accommodations

In the passenger configuration selected for the design mission, the upper deck is all-economy seating in a 3+3 arrangement. First and business class are located on the main deck, with business class in the forward fuselage. First class is a 2+1+2 arrangement as is business class. A 2+2+2 business class arrangement is just one inch too wide for the cabin – in commercial practice this arrangement would be selected for its large economic benefit.

The upper deck has six full-height emergency exits. One or more of these may also be used for passenger loading and unloading or for cabin servicing. Passengers may also reach the upper deck from the main deck via the forward staircase.

The main deck has four exits for passengers and a 106” wide by 70.4” high cargo door on the port side of the aft fuselage. The primary passenger door is in the forward left fuselage near the staircase.

There are four economy class lavatories on the upper deck in the mid and aft cabin; one first class lavatory at the rear of the first class cabin; and two business class lavatories at the front of the business class.

The economy class galley is located at the rear of the cabin and is serviced by the aft cabin doors. The first class galley is located in the nose and is serviced by the forward pair of doors. The business class galley is located at the front of the business class cabin. It is not adjacent any doors but may be serviced through either the forward or aft doors.

Cabin attendant seats are located adjacent to each of the 10 passenger doors. Two pilot rest bunks are placed at the sides of the forward upper cabin, immediately aft of the crew compartment. Six cabin attendant rest bunks are located in the aft portion of the main passenger cabin. Both crew rest areas are separated from the cabin and are accessed through doors.

Containerized cargo is accommodated in the aft main deck. One option is 10 LD-3 containers. Slightly larger purpose-built containers can utilize more of the available volume. The lower cargo hold accommodates bulk cargo with a total volume of 350 ft^3.

2.3.3.1.9 Acoustic Features

The advanced design of the 2025 T&W aircraft has both the high bypass ratio engines and the noise shielding of the engine noise because the engines are mounted on the fuselage above the wings. The engine inlet is approximately aligned with the trailing edges of the wings so that inlet noise is significantly reduced by shielding. The fuselage also shields the exhaust noise for the sideline conditions because the engine noise can only radiate to one side of the fuselage. In comparison with the conventional T&W design, the advanced T&W does not suffer the engine noise reflection by the wings when the engines are mounted under the wings.

2.3.4 2025 Blended Wing Body Configurations

A single BWB configuration, BWB-0009A, serves as the foundation for a range of alternative airplanes. Sizing and performance of the BWB designs are described in Section 2.7. A general arrangement drawing is shown in Figure 28, an inboard profile is shown in Figure 29, and an enlarged LOPA is shown in Figure 30.

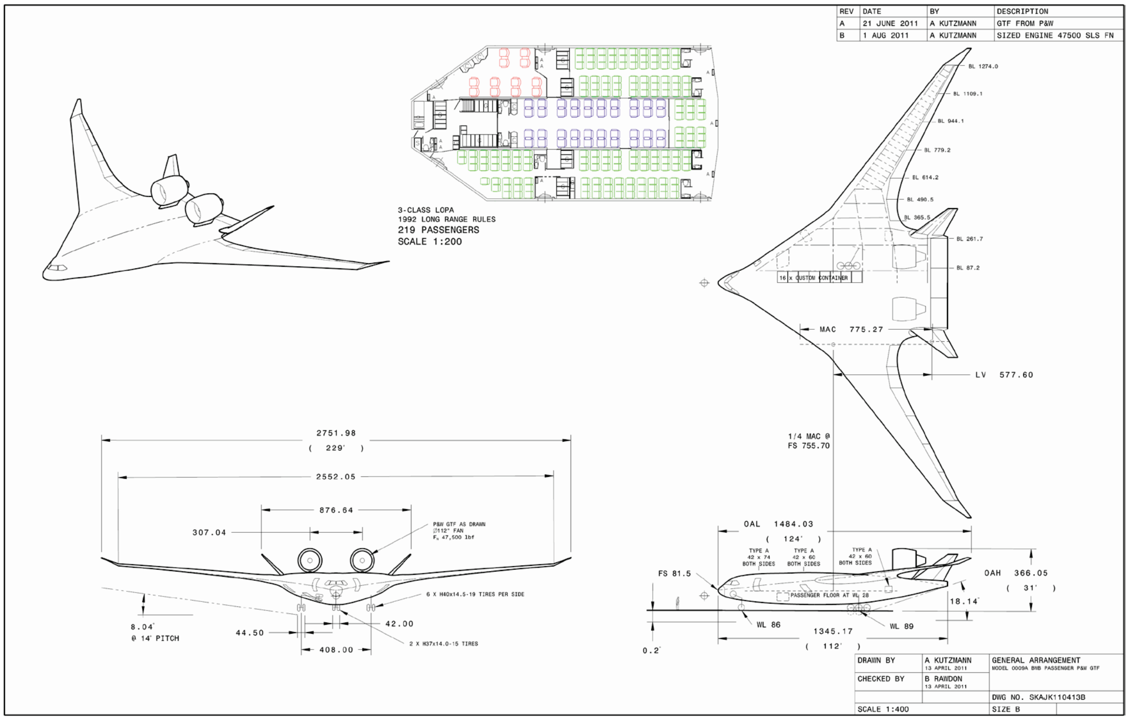


Figure 28. BWB-0009A General Arrangement

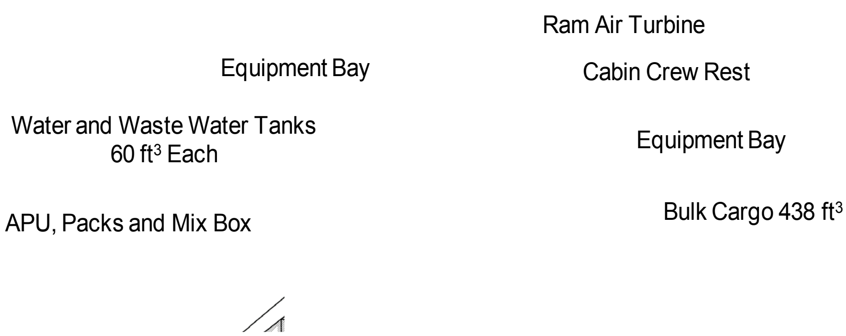


Figure 29. BWB-0009A Inboard Profile

2.3.4.1 Configuration Description

2.3.4.1.1 Design Features

The 2025 BWB-0009A is a blended wing body configuration. Three adjacent payload cabins above a single cargo bay form the core or "centerbody" of the airplane. This centerbody is wrapped with a large, swept wing form. Approximately conventional wings extend from the centerbody to form a single, large wing with an extended centerbody chord. Twin, outwardly-canted vertical stabilizers are mounted on the aft, outboard corners of the centerbody. Twin geared turbofan engines are mounted on the upper aft centerbody. Conventional tricycle landing gear extends from the lower centerbody. A crew compartment with conventional controls and transparencies is located at the nose of the centerbody.

2.3.4.1.2 Aerodynamic Features

Key aerodynamic features of the 2025 BWB-0009A include:

- The wing and centerbody are blended together in a smoothly varying planform.
- Wing chords vary widely in length across the span.
- Airfoil camber and twist is varied across the span to provide an approximately elliptical lift distribution despite the wide chord variation.
- The large centerbody chords result in low section lift coefficients. This in turn permits greater thickness-to-chord ratios despite the Mach 0.85 cruise speed.
- The centerbody's low section lift coefficients also permit reduced or reflexed aft camber there. This provides pitch trim – elevons are faired at the design center of gravity (CG).
- The outboard wing airfoils are tailored to support hybrid laminar flow control.
- As for the other 2025 airplanes, the outboard wing is equipped with a hybrid laminar flow control system as described briefly in Section 2.3.3.1.3.
- Riblet surface texture is applied to the centerbody and turbulent portions of the outboard wings and tails. This texture provides a parasite drag reduction.
- Raked wingtips provide wing load alleviation at higher g conditions.

2.3.4.1.3 Flying Controls and High Lift Systems

Flying controls include pitch, roll, yaw and drag.

Pitch control is provided by the three simply-hinged surfaces at the trailing edge of the centerbody and the next two surfaces outboard on each side. There is also the potential to use symmetrical deflection of the vertical stabilizers' rudders to augment pitch control but this is not exploited in this study.

Roll control is provided by deflection of the six trailing edge surfaces on each outboard wing. The inboard two of these surfaces are also used for pitch control, so inputs to these two surfaces are allocated and mixed. Deflection allocation of the six trailing edge devices is varied with airspeed to account for aeroelastic effects.

Yaw control is provided by the vertical stabilizers' rudders – the forward portions of the stabilizers are fixed. When additional yaw control power is needed, the rudders are augmented by the outboard two control surfaces on the trailing wing. The outboard two surfaces are each split into upper and lower portions. These can deflect together to act as an aileron or can deflect apart to form a split trailing edge spoiler. When deflected in this way on only one wing the drag results in a substantial yaw moment.

Control of drag is provided by symmetrical extension of the two outboard surfaces on each wing as described above.

High lift systems consist simply of a leading edge device on the outboard wings. The trailing edge surfaces do not function as a high lift system. The leading edge device is a Krueger flap with sealed cove. This has only two positions: extended and retracted.

2.3.4.1.4 Structure

The airframe structural system and materials are the same as for the other 2025 airplanes as described in 2.3.2.1.4. However, the structural arrangement, especially of the centerbody, is quite different.

The centerbody addresses several major loads. These include: pressurization of the upper and lower payload cabins; carry-through of the outboard wing bending loads; and concentrated loads from the landing gear, engine pylons and vertical stabilizers.

Pressurization of the large and relatively flat centerbody is efficiently achieved by several measures. The wide upper payload cabin is divided into three narrower cabins by longitudinal ribs linking the upper and lower centerbody skins. These reduce the unsupported span of the pressurized skins. The lateral and aft boundaries of the cabin are formed by pressure bulkheads. The aft bulkhead also serves as the web for the rear wing spar carry-through. The forward pressure boundary is formed by the curved centerbody leading edge.

Outboard wing carry-through loads are accepted primarily by the centerbody upper and lower skins. As noted above, the centerbody aft pressure bulkhead connects to the outboard wing rear spar web. The outboard wing front spar web connects to a centerbody bulkhead in the transition region between the payload cabin and the outboard wing. This bulkhead runs out (tapers) into the upper and lower centerbody skins. Bending shear in the forward portion of the centerbody is carried by the curved leading edges. Figure 29 also shows an intermediate spar/bulkhead that tapers into the upper centerbody skin but carries through at greater depth between the upper cabin floor and lower skin, immediately aft of the lower deck cargo hold.

The main landing gears are mounted below the upper deck to the outboard pressure bulkheads and the intermediate spar mentioned above. This arrangement distributes the gear loads longitudinally, laterally and vertically. The two engine pylons attach to bulkheads that span between extensions of the centerbody ribs. The vertical stabilizers are mechanically attached to bulkheads that span between extensions of the outboard cabin ribs and adjacent, outboard ribs. These ribs are indicated in the top view of Figure 28.

The outboard wings are conventional two-spar semi-monocoque boxes as described for the 2025 T&W designs in Section 2.3.2.1.4.

The vertical stabilizer structures are also two-spar semi-moncoque boxes.

2.3.4.1.5 Landing Gear

The landing gear is arranged in a tricycle configuration with two main gear struts and a single nose gear. Tire size, count and arrangement are set to meet the LCN requirement described in Section 2.2.1.

In the extended position, main gear tires are located to enable takeoff rotation and provide sufficient nose wheel steering authority over the airplanes center of gravity (CG) range. Main gear struts are mounted as described in Section 2.3.4.1.4 and retract inboard, upwards and forward so that the main gear is housed with the centerbody just outboard of the lower cargo bay. Each main gear strut has six tires arranged in a two-by-two-by-two configuration. This six wheel arrangement results in a narrower gear width, enabling the stowed gear to fit in the same depth as the lower deck cargo. A four wheel truck requires increased depth, adversely affecting either centerbody thickness to chord ratio or centerbody chord length. Suspension is provided by an integrated oleo strut.

The nose gear is mounted to the lower forward fuselage and retracts forward and up into the lower forward fuselage beneath the crew compartment. It has two tires mounted side-by-side. Suspension is provided by an integrated oleo strut.

Hydraulically actuated, carbon-carbon multi-disk brakes are provided in each of the eight main gear wheels. The nose gear has no braking.

2.3.4.1.6 Propulsion

BWB-0009A has twin geared turbofan engines. Other BWB versions use three smaller geared turbofans, two advanced three-spool turbofans, and three open rotor engines.

The P&W advanced engine concept configuration were defined as Geared Turbofan (GTF) propulsion systems. These were scaled from a known advanced cycle (SGTF 1781) and all were defined at a 1.25 fan pressure ratio (FPR). The engines were scaled to thrust requirements to power three (3) different advanced Boeing ERA configurations all with entry into service (EIS) in 2025. These were the Advanced 2025 Tube and Wing and two advanced Blended Wing Body (BWB) Preferred Systems Concept (PSC) aircraft; one with twin GTFs and a second with triple GTFs.

For all the advanced engine configurations the technology level was assessed for a 2020 Technology Readiness Level (TRL) of 6 / EIS 2025 and performance was updated to the expected levels pursuant with this level of technology insertion. RRNA provided open rotor propulsion system definitions. Three versions of the OR engine are used: Tri-jets at Mach 0.85 and at Mach 0.8; and a twin at Mach 0.80.

Each BWB propulsion system is mounted on a pylon on the aft body. The engines are fueled with Jet A with a fuel heating value of 18,580 BTU/lbm. Bleed air and shaft power is extracted from each engine to provide the aircraft with electrical, hydraulic and pneumatic power.

Fixed cycle data packs were provided by P&W and RRNA with simple scaling factors for propulsor diameter, weight and length to allow thrust sizing of the engine to meet airplane requirements. The "as-received" engine definitions are described above. Sized engine definitions are discussed in later sections.

Fuel is stored in the outboard wing and in the centerbody-to-outboard wing transition region as illustrated in Figure 29.

2.3.4.1.7 Accommodation

The BWB configuration is studied in passenger and freighter versions. Both versions share a crew compartment with provisions for two pilots and an observer's jump seat. BWB passenger accommodations are illustrated in Figure 30. Lower deck cargo accommodations are shown in Figure 29.

Figure 30. BWB-0009A Layout of Passenger Accommodations

Passenger

The passenger cabin is divided into three equal-width, single-aisle cabins by structural ribs described in Section 2.3.4.1.4. In the particular arrangement to meet the study requirements, economy class occupies the entire port cabin, the aft-most portion of the center cabin and the aft half of the starboard cabin. Business class occupies the central portion of the center cabin. First class is located in the forward starboard cabin.

Economy class seating is arranged 3 + 3. Business class is 2+2. First class is also 2+2 but with wider seats and increased seat pitch relative to business class.

The passenger cabin is served by a total of six doors, three on each side in a laterally symmetric arrangement. These are linked by the three longitudinal aisles as well as three lateral aisles. The forward doors are the primary loading doors. Mid-cabin doors let out into a passageway that extends forward and outboard to secondary, unpressurized doors in the centerbody leading edge. Aft-cabin doors let out through a short passageway to secondary, unpressurized doors in the centerbody side.

Galleys, indicated by "G" in Figure 30, are located in the forward portion of the center cabin and in the middle of the outboard cabins adjacent to the middle doors.

Four lavatories are located at the aft end of the outboard cabins. These can be reached from adjacent cabins via the aft cross-aisle. A total for four more lavatories are located elsewhere: one in the middle of the port cabin; one at the very front of the center cabin; and two at the front of the business class cabin.

Closets, indicated by "C" in Figure 30, are located at the front of the first and business class cabins.

An enclosed pilot rest area with double bunk beds is located immediately aft of the crew compartment. A crew rest area is located on the lower deck just ahead of the cargo compartment. This is reached via a steep staircase just in front of the starboard galley in the forward center cabin.

Cabin attendant seats are located near to each of the six exit doors. Three additional seats are located at the front port door, the starboard middle door and at the center of the aft cross aisle.

There are no passenger windows or skylights. There are small windows in each exit door to assess conditions before emergency evacuation.

Freighter

The main deck of the BWB freighter is shown in Figure 31. The lower deck arrangement is generally the same as shown in Figure 29.

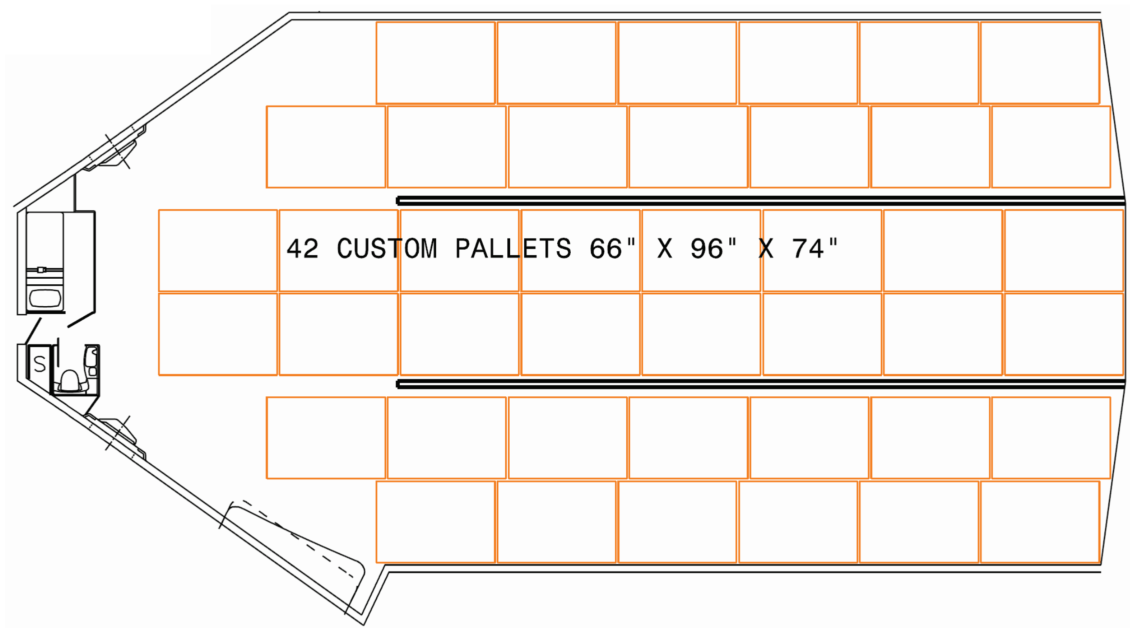
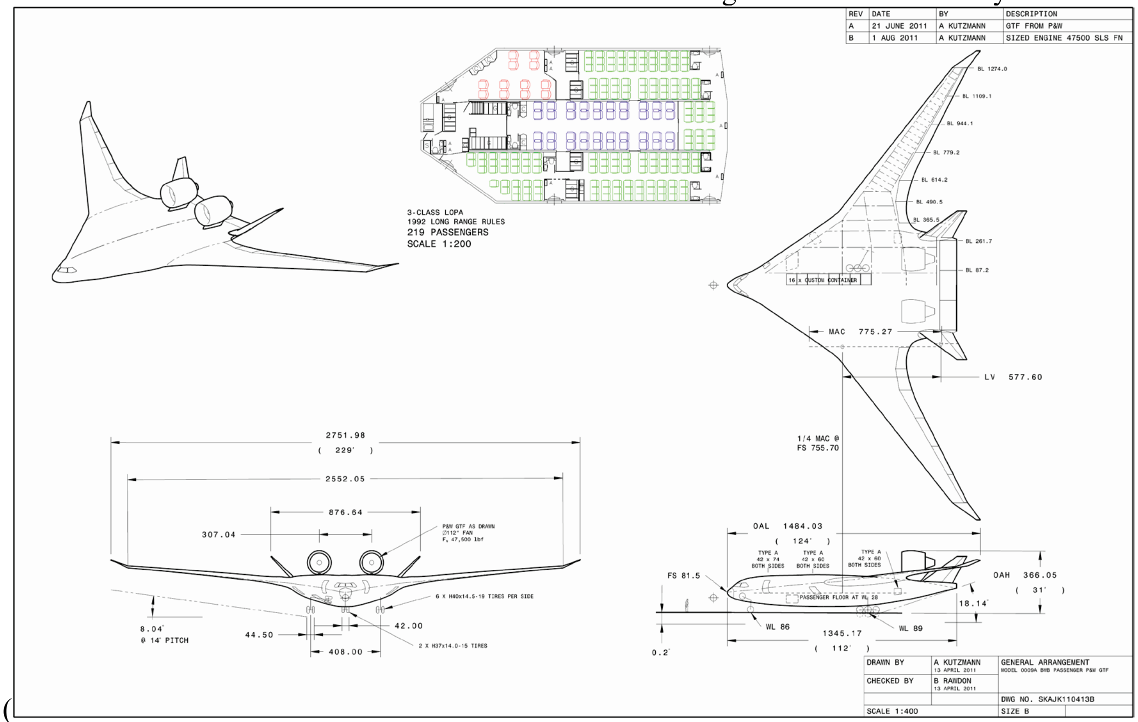


Figure 31. BWB Main Deck Cargo Arrangement

The main deck retains the pilot rest compartment and lavatory from the passenger version. Cargo unit load devices (ULD) enter the cabin through a 122" wide by 84" high cargo door on the left side of the forward centerbody. Omnidirectional rollers permit the cargo to move laterally and then aft into any of six rows of ULDs. The cargo handling system is otherwise conventional.

2.3.4.1.8 Acoustic Features

The 2025 BWB has several design features intended for reducing noise, especially the engine noise. Engine placement on the upper-aft center body provides acoustic shielding in the forward, lateral and downward directions. Upper mounting also avoids the reflection of engine noise downward from the airframe. The twin vertical stabilizers are located at the outboard edge of the aft center body. In the side view (Figure 28), the stabilizers are just aft of the engine nozzles, overlapping the most energetic efflux. The intention of the arrangement is to shield some portion of the exhaust noise from the sideline. The leading edge Krueger flaps are sealed and have a cover over the opening created by extension. This is intended to reduce turbulence and noise from separation on the aft side of the device.



2.4 Design and Evaluation Process

2.4.1 Introduction

The general purpose of the study is to assess benefits provided by the variations in aircraft designs. Variations include technological advancements, configuration, engine type, operating rules, wing aspect ratio, and wing span. Individual airplane variations are selected with the object of providing a direct or "apples-to-apples" comparison of variables. This objective is generally but not universally achieved by the study.

Figure 32 illustrates the four major airplane types investigated. Within each box, variations on that airplane type are listed.

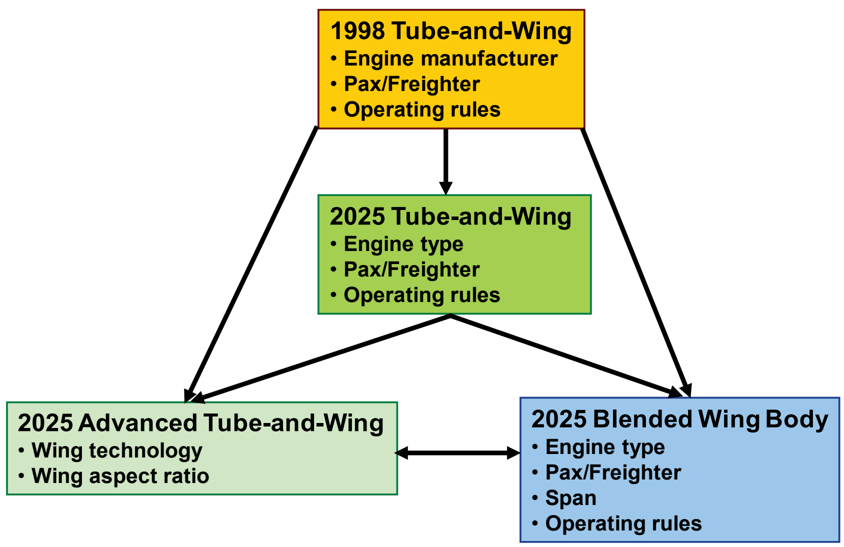


Figure 32. Study Airplane Variations

A group of 15 "core" study airplanes are developed. Additional "trade study" airplanes are developed to investigate the effect of certain variables. Figure 33 is a matrix of the core study airplanes. This matrix is read vertically and horizontally. The columns are described first.

EIS	Config	P&W Engines	RRNA Engines		Context
1998 EIS	Convent'l Config	-0001 OP Pax Twin TF			1998 OP
		-0001 Pax Twin TF	-0003 Pax Twin TF		NRA Ref
			-0004 Cargo Twin TF		
2025 EIS		-0005 Pax Twin GTF	-0007 Pax Twin ATF		
		-0006 Cargo Twin GTF			
		-0005 NG Pax Twin GTF			Next Gen
	Advanced Conventional Configuration		-0027A Pax Twin ATF		NRA Ref
	BWB	-0009A Pax Twin GTF	-0013 Pax Tri OR M0.85	-0015 Pax Tri OR M0.80	
		-0010 Cargo Twin GTF			
		-0011 Pax Tri GTF			
		-0009A NG Pax Twin GTF			Next Gen
	Preferred System Concept				NRA Ref
	Preferred System Concept Evaluated within Next Gen				Next Gen
	Preferred System Concept Resized for Next Gen; Possible New Reference Configuration				

Figure 33. Study Airplanes

"EIS" refers to the "entry into service" date. This date corresponds to a package of technological developments described in the Task 3 section of this report. These apply to structure, aerodynamics and propulsion technologies.

"Config" refers to the airplane configuration. Three configurations are investigated. The "conventional configuration" is described in Sections 2.3.1 and 2.3.2. The "advanced conventional configuration" is described in Section 2.3.3. The BWB configuration is described in Section 2.3.4.

"P&W Engines" refers to engine designs provided by Pratt & Whitney. These are a 1998 turbofan and a 2025 geared turbofan. Note that no P&W engine is studied on the advanced conventional configuration.

"RRNA Engines" refers to engine designs provided by Rolls-Royce North America. These are a 1998 turbofan, a 2025 advanced turbofan, and a 2025 open rotor. Note that open rotors were studied at Mach 0.85 and at Mach 0.80.

"Context" refers to the operating rules as described in Section 2.2.2. Note that 1998 OP rules are applied only to the 1998 T&W-0001 OP configuration. Next Gen rules are applied only to the 2025 T&W-0005 NG and BWB-0009A NG configurations.

Rows are now described:

Four 1998 EIS airplanes are developed. All have conventional configurations; one is a freighter and one uses 1998 OP operating rules.

The remaining airplanes have a 2025 EIS. Four airplanes have a conventional configuration. Two are freighters. Only one advanced conventional configuration is studied – a passenger airplane. Six BWB configurations are studied, one of which is a freighter. All BWBs have geared turbofan or open rotor engines.

1998 OP rules apply only to one 1998 EIS conventional configuration. NRA Reference rules apply to 12 of the airplanes including all four configuration types. Next Gen rules apply to one 2025 conventional configuration and one BWB configuration.

2.4.2 Method and Order of Development

Benefits of airplane and rules variations are assessed by comparing the numerous "core" airplanes described in the introduction above. Detailed advanced design methods are employed to reach the best possible design for each airplane type. Results reveal the effect of design and rules variations.

What constitutes "best" in this process is a bit complicated. Three measures of merit are described in Section 2.2.3 – fuel consumption, noise and LTO NO_x. Noise is a consideration in the technology selection of all 2025 airplanes and in the arrangement of the BWB and advanced conventional configurations but noise reduction is not integrated into the optimization process. Rather, all airplanes are optimized for fuel consumption and noise is evaluated only on selected, completed airplanes. LTO NO_x is also evaluated on the completed airplanes – the assumption is that minimizing fuel consumption provides close to the minimum LTO NO_x.

The advanced design method employed is described below. In general, the method falls into four phases. In the first phase, the geometry of the airplane is defined. This involves the configuration designer or "configurator", sometimes the aerodynamics designer and stability and control. In the second phase, the weight, aerodynamics and propulsion characteristics are parametrically modeled. In the third phase, these parametric models are "flown" in a mission simulator. Variations in airplane characteristics are systematically varied to find the combination resulting in minimum fuel burn. In the last phase, selected final airplanes are evaluated for noise and LTO NO_x.

In addition to the "core" airplanes, a number of offshoots are investigated to determine the benefit of additional variations.

2.4.2.1 Configuration Design

In the configuration design phase the initial airplane geometry is defined. The designer strives to harmonize or balance the "kit of parts" that makes up the airplane so that the initial airplane is as close as possible to the final, sized airplane. The process used in this study is somewhat different for the BWB versus the conventional and advanced conventional configurations. These are described briefly below.

2.4.2.1.1 Conventional and Advanced Conventional Configurations

Configuration design of these airplanes relies on decades of experience. Especially for the conventional configuration, existing solutions for airplane integration are adopted. These solutions are adjusted to accommodate the advanced conventional configuration.

These configurations are characterized by the relative independence of major components such as the fuselage, wing, tails and engines. Each is generally developed independently and fit together only at the end of the phase.

The fuselage is built around its cross section. A cross section is developed that efficiently encloses all three passenger classes and provides sufficient lower deck cargo volume. The size of the cross section determines the fuselage length to diameter ratio. A reduction in cross section results in a longer fuselage and vice-versa, so cross section size is a powerful variable. Given a cross section, the fuselage nose and aft section are generated that provide acceptable aerodynamics at the mission Mach number and provide adequate "meat" to support the tails. The exact length of the fuselage is determined by developing a detailed layout of passenger accommodations.

In the case of the double-deck advanced configuration, the increased number of design variables leads to more experimentation. Nonetheless, the process is generally the same as for the conventional configuration.

The initial wing design is chosen based on anticipated technology levels. While overall wing characteristics such as aspect ratio and airfoil technology are carefully selected, exact details of the wing design are not critical to estimated performance because performance is also based on anticipated trend levels and not on the detailed configuration geometry.

Tail geometry and sizing follows convention using simplified methods.

For the conventional configurations, engine placement is conventional although the very large diameter geared turbofan engines force adjustments to wing dihedral shape and landing gear length to provide adequate ground clearance. Engine placement on the advanced conventional configuration is driven by acoustic shielding and structural considerations. The engine inlet lip is located just ahead of the wing trailing edge and alongside the fuselage. The engine pylon is integrated with the upper deck floor structure.

Landing gear design and integration is conventional.

2.4.2.1.2 Blended Wing Body

Configuration design of BWBs relies on years of experience, experimentation and analysis. This process is much more integrated than for the conventional configurations – the design of each component tends to influence the entire airplane. For example, the fuselage and wing are aerodynamically integrated so it is not possible to develop the fuselage or wing in isolation. Collaboration with an aerodynamics designer is required. Considerably more iteration is required to reach a favorable design.

2.4.2.2 Aerodynamic Design

Aerodynamic designers collaborate with configurators to define the aerodynamic shape of the initial airplanes.

In the case of the conventional and advanced conventional configurations, the aerodynamic designer's roll is limited to the selection of sweep angle, airfoil technology, thickness to chord ratio, aspect ratio and planform concept. No detailed design is performed for two reasons. 1) A detailed design is complicated by static and dynamic aeroelastic effects, demanding extensive structural design and mass properties iteration. This is well beyond the scope of an advanced design study. 2) Aerodynamic performance is determined based on trends from very well developed production wings.

The aerodynamic designer is considerably more involved in the design of advanced BWB configurations. Working with the configuration designer, a three-dimensional wing is created to define a representative outer mold line. This surface represents the twist and lift distribution of a 1-g shape without delving into the deflected shape as seen in front view or considering off-design effects of wing flexure.

The aerodynamic design process employs computational fluid dynamics (CFD) analysis as well as multi-disciplinary optimization (MDO). The MDO process respects payload volume constraints and the influence of structural weight but focuses primarily on aerodynamic performance (L/D) and pitch balance as a metric. The process' ability to determine optimum wingspan is limited so wingspan is generally determined by a blend of engineering judgment and experimentation.

2.4.2.3 Stability and Control

Stability and control analysis is applied in this study to increase the fidelity of each design's performance.

For the conventional configurations the primary consideration is accurate tail sizing – this influences airplane weight and drag.

Another consideration, especially for the rear-engine advanced conventional configuration, is the longitudinal placement of the wing on the fuselage. This analysis assures that the CG travel and tail size are harmonized. Wing location is a concern because it affects tail moment arm. This in turn affects tail sizing, weight and drag.

2.4.2.4 Mass Properties

Mass properties provides a parametric model for each study airplane's weight based on the airplane's mission, geometry, thrust and weight. For some designs, additional information is generated, including center of gravity and mass moment of inertia data.

Conventional airplane weights are primarily estimated using an extensive, detailed weights database. Weights from this database are adjusted to account for specific airplane technologies and features. For example, structural weight for the 2025 EIS airplanes is adjusted to account for lighter composite materials. Weights data from the engine manufacturers is used to characterize engine weight.

BWB weights are estimated using a parametric model. This model is developed from a detailed finite element model (FEM) and considers areal weights, bending material and concentrated loads in the airframe weight buildup.

Parametric weights models are typically adjusted during the sizing process. Initial weights are provided with linear slopes to adjust for variations in geometry, thrust and weight. Following the initial sizing, weights are "re-centered" and slopes are adjusted to provide a more accurate model. This re-centering process continues until acceptable convergence is achieved.

2.4.2.5 Aerodynamics Performance

Aerodynamics provides a parametric aerodynamic model for each airplane based on geometry and aerodynamic features. This model includes maximum lift coefficient (C_{Lmax}), a drag polar and compressibility effects.

2.4.2.6 Propulsion

Propulsion system models are developed based on data provided by the engine companies. The wide scope of engine architectures studied prevents the use of medium fidelity parametric cycle models. Instead, tabular data packs are provided by the engine companies based on an initial set of installed engine data requirements. These data include basic thrust and fuel flow along with inlet and exhaust flow rate for a range of flight conditions and power settings to cover the expected flight profile. First order sizing coefficients are also provided, allowing for simple thrust scaling of primary propulsion variables such as fan diameter, engine weight and length. The engine company also provides physical definitions of the engine in the form of installation sketches which define the characteristic geometric dimensions of the engine, and nacelle if appropriate.

Installation effects are applied to the data as required for inlet and nozzle performance schedules, bleed air and shaft power extraction, and interference effects. Nacelle drag and weight estimates, along with the scaling coefficients are provided for the aerodynamic and weights models.

When using scaling coefficients ("rubberized" engine), results become less accurate with larger scale factors. Plus or minus 10% is the preferred maximum range.

2.4.2.7 Sizing and Performance Evaluation

Once aircraft geometry is defined and weight, aerodynamic and propulsion models are complete, airplane performance is simulated to determine performance. For each airplane, the best combination of characteristics is determined by multiple iterations.

Possible variations in airplane design depend on airplane configuration. For the conventional and advanced conventional configurations, variations are wing area and reference thrust. Wing geometric features such as sweep and thickness-to-chord ratio remain fixed as wing area is varied. Tail sizing varies with wing area according to stability and control algorithms. Engine geometry varies with reference thrust. The fuselage remains fixed. For the BWB, geometry of the wing-body and tails remains fixed – only thrust and resulting engine geometry are varied.

An example sizing product is shown in Figure 34. This plot shows contours of block fuel (in orange) and MTOGW (in blue) on a two dimensional field with wing area on the horizontal axis and thrust on the vertical axis. Constrained regions for initial cruise altitude, balanced field length and climb distance are shown in cross-hatching. The selected design point is circled in red. This point provides the minimum fuel burn while observing all constraints.

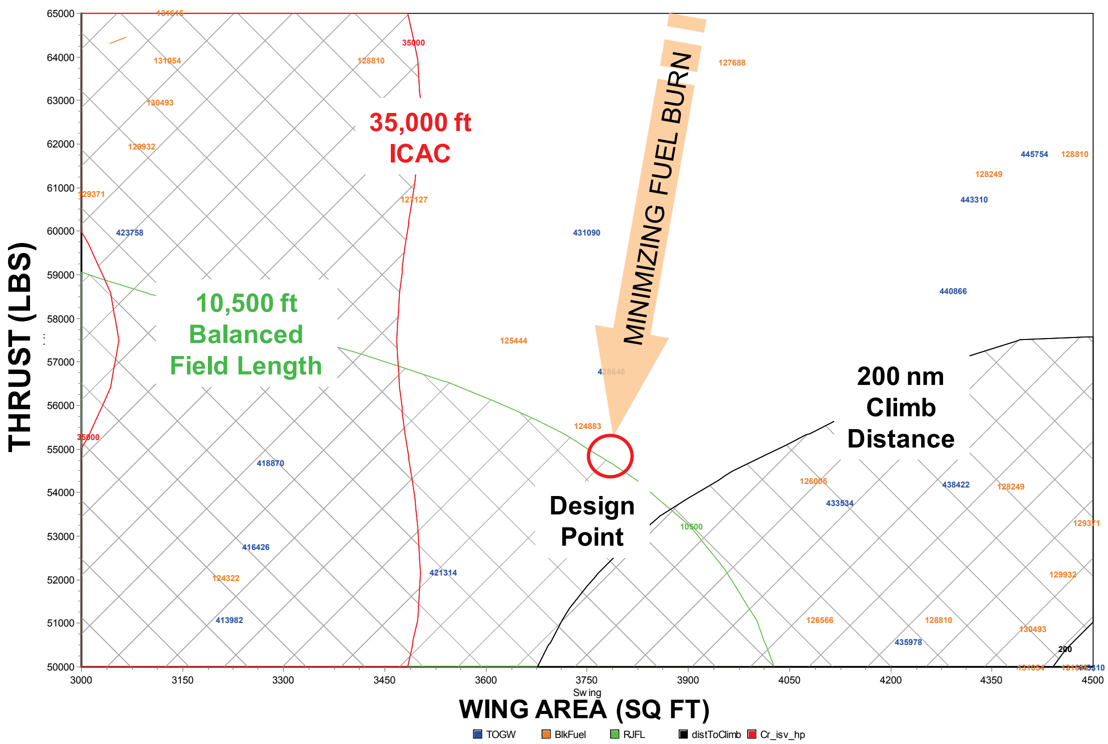


Figure 34. Example Sizing Plot

2.4.2.8 Acoustics

Acoustics analysis is performed on completed, sized airplanes. The primary product is certification noise levels and margins: approach, sideline, flyover and cumulative. Noise levels within the airplane are not considered.

Trajectory output from CASES including flight path, angle of attack, thrust levels and airspeed are used in the acoustic analysis. Airplane geometry and acoustics features are also considered.

A detailed description of the acoustics analysis and results is provided in Section 2.9.

2.4.2.9 Landing and Takeoff Emissions

Landing and takeoff oxides of nitrogen (LTO NO_x) are based on the final sized thrust, the engine cycle pressure ratio and the combustor technology. The engine companies are provided with the final sized engines and they provide their estimate of the LTO NOx emissions. A fundamental conflict exists between engine cycles that have low SFC and low NOx. As cycle pressure ratios increase to achieve higher thermal efficiency, NOx emission increase when the same combustor technology is used. Achieving reduced NOx levels with low SFC will require advanced combustor technology.

2.4.3 Derivatives and Trade Studies

The study is built around four key configurations. All other airplanes in the study are derived from these four:

- 1998 conventional configuration -0001
- 2025 conventional configuration -0005
- 2025 advanced conventional configuration -0027A
- 2025 BWB configuration -0009A

In Sections 2.5, 2.6 and 2.7 below, each of the four airplanes is described in some detail.

Derivations include freighters, propulsion system types, engine count and cruise Mach number.

2.4.3.1 Freighters

Three freighter derivatives are created: a 1998 conventional configuration (-0004); a 2025 conventional configuration (-0006); and a 2025 BWB configuration (-0010).

Each freighter has the same geometry, reference thrust and MTOGW as its parent passenger airplane. The airframes are modified with a cargo door, cargo floor, cargo barrier and structural reinforcements to increase the MZFW. These constraints and modifications are consistent with commercial freighter practice.

2.4.3.2 Engine Type

The baseline 1998 conventional configuration (-0001) uses a Pratt & Whitney (P&W) high bypass ratio turbofan. An alternative high bypass ratio engine by Rolls-Royce North America (RRNA) is used on a separately-sized passenger airplane (-0003) and its freighter derivative (-0004). The use of two engines on the 1998 baseline airplane reduces uncertainty in the study's basis for fuel consumption.

Two engines are used on the 2025 conventional configurations. A P&W geared turbofan (GTF) is used on the baseline airplane (-0005). A RRNA advanced turbofan (ATF) represents an alternate approach (-0007). The GTF engine has a very large fan and very high bypass ratio. It is relatively fuel efficient and quiet but heavy. The ATF is considerably lighter but less fuel efficient and not as quiet.

Only the RRNA ATF is used on the advanced conventional configuration (-0027A).

Two engine types are used on the 2025 BWB designs: the P&W GTF (e.g. -0009A) and a RRNA open rotor (e.g. -0013). Use of the GTF provides a direct performance comparison with the 2025 conventional configurations. Open rotor engines are investigated for their potential fuel consumption advantages. Open rotor engines are pursued only on the BWB design because it appears to offer feasible propulsion-airframe integration and provides increased acoustic shielding relative to conventional configurations. Shielding is important due to the higher expected noise signature from the open rotor blades.

2.4.3.3 Engine Count

Two engines are used on all conventional and advanced conventional configurations. This is consistent with commercial practice for a mid-size, long-range airliner.

The use of three engines on conventional configurations can provide certain advantages at the cost of a somewhat awkward configuration. The baseline BWB configuration has two engines, but a three engine version (-0011) explores potential three-engine benefits without fundamental configuration changes.

The baseline open rotor BWB (-0013) has three engines. Relative to two engines, three engines reduces rotor diameter and thrust offset. An informal trade study examined a twin-engine open rotor.

2.4.3.4 Other Trade Studies

Additional trade studies investigate alternative design features. Trade studies described below are lower in technical fidelity than the core studies described above.

2.4.3.4.1 1998 Operational Mission

The effect of the 1998 Operational mission on the baseline 1998 conventional configuration -0001 is determined. This alternate mission is described in Section 2.2.2.2

2.4.3.4.2 BWB Wing Span

The 229.3 ft wing span of the core BWB design (-0009A) is chosen by engineering judgment. Several alternative BWBs are designed with a considerably longer 261.8 ft wing span to explore its effect on fuel consumption, weight and thrust. These designs are based on the same wing-body.

2.4.3.4.3 Twin Open Rotor BWB

Performance of the three open-rotor BWB is hampered by relatively little engine core efficiency. Core efficiency is hampered by small core dimensions and consequent tip losses. A two engine open rotor is designed to increase core size and reduce tip losses.

2.4.3.4.4 Advanced Conventional Configuration with Advanced Technology Wing

The benefit of an advanced technology wing on the advanced conventional configuration is investigated. This is configuration -0027.

2.4.3.4.5 Aspect Ratio Trade Study – Advanced Conventional Configuration

The effect of an increased aspect ratio is investigated on configuration -0027.

2.4.3.4.6 BWB with Advanced Turbofan Engine

The effect of replacing geared turbofan engines with advanced turbofan engines is determined.

2.5 Baseline 1998 EIS Conventional Configurations

Results for four configurations are described in this section. The four airplanes are:

- -0001 passenger airplane with P&W engines
- -0001 OP passenger airplane with P&W engines flown with 1998 OP mission rules
- -0003 passenger airplane with RRNA engines
- -0004 freighter with RRNA engines

2.5.1 Design and Performance

2.5.1.1 Configuration

The overall configuration of the four airplanes is the same and is described in detail in Section 2.3.1.1. The general arrangement of -0001 is shown again in Figure 35, -0003 is shown in Figure 36, and -0004 is shown in Figure 37. -0001 OP is similar to the -0001 and is not illustrated. Characteristics of the three illustrated airplanes are summarized in Table 4.

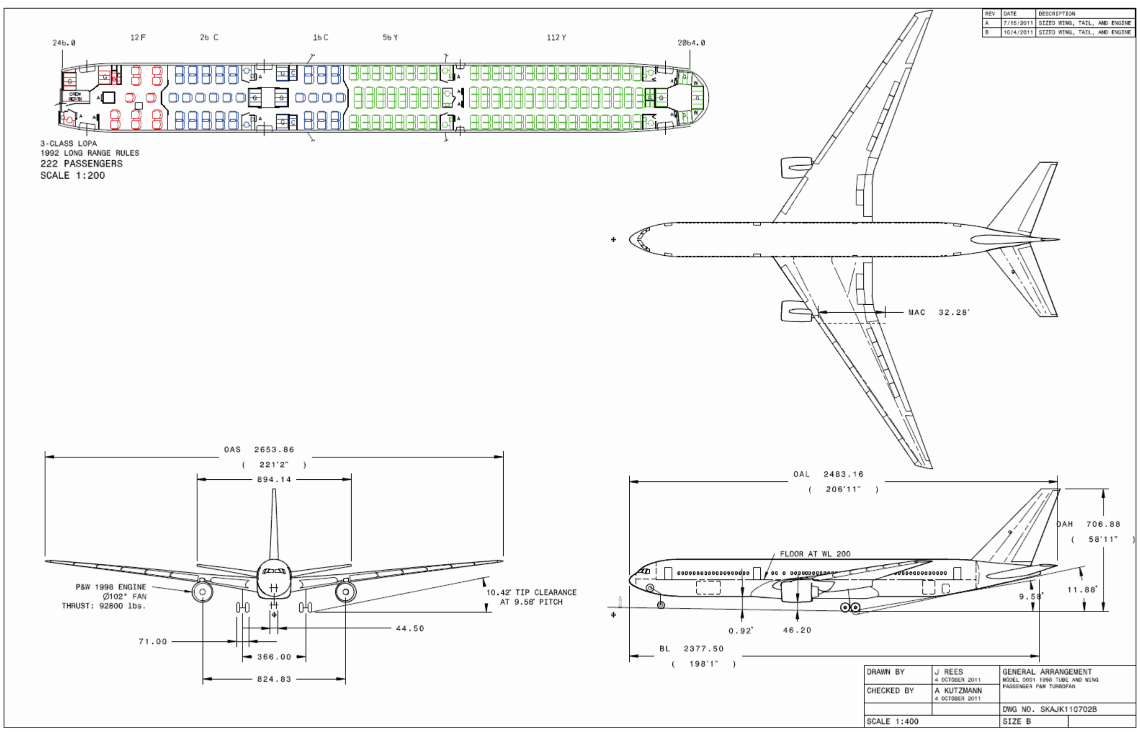


Figure 35. General Arrangement Drawing – 1998 T&W-0001 Passenger

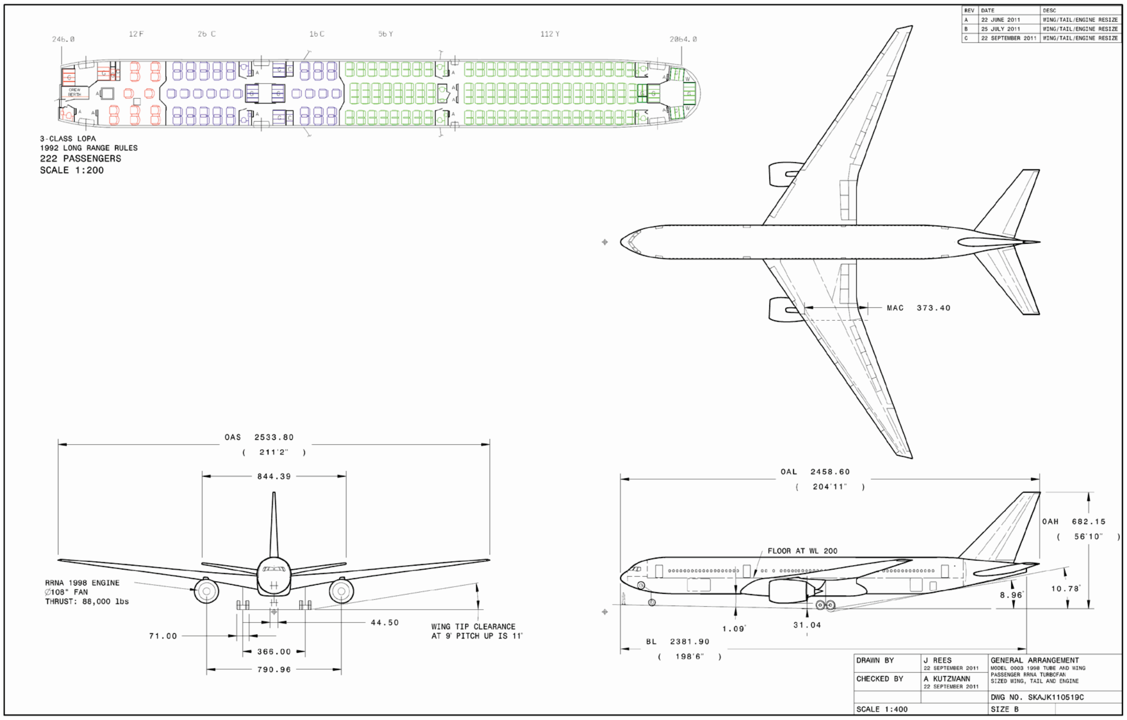


Figure 36. General Arrangement Drawing – 1998 T&W-0003 Passenger

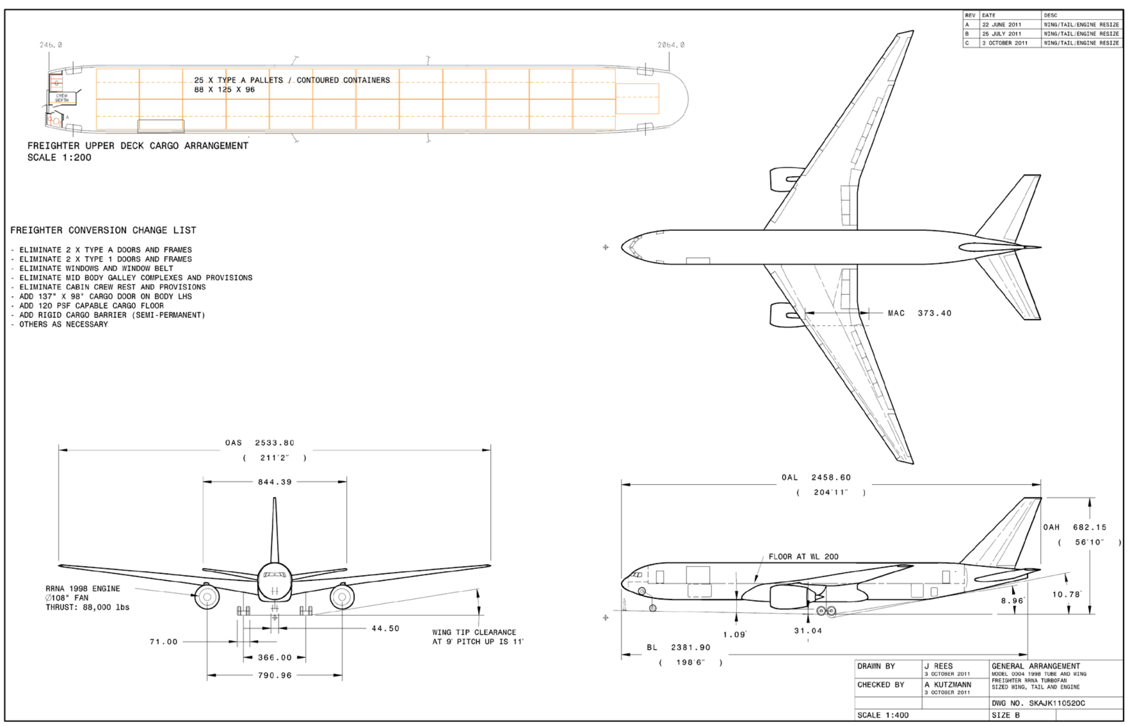


Figure 37. General Arrangement Drawing – 1998 T&W-0004 Freighter

Table 4. Summary Airplane Characteristics

	-0001 Passenger P&W TF	-0003 Passenger RRNA TF	-0004 Freighter RRNA TF
Wing Span (ft)	221.4	211.4	211.4
Wing Area (gross) (ft^2)	5808.3	5322.1	5322.1
MTOGW (lb)	624,154	581,535	581,535
OEW (lb)	291,171	268,645	243,507

Differences between the -0001 and -0003 airplanes are due solely to their different engines. The longer effective range and increased margins of the 1998 Operational mission compared to the NASA reference mission described in Section 2.2.2.1 are reflected in the larger size and greater weights and thrust of the -0001 OP airplane compared to the -0001 airplane.

Comparison of the -0003 passenger airplane with the -0004 freighter shows their common geometry, engines and MTOGW. The lighter empty weight (OEW) of the freighter reflects the absence of passenger accommodations such as seats, bagracks, galleys and lavatories.

2.5.1.2 Aerodynamic Design

Aerodynamic design of the 1998 airplanes is limited to selection of the wing geometry as discussed in Section 2.4.2.2.

2.5.1.3 Stability and Control

Stability and control analysis for 1998 conventional configurations is limited to horizontal and vertical tail sizing. Basic stability and control is assumed to be inherent in the configuration.

2.5.1.3.1 Horizontal Tail Sizing

Horizontal tail sizing is based on trend data from existing conventional transports. Trend data is referenced primarily to fuselage and wing geometry and on the required center of gravity range.

Airplane center of gravity range is estimated on the basis of the "loadability parameter". This is the allowable CG range of the payload expressed as a fraction of the flat payload floor length. These range from approximately 0.07 to 0.20 for existing airliners, with most falling between 0.10 and 0.15. Airplane CG range is estimated at maximum zero fuel weight (MZFW) when payload CG travel most affects the airplane CG. Payload weight also affects airplane CG, so alternative payload weights are examined.

2.5.1.3.2 Vertical Tail Sizing

Vertical stabilizer sizing is also based on trend data from existing conventional transports.

The vertical stabilizer may be sized by two considerations. One pertains to keeping the airplane on the runway during a takeoff roll when one engine fails at the worst possible moment. In this simplified (static) analysis, the vertical stabilizer must counter the thrust moment by rudder power alone – the airplane cannot yaw. This is the "Vmcg" requirement (minimum control speed on the ground).

The second pertains to simple yaw stability. This is based relative proportions of the wing and fuselage geometry.

The relatively long takeoff field length and high takeoff speed result in a vertical tail sized by stability and not Vmcg.

2.5.1.4 Mass Properties

Mass properties methods are described in Section 2.4.2.4. A short group weight statement for the -0001 passenger airplane is shown in Table 5. Table 6 shows the statement for the -0003 airliner and Table 7 shows the freighter -0004.

Table 5. Short Group Weight Statement -0001 Airliner

ERA 0001 1998 EIS T&W PASSENGER P&W TF	
DESCRIPTION	**WEIGHT**
WING	77,339
TAIL	10,862
FUSELAGE	45,480
LANDING GEAR	25,917
PYLON	7,153
PROPULSION	47,573
FUEL SYSTEM	2,496
FLIGHT CONTROLS	7,588
AUXILIARY POWER UNIT	1,400
HYDRAULICS	3,537
PNEUMATICS	1,398
ELECTRICAL	3,806
INSTRUMENTS	1,398
AVIONICS & AUTOPILOT	2,563
FURNISHINGS & EQUIPMENT	30,232
AIR CONDITIONING	3,434
ANTI-ICING	653
MANUFACTURER'S EMPTY WEIGHT (MEW)	**272,831**
STANDARD & OPERATIONAL ITEMS	18,340
OPERATIONAL EMPTY WEIGHT (OEW)	**291,171**
USABLE FUEL	282,983
DESIGN PAYLOAD	50,000
MAX TAKEOFF GROSS WEIGHT (MTOGW)	**624,154**

Table 6. Short Group Weight Statement -0003 Airliner

ERA 0003 1998 EIS T&W PASSENGER RRNA TF	
DESCRIPTION	**WEIGHT**
WING	70,924
TAIL	9,470
FUSELAGE	45,065
LANDING GEAR	23,977
PYLON	5,865
PROPULSION	37,682
FUEL SYSTEM	2,294
FLIGHT CONTROLS	7,041
AUXILIARY POWER UNIT	1,400
HYDRAULICS	3,278
PNEUMATICS	1,398
ELECTRICAL	3,806
INSTRUMENTS	1,398
AVIONICS & AUTOPILOT	2,563
FURNISHINGS & EQUIPMENT	30,232
AIR CONDITIONING	3,434
ANTI-ICING	595
MANUFACTURER'S EMPTY WEIGHT (MEW)	**250,423**
STANDARD & OPERATIONAL ITEMS	18,222
OPERATIONAL EMPTY WEIGHT (OEW)	**268,645**
USABLE FUEL	262,890
DESIGN PAYLOAD	50,000
MAX TAKEOFF GROSS WEIGHT (MTOGW)	**581,535**

Table 7. Short Group Weight Statement -0004 Freighter

ERA 0004 1998 EIS T&W CARGO RRNA TF	
DESCRIPTION	**WEIGHT**
WING	70,924
TAIL	9,470
FUSELAGE	45,091
LANDING GEAR	23,977
PYLON	5,865
PROPULSION	37,682
FUEL SYSTEM	2,294
FLIGHT CONTROLS	7,041
AUXILIARY POWER UNIT	1,400
HYDRAULICS	3,278
PNEUMATICS	1,398
ELECTRICAL	3,806
INSTRUMENTS	1,398
AVIONICS & AUTOPILOT	2,563
FURNISHINGS & EQUIPMENT	21,432
AIR CONDITIONING	3,434
ANTI-ICING	595
MANUFACTURER'S EMPTY WEIGHT (MEW)	**241,648**
STANDARD & OPERATIONAL ITEMS	1,858
OPERATIONAL EMPTY WEIGHT (OEW)	**243,507**
USABLE FUEL	238,028
DESIGN PAYLOAD	100,000
MAX TAKEOFF GROSS WEIGHT (MTOGW)	**581,535**

Weight differences between the -0001 and -0003 airliners reflect only the effect of different engines – without different engines the airplanes would be identical. The primary difference between engines is in their weight. The -0001 engines are some 10,000 lb heavier than those of the -0003. This difference reflects the both the greater engine weight and the re-sizing effect from the greater weight. Extra engine weight results in greater wing and tail areas so these are also significantly heavier.

Weight differences between the -0003 airliner and the -0004 freighter are primarily in furnishings and equipment and in standard and operational items. The freighter is considerably lighter in these groups.

2.5.1.5 Aerodynamics

Aerodynamics methods are described in Section 2.4.2.5. This section describes aerodynamics results for two 1998 EIS conventional configurations: the -0001 and -0003 passenger airplanes. The -0004 freighter derivative has the same geometry as the -0003 airliner from which it is derived so its aerodynamic characteristics are the same. The -0001 OP airplane is a lower fidelity trade study – aerodynamic results are not reported.

Aerodynamic results are used in performance estimation, acoustics analysis and the landing and takeoff NO_x estimates.

The -0001 has a reference wing area of 5440 ft^2; -0003 is smaller at 4960 ft^2.

2.5.1.6 Propulsion

The 1998 conventional aircraft use engines modeled after actual engines in service. Detailed technical features and performance characteristics of these engines are closely held by their manufacturers. Advanced design studies are approximate in nature – approximations of the engine data are used in this study and are summarized below for the sized engines.

2.5.1.6.1 Propulsion System Description

The Pratt and Whitney engine is on the -0001. The Rolls-Royce North America engine is on the -0003 and -0004.

2.5.1.6.2 Propulsion System Performance

The “representative slice” through the engine data follows a single speed altitude trajectory in three phases: takeoff, climb and cruise. The trajectory for the -0001, -0003 and -0004 airplanes is illustrated in Figure 38. Altitude is barometric; airspeed is shown in true knots on the left scale and Mach number on the right scale. This plot is a foundation for the thrust and efficiency plots that follow. In general, speed increases with altitude. Between 30,000 and 35,000 ft true airspeed declines slightly as the speed of sound declines – the airplane flies Mach 0.85 from 30,000 to 40,000 ft.

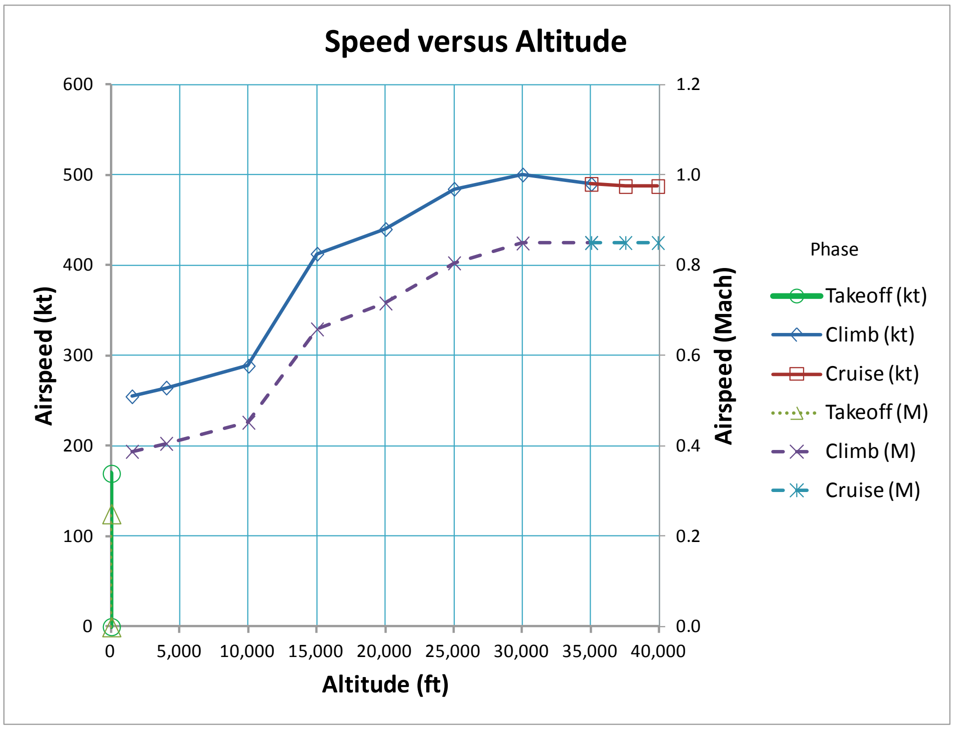


Figure 38. Speed versus Altitude for -0001 and -0003 Propulsion

2.5.1.6.3 Landing and Takeoff Emissions

LTO NOx emissions for the 1998 baseline engines are shown in Figure 39. The 1998 baseline engines represent the same emissions performance as the Trent 800 and PW4090. The LTO NOx limit for those engines was not CAEP/6. An approximate CAEP limit for the low OPR range is also shown.

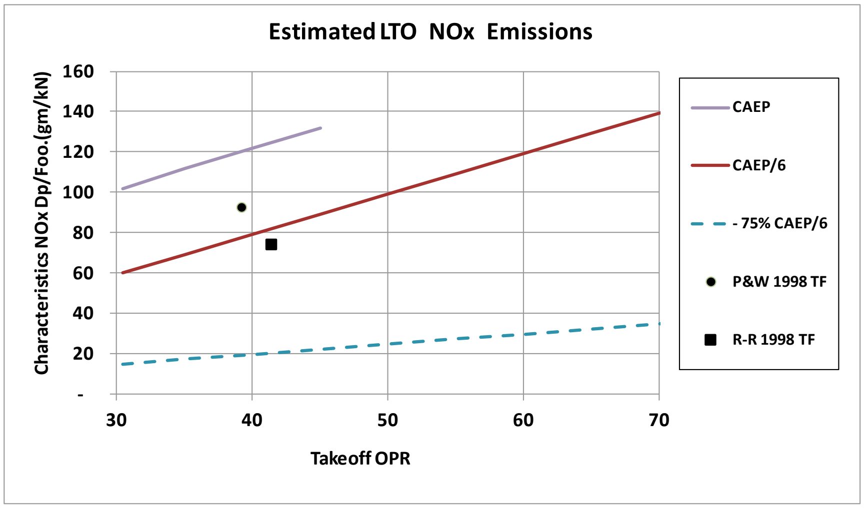


Figure 39. LTO NO_x for 1998 Airplanes

2.5.1.7 Sizing and Performance Evaluation

Sizing and performance evaluation are performed in two phases. The sizing process, as described in Section 2.4.2.7, finds the combination of airplane characteristics that provides the greatest measure of merit. The evaluation process quantifies the performance of the best version of each airplane.

2.5.1.7.1 Mission Performance

Tabular results for -0001, -0001 OP, -0003 and the -0004 freighter are shown in Table 8 and Table 9. These results are not discussed in great detail here – comparison of all airplanes is provided in Section 2.10.

Table 8 summarizes the basic aircraft characteristics as well as the fuel consumption performance. Descriptions of key characteristics follow.

"Fuel Load" is the entire quantity of usable fuel onboard at engine start – this includes reserve fuel. "Block Fuel Burned" is the quantity of fuel consumed during the entire flight from gate to gate.

"Nautical Mile/Block Fuel Burned" is simply the range divided by block fuel burned. "Nautical Miles * PL/lb Fuel" is the product of range and payload divided by block fuel burned. This is a measure of productivity per unit energy consumed – greater is better. "Ton Payload * Nautical Miles/lb Fuel" is the same as the prior measure divided by 2000 so that the payload is in tons. This measure is used prominently in prior Boeing studies.[5]

"TO Ref FN @ SL, 0.0, +27F" is the takeoff reference thrust at sea level, Mach number = 0.0 on a day 27°F warmer than standard. This is for one engine.

"Thrust to Weight Ratio" is the reference thrust divided by MTOGW. "Wing Loading" is MTOGW divided by the reference wing area.

Comparing fuel efficiency in terms of Ton Payload * NM / lb Fuel: The detrimental effect of the 1998 OP mission compared to the NASA Reference mission is shown in the reduction in efficiency from 0.78 to 0.71 ton-nm/lb fuel. The lighter -0003 is considerably more efficient than the -0001 with 0.84 ton-nm/lb fuel compared to 0.78. The -0004 freighter benefits tremendously from a combination of increased payload and shorter ranger. Its efficiency of 1.63 is nearly twice that of its parent airliner's 0.84.

Table 8. Sized 1998 Configuration Characteristics

		Final-2	Operational-2	Final-6	Cargo-6
Tare weight included in Payload		**ERA-0001-PAX**	**ERA-0001 OP-PAX**	**ERA-0003-PAX**	**ERA-0004-Cargo**
Reference	**Required**	**1998 T&W**	**1998 T&W**	**1998 T&W**	**1998 T&W**
	Perf.	**Mcr=0.85**	**Mcr=0.85**	**Mcr=0.85**	**Mcr=0.85**
		P&W TF	**P&W TF**	**RR TF**	**RR TF**
MTOGW (lb)		624154	665500	581535	581535
OEW (lb)		291170	302787	268645	243507
Payload (lb)	**50k/100k**	50000	50000	50000	100000
Fuel Load at MTOGW (lb)		282984	312713	262890	238028
Range (nm)	**8000/6500**	8000	8000	8000	6979
Block Fuel Burned (lb)		254955	283494	238367	214138
Nautical Mile/Block Fuel Burned (nm/lb)		0.03138	0.02822	0.03356	0.03259
Nautical Miles * PL/lb Fuel		1568.90	1410.96	1678.08	3258.93
Ton Payload * Nautical Miles/lb Fuel		0.78	0.71	0.84	1.63
Reference Wing Area (sq ft)		5440	5840	4960	4960
Wing Aspect Ratio		8.7222	8.7222	8.7222	8.7222
TO Ref FN @ SL, 0.0, +27F (lbf/eng)		92800	97400	88000	88000
Number of Engines		2	2	2	2
Thrust to Weight Ratio (lbf/lbm)		0.30	0.29	0.30	0.30
Wing Loading (lb/sq ft)		115	114	117	117
Time to climb to 35000 ft (min)		25.152	25.92	28.062	28.062
Dist. to climb to 35000 ft (nm)	**200**	178.27	183.82	198.6	198.6
R/C at 35000 ft (fpm)		519	494	524	524

Cruise performance is summarized in Table 9. Performance is reported at three points: initial cruise is the very beginning of cruise after the transition from climb; mid-cruise is at the approximate mid-point of the cruise leg in terms of distance; final cruise is at the very end of cruise right before descent is initiated. The NASA Reference and Operational missions of the 1998 airplanes specify a 4000-ft step climb increment. This results in off-optimum performance and accounts for much of the variation in key parameters such as L/D at successive cruise points.

The term "Tau" is used to define the thrust setting of the engine at a selected point. This is the ratio of selected thrust to maximum rated thrust for the selected altitude, speed and temperature condition.

Table 9. Sized 1998 Configuration Cruise Performance

		ERA-0001-PAX	**ERA-0001 OP-PAX**	**ERA-0003-PAX**	**ERA-0004-Cargo**
Cruise type		Step-crus	Step-crus	Step-crus	Step-crus
Initial cruise altitude (ft)	**35000**	35000	35000	35000	35000
Initial cruise Mach	**0.85**	0.85	0.85	0.85	0.85
Initial cruise L/D		19.786	19.954	19.371	19.371
Initial cruise total thrust (lbf)		30749	32500	29235	29235
Initial cruise tau (fraction of max thrust)		0.829	0.834	0.832	0.832
Initial cruise CL		0.4441	0.441	0.4534	0.4534
Mid cruise altitude (ft)		35000	35000	39000	39000
Mid cruise Mach	**0.85**	0.85	0.85	0.85	0.85
Mid cruise L/D		18.537	18.52	18.948	19.065
Mid cruise total thrust (lbf)		26761	27928	23873	24336
Mid cruise tau (fraction of max thrust)		0.721	0.717	0.803	0.819
Mid cruise CL		0.3621	0.3517	0.4388	0.4501
Final cruise altitude (ft)		43000	43000	43000	43000
Final cruise Mach	**0.85**	0.85	0.85	0.85	0.85
Final cruise L/D		18.622	18.67	18.224	18.615
Final cruise total thrust (lbf)		20007	20823	18968	19872
Final cruise tau (fraction of max thrust)		0.79	0.784	0.795	0.833
Final cruise CL		0.3994	0.3882	0.4064	0.4349

Takeoff and landing performance is summarized in Table 10.

Engine thrust is generally set by one of the following performance requirements:

- Balanced or all-engine takeoff field length
- Second segment climb gradient
- Distance to climb to 35,000 ft (200 nm) (in Table 8)
- Initial cruise altitude (ICA) (35,000 ft) (in Table 9)

Engines for the -0001 and -0001 OP are sized by the ICA requirement. -0003 and -0004 are sized by the 200 nm distance-to-climb requirement. All four airplanes easily make the takeoff field length requirements and have adequate second segment climb gradients.

The sizing process insures that takeoff rotation angles do not exceed the geometric capability of the airplane. Each airplane has approximately three degrees of clearance, so this is not a factor in the sizing.

Flap settings at takeoff are approximately 20°. This is a favorable combination of low drag and high maximum CL..

Landing performance does not size any of the four 1998 airplanes. Landing field length and landing approach speeds are well below the required values.

"Top of climb thrust" reports the per-engine thrust just before throttling back and initiating cruise. Comparison of this value with the "Initial cruise total thrust" value from Table 9 highlights the degree to which the engines are throttled back. For example, -0001 cuts total thrust from 37,111 lbf to 30,749 lbf, a 17% reduction.

The FAR 36 flyover noise measurement reference point is defined as the point on the extended centerline of the runway that is 21,325 feet (6,500 m) from the start of the takeoff roll. Engine throttle may be reduced ("cutback") prior to reaching this measurement point. However, a minimum altitude must be reached before initiation of any cutback. For Stage 3 airplanes the minimum altitude is: (a) 984 ft for airplanes with less than 3 engines, (b) 853 ft for airplanes with 3 engines, and (c) 689 ft for airplanes with more than 3 engines. Once reaching the certification point, airplane thrust or power must not be reduced below that required to maintain either of the following, whichever is greater: (a) A climb gradient of 4 per cent; or (b) level flight with one engine inoperative (for airplanes with multiple engines).

All of the 1998 airplanes are far higher than the minimum altitude at the measurement point so they are all able to throttle back for the noise measurement.

Table 10. Sized 1998 Configuration Takeoff and Landing Performance

		ERA-0001-PAX	ERA-0001 OP-PAX	ERA-0003-PAX	ERA-0004-Cargo
Balanced field length @ SL, 86 degF (ft)	**10500**	7932	7994	7778	7778
2nd Segment Gradient (%)	**2.4 / 2.7**	2.47	2.488	2.553	2.553
Balanced field liftoff velocity (ktas)		154.72	154.82	154.13	154.13
All engine field length over 35 ft. (ft)	**10500**	7249	7342	7079	7079
All engine liftoff velocity (ktas)		159.9	160.01	159.49	159.49
Tail scrape angle (deg)		10.777	10.777	10.777	10.777
Balanced field liftoff angle (deg)		7.69	7.75	7.8	7.8
Flap deflection (deg or setting)		20.54	19.56	20.86	20.86
Landing weight (lbm)		370128	383759	344098	368327
Landing ground roll @ SL, Std (ft)		1299.48	1257.71	1296.18	1382.73
Landing distance over 50 ft. (ft)		2348.96	2307.19	2345.66	2432.21
Landing field length (ft)	**5200**	3915	3845	3909	4054
Landing approach speed (ktas)	**150**	107.37	105.51	108.42	112.17
Top of climb thrust (lbf/eng)		18555.5	19475.5	17561	17561
Takeoff thrust @ M=0.25 (lbf/eng)		75191	78918	71094	71094
Boeing Equivalent Thrust-BET (lbf/eng)		94365	99042	89223	89223
Engine Reference Thrust (lbf/eng)		61339	61339	73177	73177
Engine Scale Factor		1.5129	1.5879	1.2026	1.2026
FAR-36 Cutback altitude (ft)	**984 / 853**	1682	1652	1735	1735

2.5.1.7.2 Payload-Range Performance

Payload-range performance for the -0003 passenger airplane and -0004 freighter are shown in Figure 40. Other 1998 airplanes have similar performance because they are sized to the same missions.

The passenger airplane is plotted in blue for two payloads. The design payload of 50,000 lb is plotted as a solid line. The maximum payload of 90,000 lb is plotted as a dashed line. For ranges between zero and ~6375 nm, the passenger airplane can carry any payload between zero and 90,000 lb. To fly beyond 6375 nm, payload must be offloaded so that additional fuel may be loaded without exceeding the MTOGW limitation. At 8000 nm, the airplane carries the design payload of 50,000 lb – the design mission. Beyond 8000 nm, the payload continues to decline to zero and maximum or "ferry" range is reached. This is ~10,235 nm.

The freighter is plotted in magenta – solid for the design mission payload of 100,000 lb and dashed for the maximum payload of 150,000. As noted in the requirements section, Section 2.2.1.2, the freighter mission is a "fallout" from the passenger mission. The design and maximum payloads are specified but the range performance at these payloads is not. The magenta dot shows the payload-range combination originally requested by NASA. The -0004 freighter exceeds this combination by about 475 nm. The -0004 freighter and -0003 passenger airplanes have the same MTOGW. The extra payload capability of the freighter is the direct result of its 25,138 lb lighter OEW.

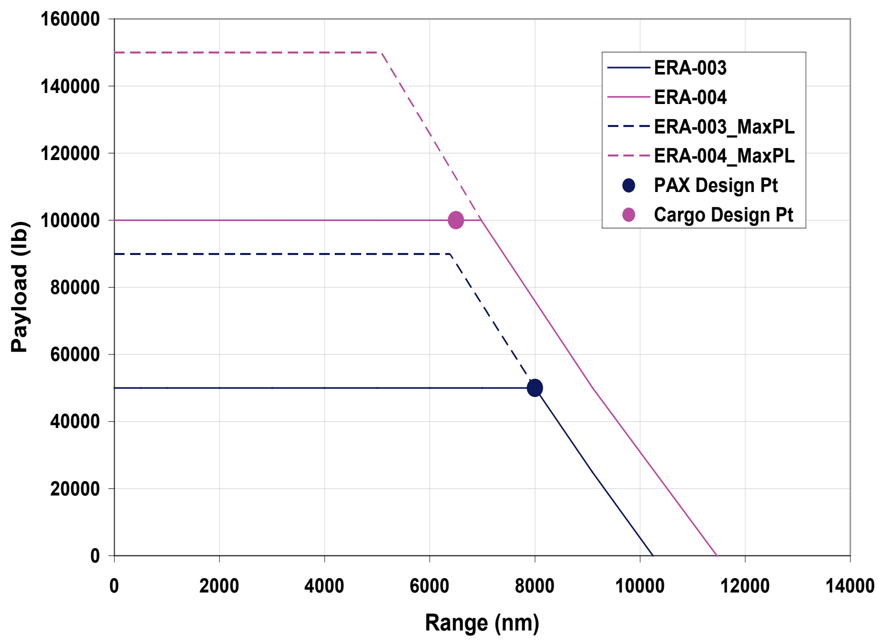


Figure 40. Payload-Range for -0003 Passenger and -0004 Freighter

2.5.1.7.3 Fuel Efficiency versus Range

Figure 41 plots fuel efficiency versus range for the -0003 passenger airplane and the -0004 freighter. These curves are created by "flying" multiple, separate missions at different ranges with design and maximum payloads. Fuel efficiency is reported in terms of ton-nm per pound of fuel burned as defined in Section 2.5.1.7.1.

Fuel efficiency versus range is influenced by several factors. Each flight at a given range burns approximately the same amount of fuel for the taxi, takeoff, climb and descent portion. These flight segments are not as productive in terms of ton-nm as the cruise segment so flights with shorter cruise segments tend to burn extra fuel per ton-nm – their fuel efficiency is reduced. On the other hand, longer flights require extra fuel and greater takeoff weights, so more thrust is required throughout the flight –

more fuel is burned per ton-nm. These two tendencies are most influential at very short ranges and very long ranges – the mid range flights provide the best fuel efficiency.

Another very important factor is the payload. At the payload-range "corner point" with the maximum or design payload at its longest possible range, fuel efficiency begins a sharp decline as payload is reduced. This effect is compounded by the increasing fuel load. This effect is reflected in the much greater fuel efficiency for the maximum payloads compared to those of the design payloads.

For the -0003 passenger airplane, fuel efficiency with the design payload is a maximum at ~0.95 ton-nm/lb fuel at a range of ~2500 nm. With the maximum payload, this increases to ~1.58 ton-nm/lb fuel at 2000 nm.

For the -0004 freighter, increased payloads provide increased fuel efficiency relative to the -0003 passenger airplane. With the 100,000 lb design payload, fuel efficiency is a maximum at ~1.83 ton-nm/lb fuel at 2000 nm range. With the maximum 150,000 lb payload, this increases to ~2.42 ton-nm/lb fuel, also at 2000 nm.

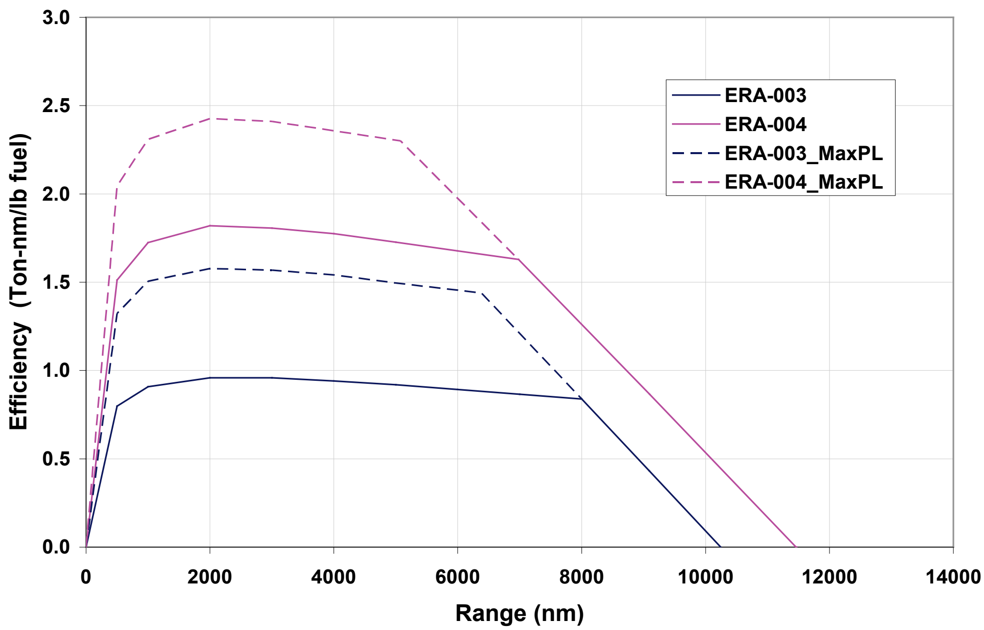


Figure 41. Fuel Efficiency versus Range for -0003 Passenger and -0004 Freighter

2.6 2025 EIS Conventional Configurations

Results for four configurations are described in this section. These are:

- -0005 passenger airplane with P&W geared turbofan (GTF) engines
- -0005 NG passenger airplane, a resized derivative of -0005 flown with NextGen rules
- -0006 freighter with P&W GTF engines (a derivative of -0005)
- -0007 passenger airplane with RRNA advanced turbofan (ATF) engines

The structure of Section 2.6 mimics that of Section 2.5 above. Reference to Figure 33 can help the reader to keep track of the airplanes.

2.6.1 Design and Performance

2.6.1.1 Configuration

Configuration of the 2025 conventional airplanes is described in some detail in Section 2.3.2.1. General arrangement drawings with interiors are shown below; -0005 in Figure 42, -0005 NG in Figure 43, -0006 in Figure 44, and -0007 in Figure 45. Characteristics of the four airplanes are summarized in Table 11.

The three P&W GTF-powered airplanes are notable for their very large nacelle diameters and resultant "gull wing" dihedral. The gull wing provides adequate nacelle-to-ground clearance without lengthening the landing gear legs. The smaller diameter RRNA ATF nacelles permit a conventional wing dihedral arrangement.

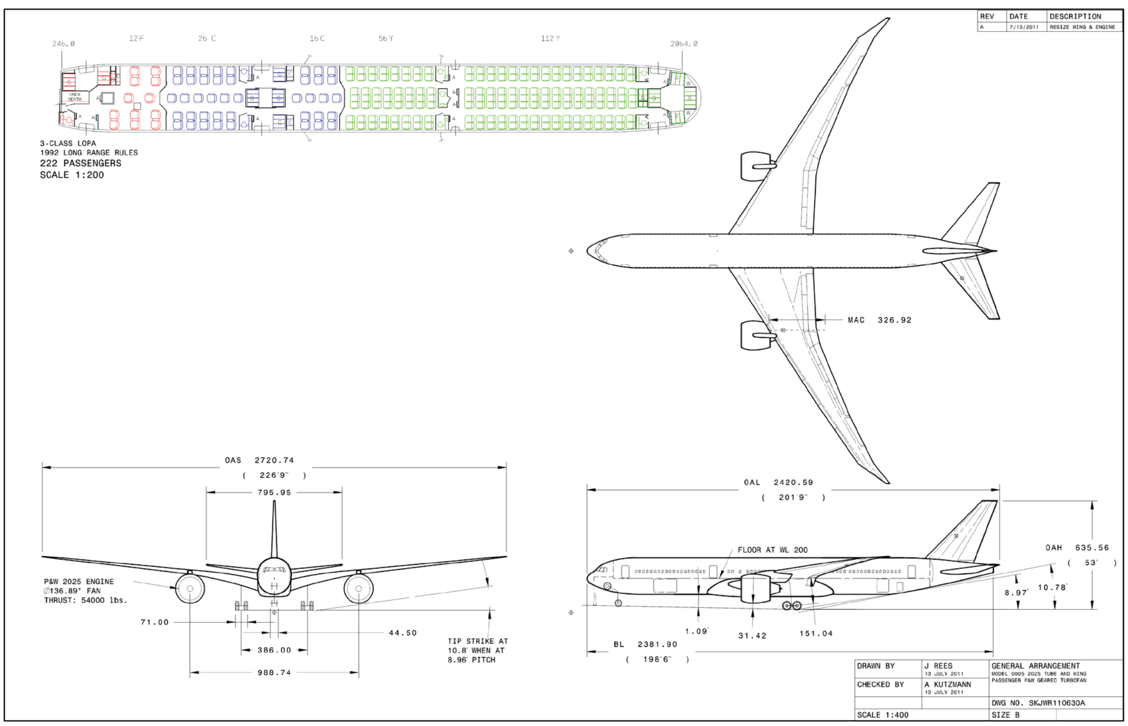


Figure 42. General Arrangement Drawing – 2025 T&W-0005 Passenger

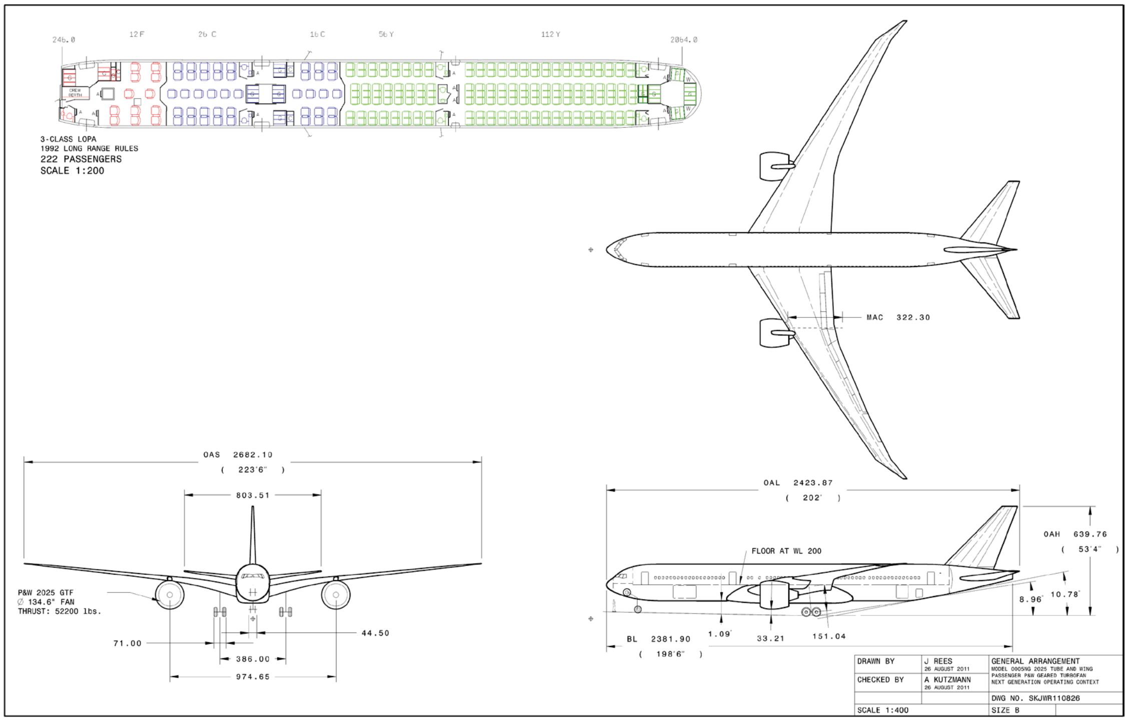


Figure 43. General Arrangement Drawing – 2025 T&W-0005 NG Passenger

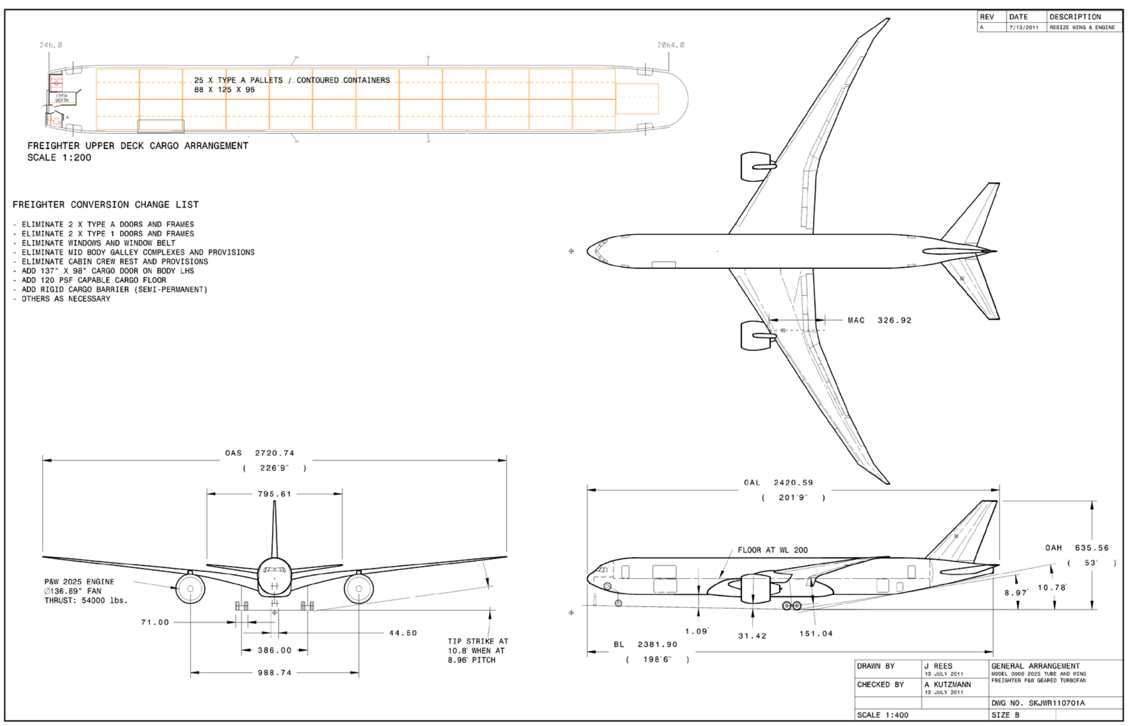


Figure 44. General Arrangement Drawing – 2025 T&W-0006 Freighter

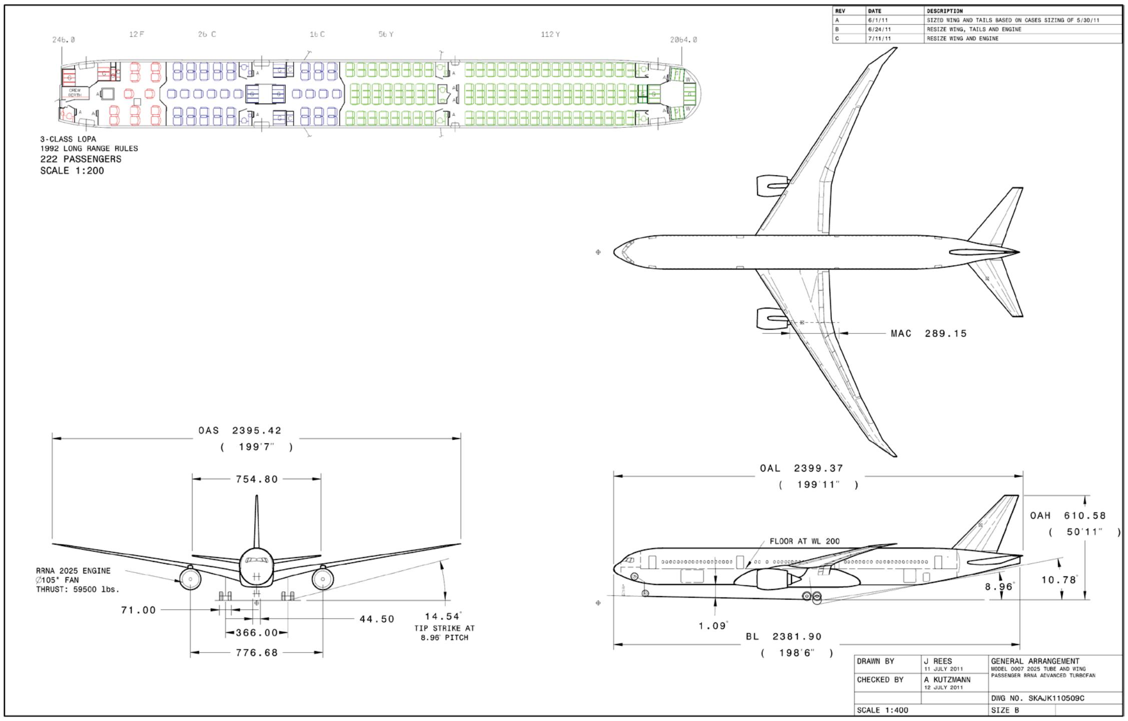


Figure 45. General Arrangement Drawing – 2025 T&W-0007 Passenger

Table 11. Summary Airplane Characteristics

	-0005 Passenger P&W GTF	-0005 NG Passenger P&W GTF	-0006 Freighter P&W GTF	-0007 Passenger RRNA ATF
Wing Span (ft)	226.7	223.5	226.7	199.6
Wing Area (gross) (ft^2)	4678.4	4547.1	4678.4	3673.8
MTOGW (lb)	449,852	436,666	449,852	428,624
OEW (lb)	251,009	246,510	227,903	226,697
Reference Thrust (lbf) (total)	108,000	104,400	108,000	119,000

Differences between the -0005 and the -0005 NG derive only from the difference in mission rules. Clearly, the NextGen used for the -0005 NG provides a significant savings in airplane dimensions, weights and thrust.

The -0006 freighter is identical to the -0005 from which it is derived with the exception of empty weight. The freighter is some 23,000 lb lighter.

Differences between the -0005 and -0007 derive only from their different engines. As described below, the GTF engine is more efficient but heavier than the ATF.

2.6.1.2 Aerodynamic Design

Aerodynamic design of the 2025 conventional airplanes is limited to selection of the wing geometry as discussed in Section 2.4.2.2.

Wing geometry is based loosely on that of the Boeing 787 design. The 787 has similar mission requirements in terms of range and Mach number. It is also a composite structure, roughly similar to that of the 2025 study airplanes. The primary change from the 787 aerodynamic design is an increase in aspect ratio to approximately account for potential aerodynamic and structural advances in the coming decade.

2.6.1.3 Stability and Control

The stability and control process used for the 2025 conventional configurations is almost the same as for the 1998 conventional configurations as described in Section 2.5.1.3. The trapezoidal areas of the tails are reduced 5% from the method's results to account for unspecified and uncertain improvements anticipated in the 27 years between the two airplane sets. Potential improvements include: reduced stability margins; increased maximum lift coefficient capability of the tails; and active center of gravity management.

2.6.1.3.1 Horizontal Tail Sizing

As for the 1998 airplanes, selection of the loadability parameter drives the horizontal tail size. Because no advancements to reduce loadability requirements are foreseen, the same loadability parameter as the 1998 airplanes is selected.

2.6.1.3.2 Vertical Tail Sizing

The vertical tail sizing method is as described in Section 2.5.1.3.2 but with a 5% reduction in trapezoidal area.

2.6.1.4 Mass Properties

Mass properties methods are described in Section 2.4.2.4.

A short group weight statement for the -0005 passenger airplane is shown in Table 12. Table 13 shows the statement for the -0005 NG airliner. Table 14 shows the freighter -0006, and Table 15 shows airliner -0007.

Efficiencies provided by the NextGen mission relative to the NASA Reference mission reduce the size of the -0005 NG relative to the -0005. As a result, there are incremental reductions in the -0005 NG's airframe weight leading to a 4499 lb savings in OEW. This, combined with a usable fuel reduction of 8687 lb, results in a MTOGW reduction of 13,186 lb.

The -0006 freighter has a 23,106 lb lighter OEW than its -0005 parent due primarily to reductions in furnishings and equipment plus standard and operational items. Wing, tail and fuselage weights are nearly identical.

Comparison of the -0005 GTF airliner with the -0007 ATF airliner highlights the differences in airplane characteristics that arise from the distinctly different engines. As shown in Table 11, the -0005's wing area is considerably greater. As a result, the -0005's wing weighs 11,949 lb more. The tails weigh 1155 lb more. The GTF propulsion and pylon weight is 6999 lb heavier. Overall, the -0005's OEW is 24,312 lb heavier than that of the -0007. On the other hand, the useable fuel load of the -0005 is 3084 lb less, a 2.0% reduction.

Table 12. Short Group Weight Statement -0005 Airliner

ERA 0005 2025 EIS T&W PASSENGER P&W GTF	
DESCRIPTION	**WEIGHT**
WING	70,586
TAIL	7,438
FUSELAGE	44,642
LANDING GEAR	18,995
PYLON	5,057
PROPULSION	31,813
FUEL SYSTEM	2,256
FLIGHT CONTROLS	6,032
AUXILIARY POWER UNIT	1,434
HYDRAULICS	2,799
PNEUMATICS	1,431
ELECTRICAL	4,797
INSTRUMENTS	1,395
AVIONICS & AUTOPILOT	2,557
FURNISHINGS & EQUIPMENT	28,182
AIR CONDITIONING	3,088
ANTI-ICING	485
MANUFACTURER'S EMPTY WEIGHT (MEW)	**232,988**
STANDARD & OPERATIONAL ITEMS	18,021
OPERATIONAL EMPTY WEIGHT (OEW)	**251,009**
USABLE FUEL	148,843
DESIGN PAYLOAD	50,000
MAX TAKEOFF GROSS WEIGHT (MTOGW)	**449,852**

Table 13. Short Group Weight Statement -0005 NG Airliner

ERA 0005 2025 EIS T&W PASSENGER P&W GTF	
DESCRIPTION	**WEIGHT**
WING	68,374
TAIL	7,277
FUSELAGE	44,496
LANDING GEAR	18,384
PYLON	4,888
PROPULSION	30,909
FUEL SYSTEM	2,205
FLIGHT CONTROLS	5,893
AUXILIARY POWER UNIT	1,434
HYDRAULICS	2,733
PNEUMATICS	1,431
ELECTRICAL	4,797
INSTRUMENTS	1,395
AVIONICS & AUTOPILOT	2,557
FURNISHINGS & EQUIPMENT	28,182
AIR CONDITIONING	3,088
ANTI-ICING	471
MANUFACTURER'S EMPTY WEIGHT (MEW)	**228,514**
STANDARD & OPERATIONAL ITEMS	17,996
OPERATIONAL EMPTY WEIGHT (OEW)	**246,510**
USABLE FUEL	140,156
DESIGN PAYLOAD	50,000
MAX TAKEOFF GROSS WEIGHT (MTOGW)	**436,666**

Table 14. Short Group Weight Statement -0006 Freighter

ERA 0006 2025 EIS T&W CARGO P&W GTF	
DESCRIPTION	**WEIGHT**
WING	70,586
TAIL	7,438
FUSELAGE	44,770
LANDING GEAR	18,995
PYLON	5,057
PROPULSION	31,813
FUEL SYSTEM	2,256
FLIGHT CONTROLS	6,032
AUXILIARY POWER UNIT	1,434
HYDRAULICS	2,799
PNEUMATICS	1,431
ELECTRICAL	4,797
INSTRUMENTS	1,395
AVIONICS & AUTOPILOT	2,557
FURNISHINGS & EQUIPMENT	21,313
AIR CONDITIONING	3,088
ANTI-ICING	485
MANUFACTURER'S EMPTY WEIGHT (MEW)	**226,246**
STANDARD & OPERATIONAL ITEMS	1,657
OPERATIONAL EMPTY WEIGHT (OEW)	**227,903**
USABLE FUEL	121,949
DESIGN PAYLOAD	100,000
MAX TAKEOFF GROSS WEIGHT (MTOGW)	**449,852**

Table 15. Short Group Weight Statement -0007 Airliner

ERA 0007 2025 EIS T&W PASSENGER RRNA ATF	
DESCRIPTION	**WEIGHT**
WING	58,637
TAIL	6,283
FUSELAGE	44,338
LANDING GEAR	17,316
PYLON	4,162
PROPULSION	25,709
FUEL SYSTEM	1,903
FLIGHT CONTROLS	4,954
AUXILIARY POWER UNIT	1,434
HYDRAULICS	2,287
PNEUMATICS	1,431
ELECTRICAL	4,797
INSTRUMENTS	1,395
AVIONICS & AUTOPILOT	2,557
FURNISHINGS & EQUIPMENT	28,182
AIR CONDITIONING	3,088
ANTI-ICING	381
MANUFACTURER'S EMPTY WEIGHT (MEW)	**208,855**
STANDARD & OPERATIONAL ITEMS	17,842
OPERATIONAL EMPTY WEIGHT (OEW)	**226,697**
USABLE FUEL	151,927
DESIGN PAYLOAD	50,000
MAX TAKEOFF GROSS WEIGHT (MTOGW)	**428,624**

2.6.1.5 Aerodynamics

Aerodynamics methods are described in Section 2.4.2.5. This section describes aerodynamics results for the 2025 conventional configurations by reporting on the -0005 and -0007.

The four 2025 airplanes vary only in wing and tail area. The aerodynamics differences between the airplanes are a result only of this. The geometric characteristics of the -0005 and -0006 freighter derivative are identical – their aerodynamic characteristics are also identical. The wing reference areas of the -0005, -0005 NG and -0007 diminish in order as noted below:

- -0005: 3920 ft^2
- -0005 NG: 3810 ft^2
- -0007: 3080 ft^2

When results vary from airplane to airplane, only results for the -0005 and -0007 are reported. Results for the -0005 NG are very close to those of the -0005 and may be proportionally interpolated between the -0005 and -0007 results.

This section follows the arrangement of Section 2.5.1.5 and attempts to avoid repetition except to improve clarity. Because variations between the 2025 aerodynamics are small, more discussion is provided describing the differences between 2025 and 1998 aerodynamics.

2.6.1.6 Propulsion

Propulsion systems of the 2025 conventional configurations represent two distinctly different approaches. The P&W geared turbofan (GTF) engine drives a very large, lightly loaded fan with a relatively small turbine core via a gearbox. The RRNA advanced turbofan drives a smaller fan directly from the third stage of a three-stage core.

2.6.1.6.1 Propulsion System Performance

Comments from Section 2.5.1.6.2 apply here and are not repeated.

In this section, the three P&W GTF engines are represented by the sized engine from the -0005 airplane. The RRNA ATF engine is from the -0007.

Engine data are supplied to the study by the engine manufacturers. These data are in a multi-dimensional matrix with input variables including altitude, Mach number and throttle setting. Outputs include maximum thrust and fuel flow. The representative speed versus altitude slice is the same as for the 1998 airplanes shown in Figure 38 except that the maximum altitude is extended to 42,000 ft. This is shown in Figure 46.

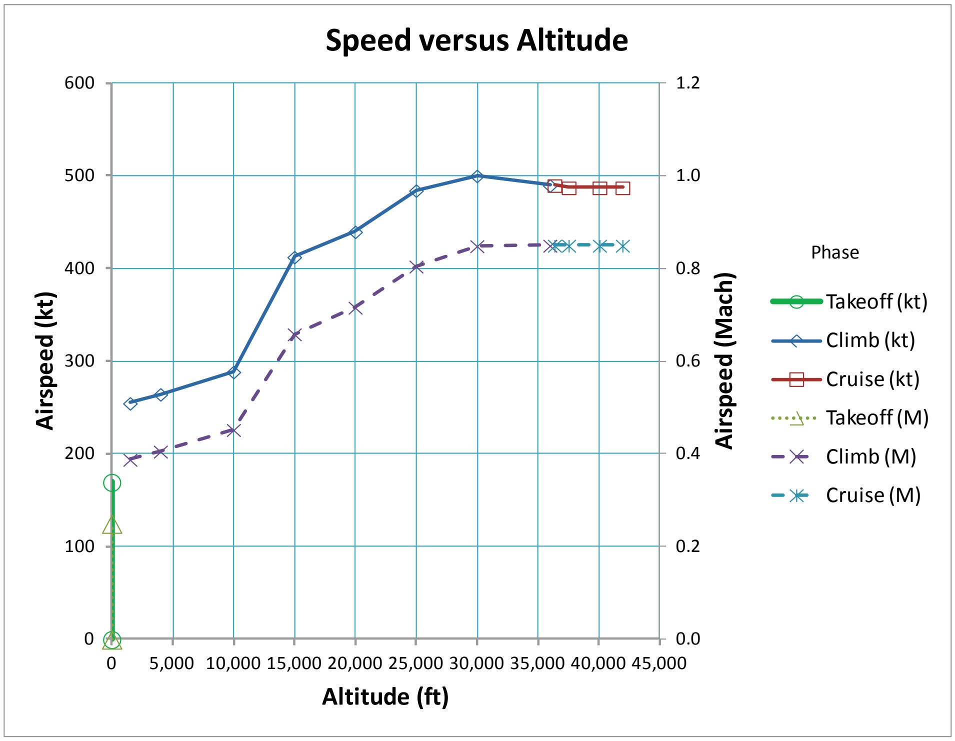


Figure 46. Speed versus Altitude for -0005 and -0007 Propulsion

2.6.1.7 Sizing and Performance Evaluation

This section is consistent with the section that describes sizing and performance for the 1998 airplanes – Section 2.5.1.7. Explanation of terms is not repeated here.

2.6.1.7.1 Mission Performance

Tabular results for the -0005, -0005 NG, -0006 freighter and -0007 are shown in Table 16, Table 17 and Table 18. Notable comparisons include -0005 to -0007 and -0005 to -0005 NG. The former shows the effect of different engine concepts. The latter shows the benefit of the NextGen mission relative to the NASA Reference mission.

The -0007 has an OEW 24,314 lb lighter than that of the -0005. This is a 9.7% reduction in OEW. However, the -0007 burns 2225 lb more fuel, an extra 1.6%.

For the -0005, the NextGen mission reduces sized airplane empty weight by 4508 lb (1.8%) and reduces fuel burned by 4678 lb (3.4%).

Comparison of the -0005 fuel burned with that of the 1998 -0001 gives a feel for the benefit provided by the selected advanced 2025 technologies. From the -0005 to the -0001, OEW drops 40,161 lb, or 13.8%. Fuel burned drops 118,858 lb, or 46.6%.

Table 16. Sized 2025 Configuration Characteristics

Tare weight included in Payload		**ERA-005-PAX**	**ERA-005-NG-PAX**	**ERA-006-Cargo**	**ERA-007-PAX**
Reference	**Required**	**2025 T&W**	**2025 T&W**	**2025 T&W**	**2025 T&W**
	Perf.	**Mcr=0.85**	**Mcr=0.85**	**Mcr=0.85**	**Mcr=0.85**
		PW GTF	**PW GTF**	**PW GTF**	**RR ATF**
MTOGW (lb)		449852	436666	449852	428624
OEW (lb)		251009	246501	227903	226695
Payload (lb)	**50k/100k**	50000	50000	100000	50000
Fuel Load at MTOGW (lb)		148843	140165	121949	151929
Range (nm)	**8000/6500**	8000	8000	6302	8000
Block Fuel Burned (lb)		136097	131419	110285	138322
nm/lb		0.05878	0.06087	0.05714	0.05784
NM*PL/LBf		2939.08	3043.70	5713.83	2891.80
Ton-nm/lbf		1.47	1.52	2.86	1.45
Reference Wing Area (sqft)		3920	3810	3920	3080
Wing Aspect Ratio		11	11	11	10.946
TO Ref FN @ SL, 0.0, +27F (lbf/eng)		54000	52200	54000	59500
Number of Engines		2	2	2	2
T/W		0.24	0.24	0.24	0.28
W/S		115	115	115	139
Time to climb to 35000 ft (min)		27.12	24.846	25.506	28.452
Dist. to climb to 35000 ft (nm)	**200**	167.86	163.87	167.92	197.36
R/C at 35000 ft (fpm)		584	617	583	492

Table 17 shows cruise performance at three points: beginning of cruise; midpoint of cruise (based on distance); and at the end of cruise.

Again, the notable comparisons are those between the -0005 and -0005 NG configurations and between -0005 and -0007.

-0005 NG cruise performance compared to that of the -0005 shows the benefit of flying a cruise-climb profile. This profile permits the airplane to stay right at the altitude (and lift coefficient) that provide the lowest fuel consumption. The key characteristic is airplane L/D. Engine SFC is a potential factor but the data shows little change in SFC with altitude for either airplane. A comparison of L/D between the -0005 and -0005 NG is illuminating, keeping in mind that the maximum L/D for the -0005 NG is some 0.6% less due to its smaller wing. At the start of cruise, the NG has 1.03% more L/D. At mid-cruise this margin is still 1.03%. At the end of cruise the NG's L/D is 0.8% worse because both airplanes have reached the 43,000 ft altitude limit used in this study – the NG is more off-design than the -0005.

The -0007 performance relative to the -0005 shows a general reduction in cruise L/D resulting from the -0007's smaller wing. At the beginning of cruise, the -0007's L/D is up 0.2%; at mid cruise it is down by 3.8%; at the end of cruise it is down by 5.4%. These numbers are roughly consistent with the -0007's 5.2% lower maximum L/D so the effect of step-climbing does not appear to affect one airplane significantly more than the other.

Table 17. Sized 2025 Configuration Cruise Performance

		ERA-005-PAX	ERA-005-NG-PAX	ERA-006-Cargo	ERA-007-PAX
Cruise type		Step-crus	Climb-crus	Step-crus	Step-crus
Initial cruise altitude (ft)	**35000**	35000	38958	35000	35000
Initial cruise Mach	**0.85**	0.85	0.85	0.85	0.85
Initial cruise L/D		22.104	22.844	22.105	22.146
Initial cruise total thrust (lbf)		20006	18810	20008	18969
Initial cruise tau		0.799	0.929	0.799	0.82
Initial cruise CL		0.4479	0.5386	0.448	0.5416
Mid cruise altitude (ft)		39000	42430	39000	35000
Mid cruise Mach	**0.85**	0.85	0.85	0.85	0.85
Mid cruise L/D		21.929	22.554	22.316	21.09
Mid cruise total thrust (lbf)		17117	16288	17630	17073
Mid cruise tau		0.82	0.958	0.844	0.738
Mid cruise CL		0.4607	0.5454	0.4829	0.4642
Final cruise altitude (ft)		43000	43000	43000	39000
Final cruise Mach	**0.85**	0.85	0.85	0.85	0.85
Final cruise L/D		21.656	21.49	22.258	20.489
Final cruise total thrust (lbf)		14563	14259	15329	14296
Final cruise tau		0.852	0.863	0.897	0.742
Final cruise CL		0.4691	0.469	0.5075	0.4576

Table 18 reports takeoff and landing performance as well as engine characteristics.

Engine thrust for all four airplanes is set by the 2.4% second-segment climb gradient requirement. The balanced and all-engine field length requirement is made with significant margin. The high lift curve slope of all these airplanes result in ample lift at modest rotation angles – the liftoff angle is far less than the tail scrape angle.

Landing field length and approach speed requirements are met with large margins by all four airplanes.

All of the sized engines are slightly smaller than the reference engines used for engine performance. Scale factors range from 0.9250 to 0.9575.

All of the airplanes reach a FAR-36 cutback altitude well in excess of the minimum 984 ft for twin-engine airplanes.

Table 18. Sized 2025 Configuration Takeoff and Landing Performance

		ERA-005-PAX	ERA-005-NG-PAX	ERA-006-Cargo	ERA-007-PAX
Balanced field length @ SL, 86 degF (ft)	**10500**	9912	10274	9912	9169
2nd Segment Gradient (%)	**2.4 / 2.7**	2.4	2.4	2.4	2.4
Balanced field liftoff velocity (ktas)		159.82	162.11	159.83	160.12
All engine field length over 35 ft. (ft)	**10500**	9092	9381	9093	8487
All engine liftoff velocity (ktas)		163.87	165.87	163.88	165.7
Tail scrape angle (deg)		10.777	10.777	10.777	10.777
Balanced field liftoff angle (deg)		5.38	4.92	5.38	7.79
Flap deflection (deg or setting)		10.26	10.17	10.26	10.45
Landing weight (lbm)		314685	305821	340497	291232
Landing ground roll @ SL, Std (ft)		1359.88	1359.07	1463.97	1599.02
Landing distance over 50 ft. (ft)		2409.36	2408.55	2513.45	2648.5
Landing field length (ft)	**5200**	4016	4014	4189	4414
Landing approach speed (ktas)	**150**	118.13	118.12	122.88	127.99
Top of climb thrust (lbf/eng)		12604	10193.5	12604	11567.5
Takeoff thrust @ M=0.25 (lbf/eng)		43201	41761	43201	43487
Boeing Equivalent Thrust-BET (lbf/eng)		54217	52410	54217	54576
Engine Reference Thrust (lbf/eng)		56395	56395	56395	64323
Engine Scale Factor		0.9575	0.9256	0.9575	0.9250
FAR-36 Cutback altitude (ft)	**984 / 853**	1289	1125	1289	1392

2.6.1.7.2 Payload-Range Performance

Payload-range performance of the -0005 passenger airplane and -0006 freighter are shown in Figure 47. This plot is quite similar to that of the -0003 and -0004 shown in Figure 40 and discussed in Section 2.5.1.7.2.

The key difference is that the 2025 airplanes fly farther per pound of fuel so the slope of the payload-range line at MTOGW is shallower. As a result, the freighter as slightly less range than originally requested by NASA at 100,000 lb payload (magenta dot in the plot). Range at maximum passenger and freighter payloads are significantly shorter than those of the 1998 airplanes; ferry ranges with zero payload are significantly longer.

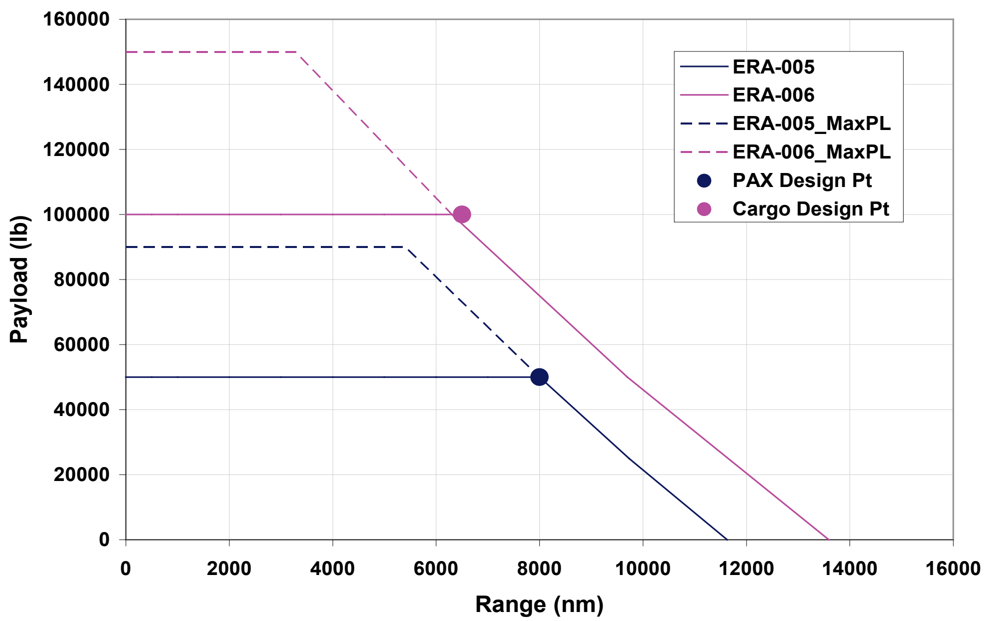


Figure 47. Payload-Range for -0005 Passenger and -0006 Freighter

2.6.1.7.3 Fuel Efficiency versus Range

Fuel efficiency versus range is shown for the -0005 passenger airplane and -0006 freighter in Figure 48. This is comparable to the 1998 airplanes shown Figure 41 as discussed in Section 2.5.1.7.3.

Compared to the efficiency versus range results for the 1998 airplanes, the 2025 airplanes have much higher fuel efficiency. Variation in fuel efficiency with range is less, at least with full design or maximum payloads. Fuel efficiency peaks at somewhat longer range. Where the 1998 airplanes peak at ~2000 nm, the 2025 airplanes peak at ~3000 nm. This indicates that the penalty for “tankering” fuel is less in the more efficient 2025 airplanes.

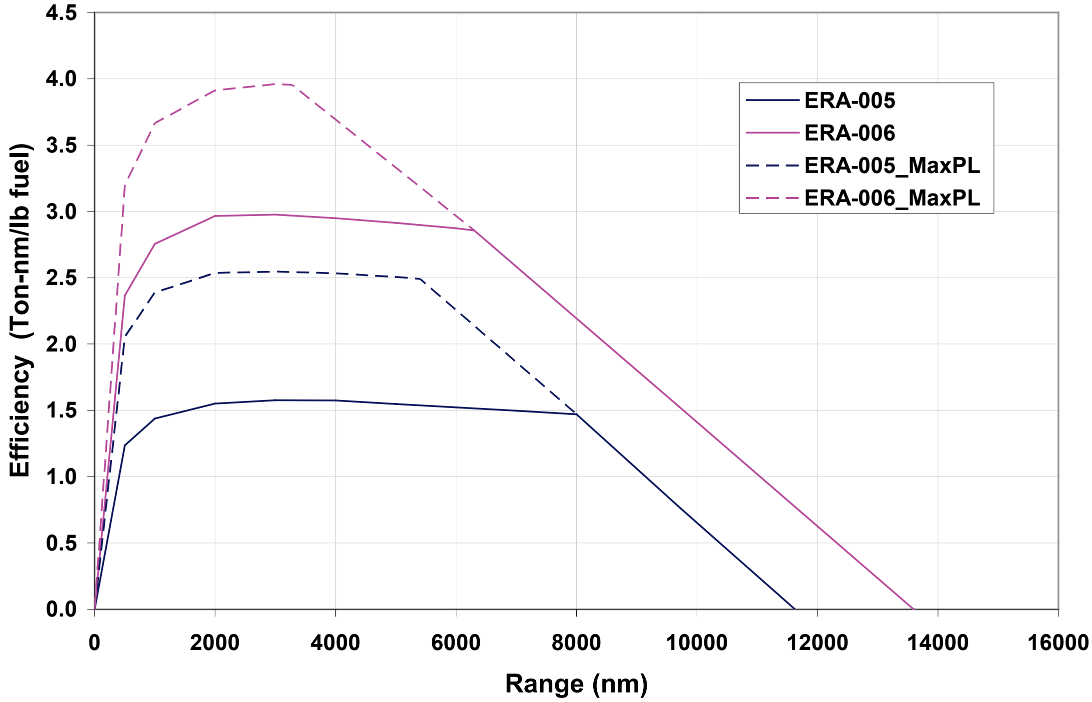


Figure 48. Fuel Efficiency versus Range for -0005 Passenger and -0006 Freighter

2.6.1.8 Acoustics

The acoustic results for 2025 conventional T&W design are summarized in Section 2.9.

2.7 2025 Advanced Conventional Configuration

Results for the -0027A passenger airplane with RRNA advanced turbofan (ATF) engines described in this section. This airplane has wing geometry and technology levels consistent with the 2025 conventional configurations such as the -0005.

The structure of this section mimics that of Section 2.6 above.

2.7.1 Design and Performance

2.7.1.1 Configuration

Configuration of the 2025 advanced conventional passenger airplane -0027A is described in Section 2.3.3.1.1. Its general arrangement drawing is shown again in Figure 49. Characteristics of the -0027A are summarized in Table 19.

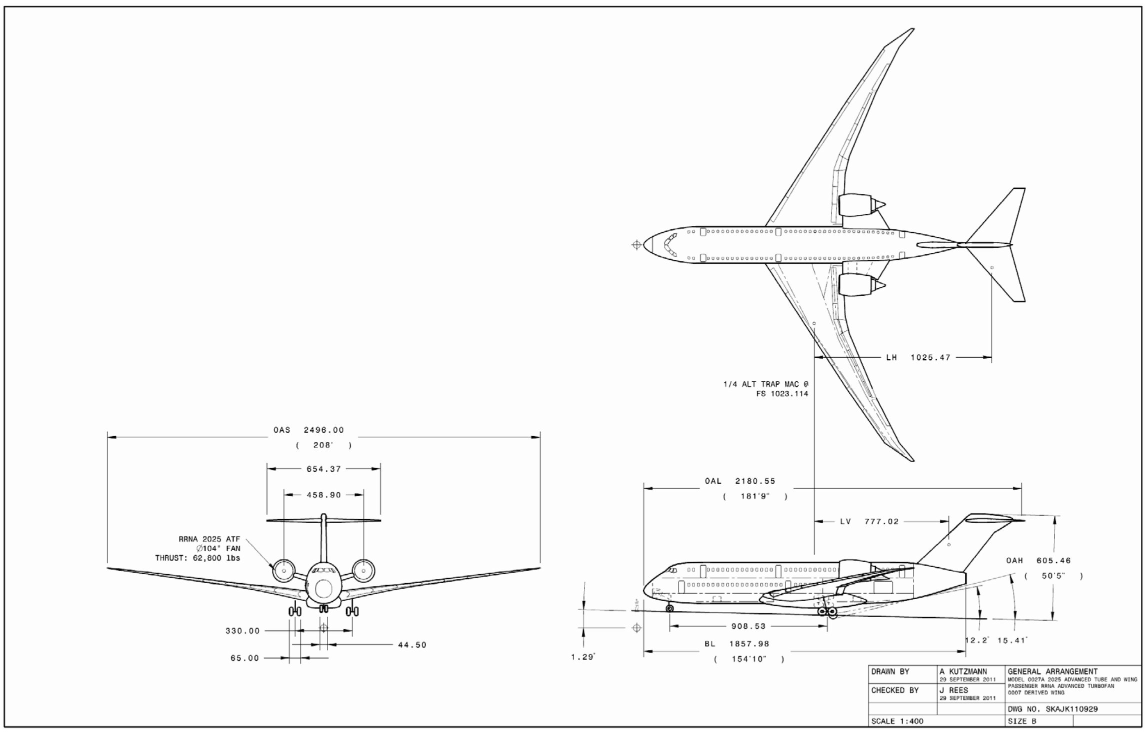


Figure 49. General Arrangement Drawing – 2025 AT&W-0027A Passenger

Table 19. -0027A Airplane Characteristics

	-0027A Passenger
Wing Span (ft)	208.0
Wing Area (gross) (ft^2)	3960.0
MTOGW (lb)	453,159
OEW (lb)	242,354
Reference Thrust (lbf) (total)	125,600

2.7.1.2 Aerodynamic Design

Aerodynamic design of the -0027A is consistent with that of the 2025 conventional airplanes as described in Section 2.6.1.2. With the exception of precise sizing, the -0027A's wing geometry is the same as the 2025 conventional airplanes. Overall, the -0027A is most similar to the 2025 conventional configuration -0007. These two airplanes share the same wing geometry and share the same engine type – the RRNA ATF.

2.7.1.3 Mass Properties

Mass properties methods are described in Section 2.4.2.4. Short group weight statements are presented in Table 20 for -0027A.

Table 20. Short Group Weight Statement -0027A Airliner

ERA 0027A 2025 EIS ADV T&W PASSENGER RRNA ATF	
DESCRIPTION	**WEIGHT**
WING	63,665
TAIL	9,155
FUSELAGE	47,136
LANDING GEAR	18,391
PYLON	6,864
PROPULSION	27,356
FUEL SYSTEM	2,014
FLIGHT CONTROLS	5,061
AUXILIARY POWER UNIT	1,441
HYDRAULICS	2,339
PNEUMATICS	1,431
ELECTRICAL	4,797
INSTRUMENTS	1,355
AVIONICS & AUTOPILOT	2,484
FURNISHINGS & EQUIPMENT	28,889
AIR CONDITIONING	3,088
ANTI-ICING	411
MANUFACTURER'S EMPTY WEIGHT (MEW)	**225,877**
STANDARD & OPERATIONAL ITEMS	16,477
OPERATIONAL EMPTY WEIGHT (OEW)	**242,354**
USABLE FUEL	160,805
DESIGN PAYLOAD	50,000
MAX TAKEOFF GROSS WEIGHT (MTOGW)	**453,159**

A comparison of -0027A with the most-similar 2025 conventional configuration, the -0007, is provided in Table 21. This table compares weights from the short group weight statement, provides a weight difference column and lists discriminating features of the -0027A relative to the -0007. The weight difference column is color-coded. Orange indicates a significantly heavier weight on the -0027A; yellow is somewhat heavier; green is lighter.

The -0027A has a MTOGW 24,535 lb greater than the -0007, and increase of 5.7%. Some of the -0027A components are heavier simply because of its greater MTOGW. These include the wing, landing gear and propulsion system. Other components are heavier as result of the different configuration. These include the T-tail, fuselage, engine pylon and furnishings and equipment. The -0027A is significantly lighter in only one category – standard and operational items.

Table 21. Weight Comparison -0007 versus -0027A

	WEIGHT (LB)			
DESCRIPTION	**-0007**	**-0027A**	**0007 to 0027A**	Discriminating -0027A Features
WING	58,637	63,665	5,028	Larger wing
TAIL	6,283	9,155	2,872	T-tail
FUSELAGE	44,338	47,136	2,797	T-tail attachment, body-mounted pylon, main deck cargo door
LANDING GEAR	17,316	18,391	1,075	Higher MTOGW
PYLON	4,162	6,864	2,702	Body-mounted pylon
PROPULSION	25,709	27,356	1,646	Higher MTOGW
FUEL SYSTEM	1,903	2,014	111	
FLIGHT CONTROLS	4,954	5,061	107	
AUXILIARY POWER UNIT	1,434	1,441	7	
HYDRAULICS	2,287	2,339	52	
PNEUMATICS	1,431	1,431	0	
ELECTRICAL	4,797	4,797	0	
INSTRUMENTS	1,395	1,355	-40	
AVIONICS & AUTOPILOT	2,557	2,484	-73	
FURNISHINGS & EQUIPMENT	28,182	28,889	707	Upper deck stairway, revised cargo handling system, rigid cargo barrier
AIR CONDITIONING	3,088	3,088	1	
ANTI-ICING	381	411	30	
MANUFACTURER'S EMPTY WEIGHT (MEW)	**208,855**	**225,877**	17,021	
STANDARD & OPERATIONAL ITEMS	17,842	16,477	-1,365	Revised quantity and type cargo containers, increased quantity emergency escape slides
OPERATIONAL EMPTY WEIGHT (OEW)	**226,697**	**242,354**	15,656	
USABLE FUEL	151,927	160,805	8,879	
DESIGN PAYLOAD	50,000	50,000	0	
MAX TAKEOFF GROSS WEIGHT (MTOGW)	**428,624**	**453,159**	24,535	

2.7.1.4 Propulsion

The propulsion system of the -0027A is the same as that of the -0007 – it is the Rolls-Royce North America advanced turbofan engine described in Section 2.6.1.6. The engine is optimally sized for each airplane; the engine cycle design remains fixed.

2.7.1.5 Sizing and Performance Evaluation

This section is consistent with the section that describes sizing and performance for the 1998 airplanes – Section 2.5.1.7. Explanation of terms is not repeated here.

2.7.1.5.1 Mission Performance

Tabular results for the sized -0027A are presented in Table 22, Table 23 and Table 24.

Table 22. Sized -0027A Characteristics

		Final-1
Tare weight included in Payload		**ERA-027A-PAX**
Reference	**Required Perf.**	**2025 T&W Mcr=0.85 RR ATF**
MTOGW (lb)		453159
OEW (lb)		242354
Payload (lb)	**50k/100k**	50000
Fuel Load at MTOGW (lb)		160805
Range (nm)	**8000/6500**	8000
Block Fuel Burned (lb)		146393
nm/lb		0.05465
NM*PL/LBf		2732.37
Ton-nm/lbf		1.37
Reference Wing Area (sqft)		3320
Wing Aspect Ratio		10.95
TO Ref FN @ SL, 0.0, +27F (lbf/eng)		62800
Number of Engines		2
T/W		0.28
W/S		136
Time to climb to 35000 ft (min)		28.68
Dist. to climb to 35000 ft (nm)	**200**	197.78
R/C at 35000 ft (fpm)		490

Table 23. Sized -0027A Cruise Performance

		ERA-027A-PAX
Cruise type		Step-crus
Initial cruise altitude (ft)	**35000**	35000
Initial cruise Mach	**0.85**	0.85
Initial cruise L/D		22.087
Initial cruise total thrust (lbf)		20108
Initial cruise tau		0.823
Initial cruise CL		0.5312
Mid cruise altitude (ft)		35000
Mid cruise Mach	**0.85**	0.85
Mid cruise L/D		20.966
Mid cruise total thrust (lbf)		18157
Mid cruise tau		0.744
Mid cruise CL		0.4553
Final cruise altitude (ft)		39000
Final cruise Mach	**0.85**	0.85
Final cruise L/D		20.372
Final cruise total thrust (lbf)		15191
Final cruise tau		0.747
Final cruise CL		0.4485

Table 24 describes takeoff and landing performance as well as engine characteristics. Engine thrust is set by the 2.4% second-segment climb gradient requirement. Balanced field length is achieved with a ~700-ft margin; all-engine field length margin is greater at ~1300 ft. Liftoff angle is far less than the tail scrape angle.

Landing field length and approach speed requirements are met with ample margins.

The -0027A reaches a FAR-36 cutback altitude well in excess of the minimum 984 ft for twin-engine airplanes.

Table 24. Sized -0027A Takeoff and Landing Performance

		ERA-027A-PAX
Balanced field length @ SL, 86 degF (ft)	**10500**	9836
2nd Segment Gradient (%)	**2.4 / 2.7**	2.4
Balanced field liftoff velocity (ktas)		165.5
All engine field length over 35 ft. (ft)	**10500**	9237
All engine liftoff velocity (ktas)		171.95
Tail scrape angle (deg)		13.97
Balanced field liftoff angle (deg)		9.52
Flap deflection (deg or setting)		10.59
Landing weight (lbm)		307696
Landing ground roll @ SL, Std (ft)		1761.8
Landing distance over 50 ft. (ft)		2811.28
Landing field length (ft)	**5200**	4685
Landing approach speed (ktas)	**150**	126.71
Top of climb thrust (lbf/eng)		12209
Takeoff thrust @ M=0.25 (lbf/eng)		45900
Engine Reference Thrust (lbf/eng)		64323
Engine Scale Factor		0.9763
FAR-36 Cutback altitude (ft)	**984 / 853**	1282

2.7.1.6 Acoustics

The acoustic results for 2025 conventional T&W design are summarized in Section 2.9.

2.8 2025 EIS Blended Wing Body Configurations

Results for six BWB configurations are described in this section.

- -0009A passenger twin geared turbofan (GTF)
- -0010 cargo twin GTF
- -0011 passenger tri GTF
- -0013 passenger tri open rotor (OR)
- -0015 passenger tri OR with Mach 0.80 cruise
- -0009A NG passenger twin GTF

The structure of this section is similar to that of Sections 2.5, 2.6 and 2.7. Reference to Figure 33 can help to keep track of the airplanes.

2.8.1 Design and Performance

2.8.1.1 Configuration

2.8.1.1.1 Configuration of Primary BWBs

Configuration design of the 2025 BWB design is described in Section 2.3.4.1. General arrangement drawings with payload accommodations are shown below: -0009A in Figure 50, -0010 in Figure 51, -0011 in Figure 52, -0013 in Figure 53, -0015 in Figure 54, and -0009A NG in Figure 55.

The planform of all six airplanes is the same. The three-dimensional surface contour (or "outer mold line" (OML)) of the wing-body and tails is the same for all six airplanes with the exception of the Mach 0.80 -0015 airplane. Its outboard wing average thickness to chord ratio is increased to reduce wing weight.

Primary variations among airplanes are in propulsion system type and number. The -0009A shown in Figure 50 has two large GTF engines.

The -0010 configuration is the freighter derivative of the -0009A. It shares outer mold line, engines and MTOGW. Variations are described in Section 2.3.4.1.

Configuration -0011 is a three-GTF version of the -0009A.

Configuration -0013 is a triple open rotor design. Counter-rotating rotors are mounted ahead of the gearbox, engine core and tall pylon in a tractor arrangement.

Configuration -0015 is also a triple open rotor design very similar to the -0013.

The -0009A NG is nearly identical to the -0009A on which it is based. The -0009A NG has slightly smaller engines and lighter weights that reflect the reduced fuel burn enabled by its more-efficient NextGen mission.

Table 25 summarizes the primary BWB characteristics.

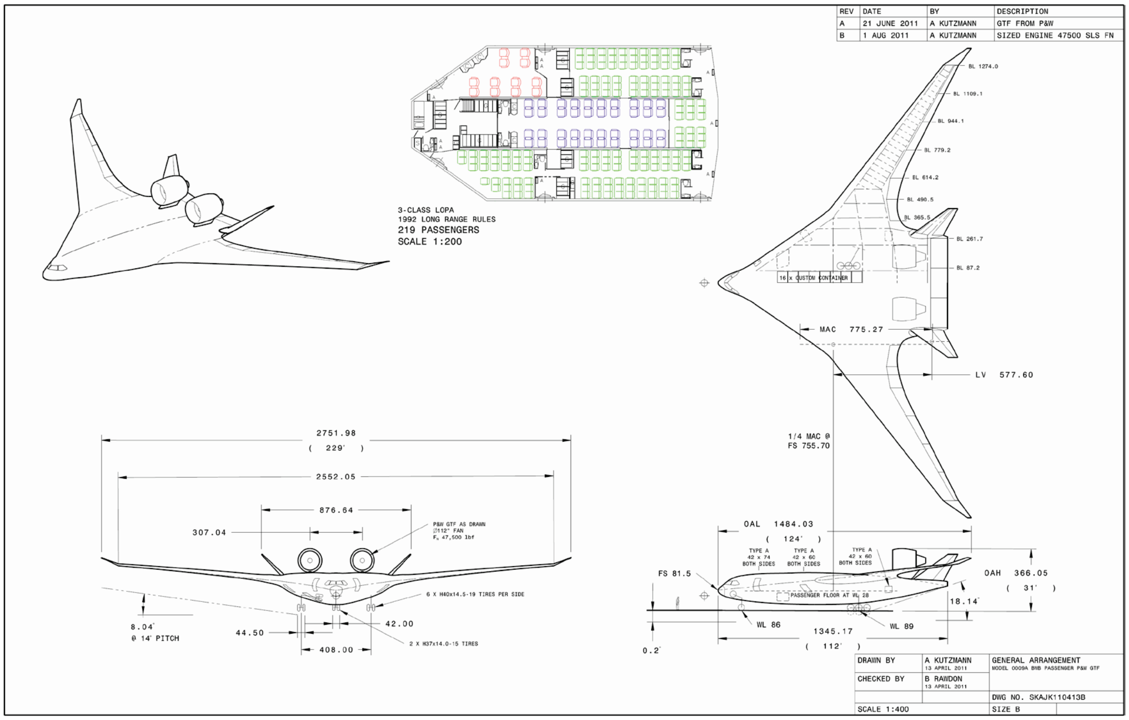


Figure 50. General Arrangement Drawing – 2025 BWB-0009A Passenger

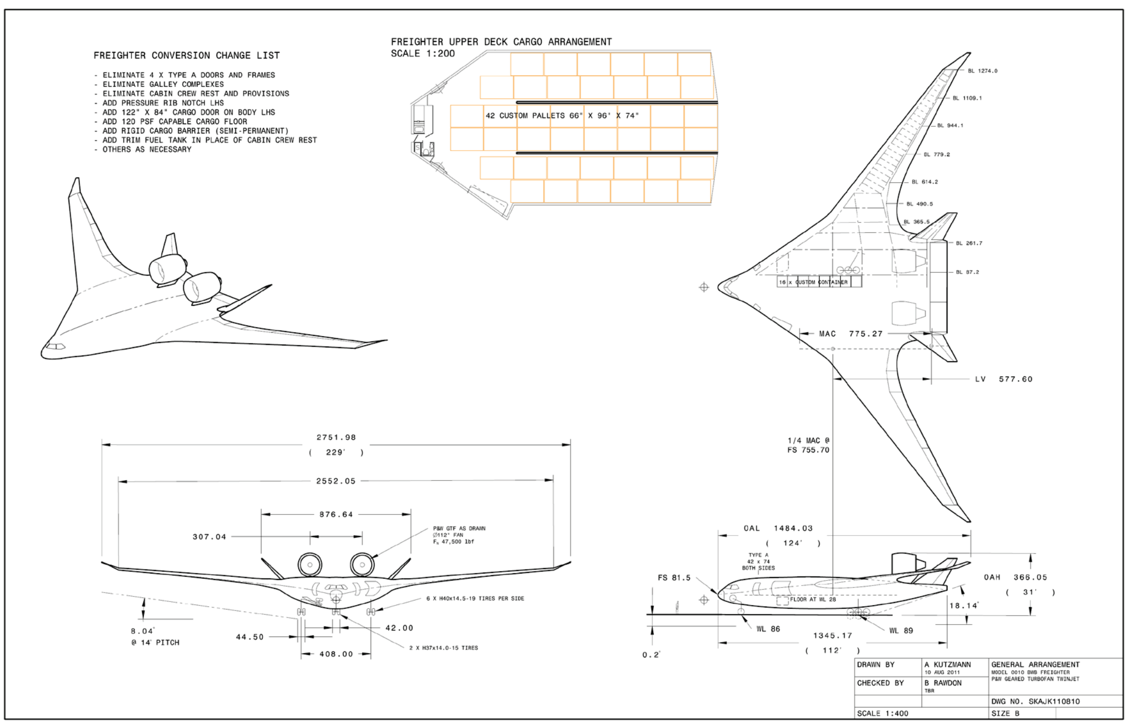


Figure 51. General Arrangement Drawing – 2025 BWB-0010 Freighter

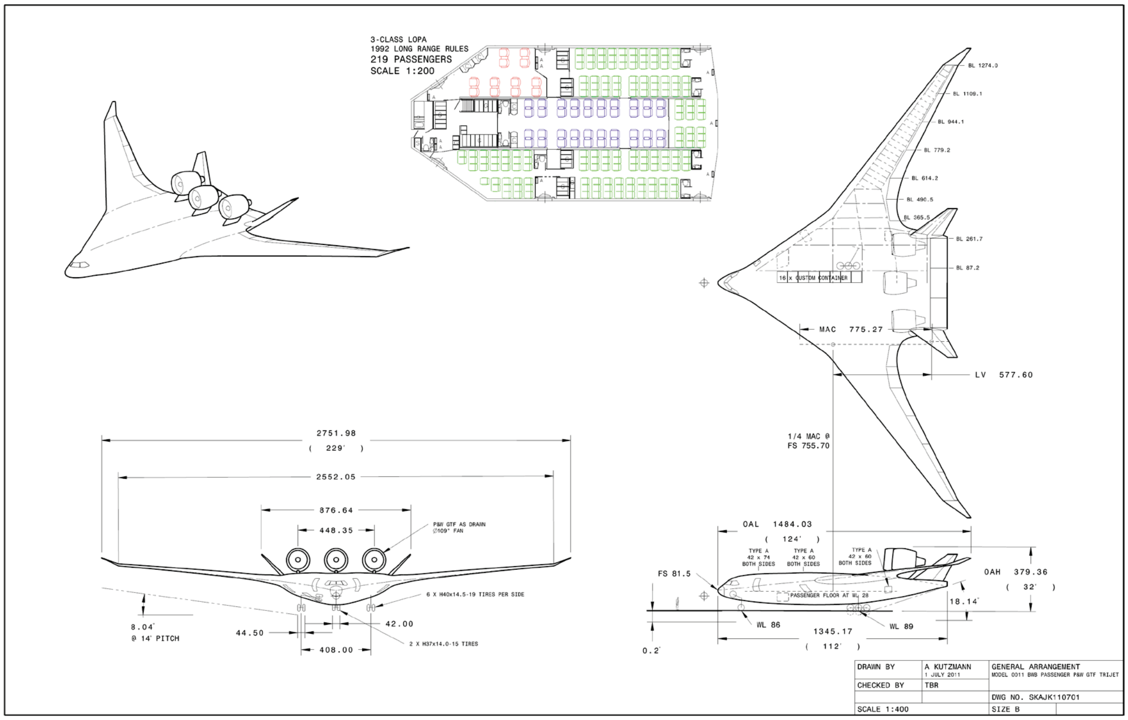


Figure 52. General Arrangement Drawing – 2025 BWB-0011 Passenger

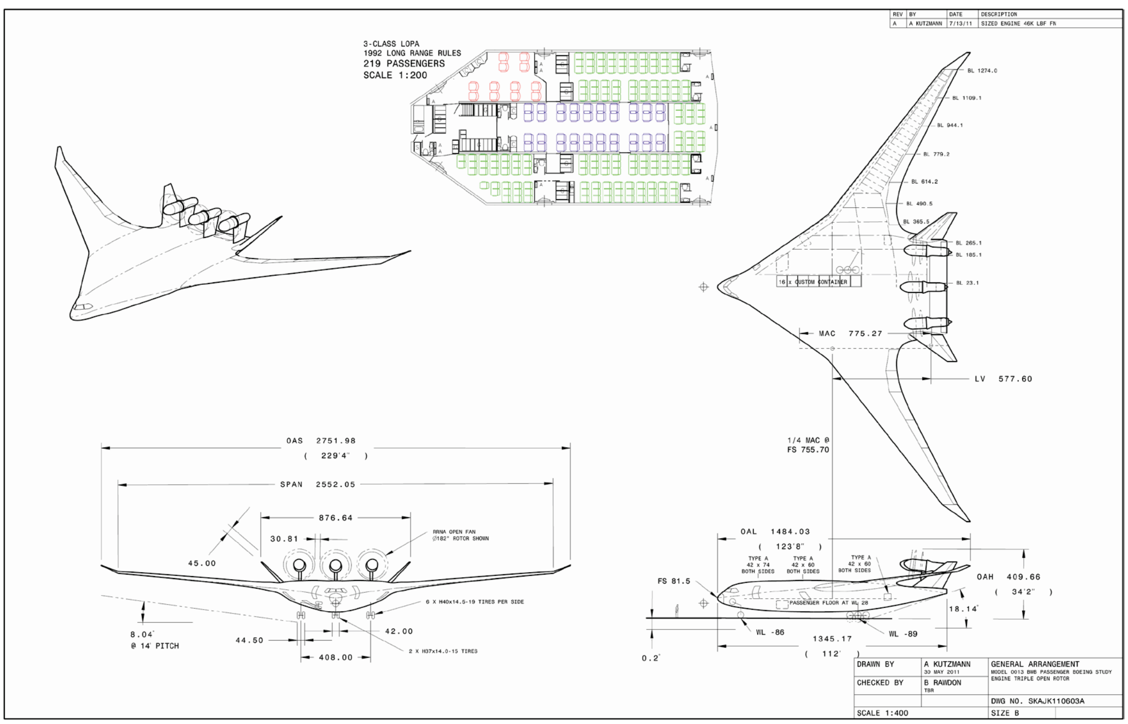


Figure 53. General Arrangement Drawing – 2025 BWB-0013 Passenger

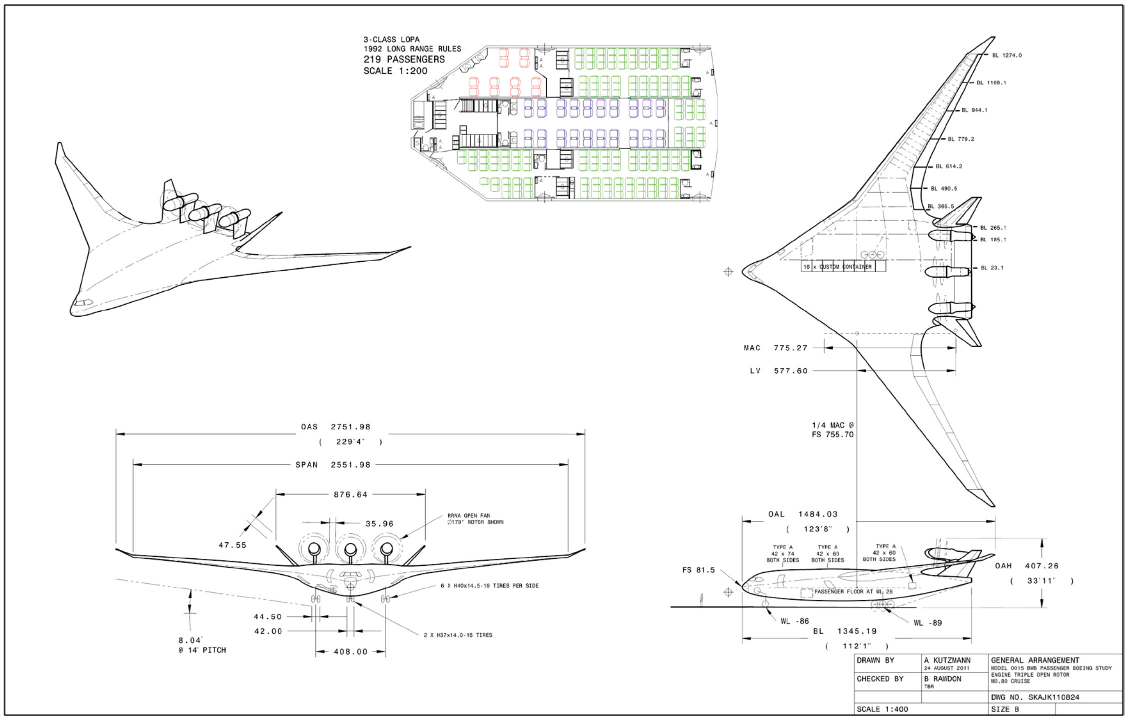


Figure 54. General Arrangement Drawing – 2025 BWB-0015 Passenger

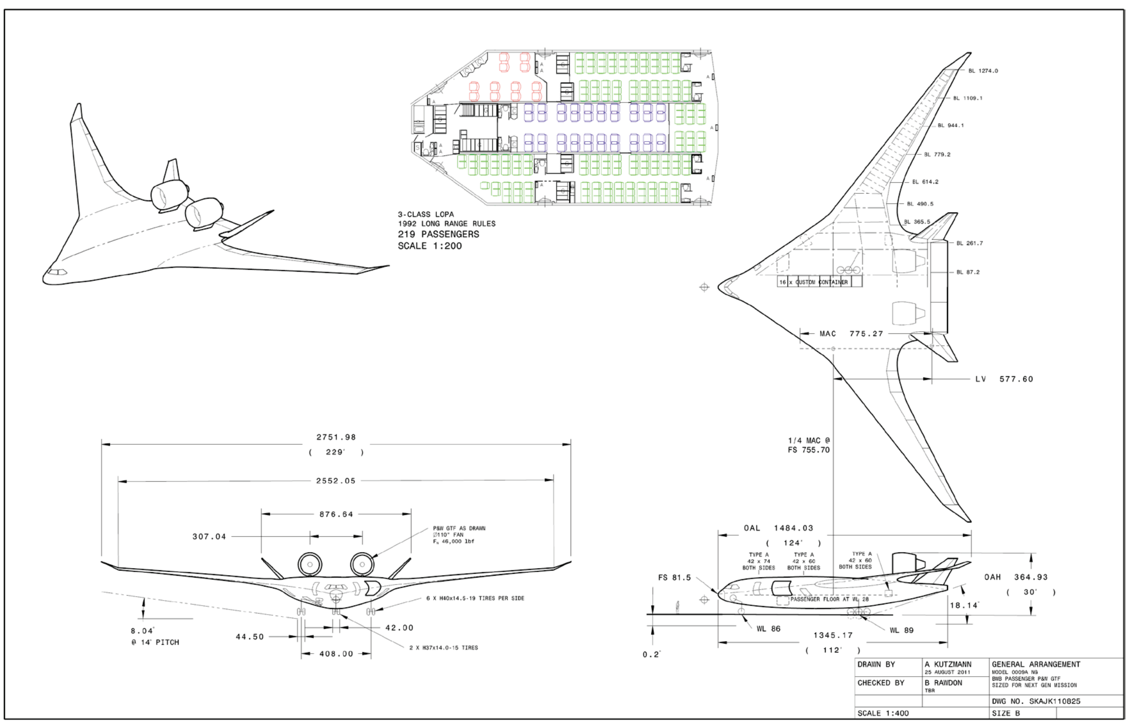


Figure 55. General Arrangement Drawing – 2025 BWB-0009A NG Passenger

Table 25. Summary Airplane Characteristics

	-0009A Passenger	-0010 Freighter	-0011 Passenger	-0013 Passenger	-0015 Passenger	-0009A NG

						Passenger
Wing Span (ft)	229.3	229.3	229.3	229.3	229.3	229.3
MTOGW (lb)	412,199	412,199	423,572	419,848	407,295	403,930
OEW (lb)	229,935	210,395	235,412	236,214	229,719	228,389
Reference Thrust (lbf) (total)	95,000	95,000	96,000	138,000	130,500	92,000

2.8.1.1.2 Configuration of Long-Span BWBs

Several additional longer-span BWB designs are explored to assess the benefits and shortcomings of increased span. As for the primary designs described above, these designs have common wing-body geometry. Variations are made in the propulsion systems as for the primary airplanes.

The longer-span airplane is designed and analyzed with a lower level of detail and fidelity than the primary BWB designs. The planform of the longer wing airplanes is shown in Figure 56. The outboard wing has geometry similar to that of the 2025 conventional configurations such as -0005. Coincidentally, the resulting 79.8-meter wingspan falls just under the 80-meter limit for Class VI airports. The centerbody and vertical stabilizer geometry is unchanged from the shorter-span versions.

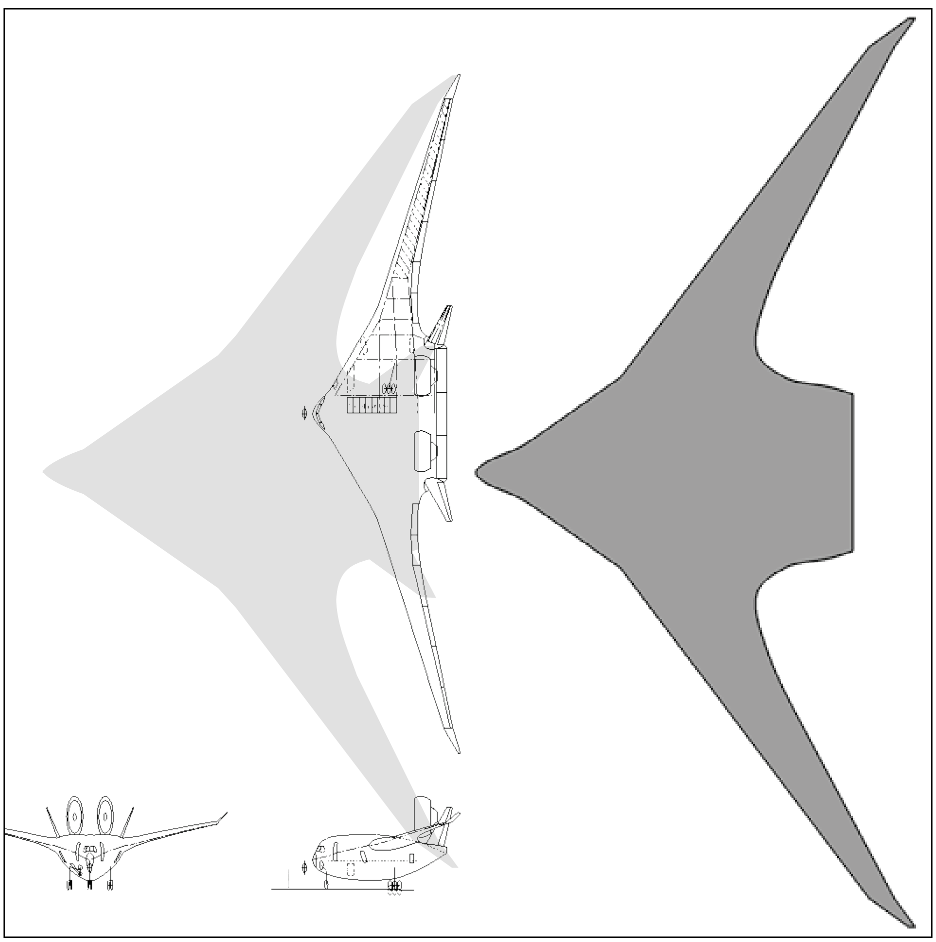


Figure 56. Planview Comparison of Long-Wing BWB with -0009A

Three versions of the long-wing BWB are explored:

- BWB-0031 powered by twin P&W geared turbofans; Mach 0.85 cruise

- BWB-0033 powered by three RRNA open rotor engines; Mach 0.85 cruise
- BWB-0035 powered by three RRNA open rotor engines; Mach 0.80 cruise

Approximate characteristics are summarized in Table 26.

Table 26. Summary Characteristics – Long-Wing BWBs

	-0031 Passenger	-0033 Passenger	-0035 Passenger
Wing Span (ft)	261.8	261.8	261.8
MTOGW (lb)	427,465	434,907	420,297
OEW (lb)	251,063	255,489	248,198
Reference Thrust (lbf) (total)	109,000	144,000	126,000

2.8.1.2 Aerodynamic Design

Aerodynamic design of the study's BWB airplanes is considerably more involved than for the conventional designs. Performance estimates of the conventional airplanes may be made on the basis of extensive historical databases. No such database exists for BWB designs. Furthermore, aerodynamic design of BWBs has a strong influence on numerous aspects of the airplane including wrapping of the payload (and resulting wetted area); structural efficiency and weight; trim, stability and control; and propulsion system integration. As a result, the quality of aerodynamic design is unusually important and is done with care.

Detailed aerodynamic design of BWB-0009A is preceded by several studies intended to address perceived opportunities and concerns. These include:

- Compare conventional and advanced outboard wing airfoils
- Investigate measures to reduce BWB cruise deck angle (angle of attack)
- Investigate the effect of centerbody camber and twist on deck angle
- Optimize BWB aerodynamic design for revised center of pressure

2.8.1.3 Mass Properties

Mass properties methods are described in Section 2.4.2.4.

BWB mass properties results are presented in short group weight statements such as Table 27. The weight statement format is somewhat different from that for conventional designs, such as Table 5 for the -0001 airliner. The primary difference is that "wing" and "fuselage" in conventional designs is now part of the BWB "wing-body". "Wing-body" is divided into six subsections to improve clarity. The BWB "nose & cockpit", "centerbody" and "afterbody-fixed" is roughly equivalent to the conventional design's fuselage. The remainder is roughly equivalent to "wing" except that some of the "aerodynamic surfaces" are located at the trailing edge of the centerbody.

Each of the passenger BWB short group weight statement tables below contains a note that the "standard and operational items" category includes 2400 lb for underfloor cargo container tare weight. This is true for all passenger airplanes in this study. (For the freighters, tare weight is counted as part of the payload.)

It is important to keep in mind that all six of the study airplanes described below have the same planform and same centerbody geometry. All but the -0015 have the same outer wing geometry – the -0015's outer wing has a t/c increased by 2%. This means that weight increments from design variations are less amplified than they might be in a conventional design for which the wing and tail areas vary widely with airplane gross weight. On the other hand, weight variations can be attributed with greater precision to the design changes.

The short group weight statement for BWB-0009A is shown in Table 27. Comparison with other airplanes may provide insight.

The conventional airplane most similar to the BWB-0009A is the T&W-0005. These two airplanes share engine type, structural materials and technologies. Key comparisons are:

- The BWB MTOGW is 36,653 lb lighter than the T&W. This is an 8.4% reduction.
- The BWB OEW is 21,074 lb lighter than the T&W. This is also an 8.4% reduction.
    - 2932 lb of this savings is from engines, pylons and engine systems.
- The three components making up the BWB "fuselage" as described above weigh 57,462 lb. The T&W fuselage weighs 44,642 lb. The BWB fuselage is 12,820 lb heavier or 28.7% more.
- The three components making up the BWB "wing" weigh 44,230 lb. The T&W wing weighs 70,586 lb, so the BWB is 26,356 lb lighter in this category.
- Taken together, the BWB wing-body is 13,536 lb lighter than the T&W wing and body together.
- BWB tails weigh 2742 lb. T&W tails weigh 7438 lb. The BWB is 4696 lb lighter.
- Adding up the differentials noted above for propulsion, fuselage, wing and tails: the BWB is 21,164 lb lighter – almost the same as the differential in OEW. Most of the OEW weight benefit of the BWB derives from propulsion, body, wing and tails.
    - Some portion of this weight differential stems from the lower gross weight of the BWB – this permits a lighter airframe and, for the T&W, drives a larger and heavier wing and tail.

Table 27. Short Group Weight Statement -0009A Airliner

BWB-0009A			
FUNCTIONAL GROUP		WEIGHT (LB)	
WING-BODY		101,691	
	Outerwing Box, LE & TE		35,918
	Aerodynamic Surfaces		7,329
	Nose & Cockpit		1,988
	Centerbody		48,846
	Afterbody-FIXED		6,628
	Outer Wing Lightning Protection Allowance		983
WINGLET/VERTICAL TAILS		2,724	
LANDING GEAR		18,049	
Propulsion Pod		29,732	
Pylons		3,806	
ENGINE SYSTEMS		400	
FUEL SYSTEM		5,696	
FLIGHT CONTROLS		8,302	
HYDRAULICS		1,943	
PNEUMATICS		1,142	
AUXILIARY POWER PLANT		1,423	
ELECTRICAL		4,394	
INSTRUMENTS		1,247	
AVIONICS & AUTOPILOT		3,609	
FURNISHINGS & EQUIPMENT		25,983	
AIR CONDITIONING		2,598	
ANTI-ICING		427	
Non-Cbdy Exterior Paint, Primer & Sealant		874	
WEIGHT EMPTY		214,041	
Standard & Operational Items*		15,894	
OPERATING WEIGHT EMPTY		229,935	
Mission FUEL		132,264	
Payload		50,000	
MAX TAKEOFF WEIGHT		412,199	
* Op Items includes 2,400 lbs underfloor container tare (16 containers)			

The BWB-0010 freighter is derived from the -0009A passenger airplane. Table 28 shows a short group weight statement for the -0010 configuration. According to the study's requirements, the freighter is constrained to the same MTOGW and engine size as the passenger airplane from which it is derived.

A comparison of the -0010 freighter with the -0009A passenger airplane shows that the -0009A operating weight is 19,540 pounds higher than the -0010's, predominantly because the passenger's summed Furnishings and Equipment and Load and Handling, and its standard and operational items are respectively 7,125 pounds and 14,120 pounds heavier than for the freighter derivative.

To conclude – the freighter conversion adds weight in minor structural reinforcements and in load and handling. It saves substantial weight in furnishings and equipment and in standard and operational items. As a result, the freighter's OEW is 19,540 lb lighter.

Table 28. Short Group Weight Statement -0010 Freighter

BWB-0010			
FUNCTIONAL GROUP		WEIGHT (LB)	
WING-BODY		103,490	
	Outerwing Box, LE & TE		37,134
	Aerodynamic Surfaces		7,329
	Nose & Cockpit		1,988
	Centerbody		49,430
	Afterbody-FIXED		6,628
	Outer Wing Lightning Protection Allowance		983
WINGLET/VERTICAL TAILS		2,630	
LANDING GEAR		18,049	
Propulsion Pod		29,732	
Pylons		3,806	
ENGINE SYSTEMS		400	
FUEL SYSTEM		5,696	
FLIGHT CONTROLS		8,302	
HYDRAULICS		1,943	
PNEUMATICS		1,142	
AUXILIARY POWER PLANT		1,423	
ELECTRICAL		4,394	
INSTRUMENTS		1,247	
AVIONICS & AUTOPILOT		3,609	
FURNISHINGS & EQUIPMENT		9,470	
AIR CONDITIONING		2,598	
ANTI-ICING		427	
Non-Cbdy Exterior Paint, Primer & Sealant		874	
LOAD & HANDLING		9,388	
Weight Empty		208,621	
Standard & Operational Items		1,775	
OPERATING WEIGHT EMPTY		210,395	
Mission FUEL		101,804	
PAYLOAD*		100,000	
MAX TAKEOFF WEIGHT		412,199	

A short group weight statement for BWB-0011 is shown in Table 29. This airplane is a three-engine version of the -0009A twin. A comparison of the -0011 with the -0009A highlights the differences between three and two-engine BWBs for this mission:

- The MTOGW of the -0011 is 11,373 lb greater than the -0009A's.
- 5897 lb of this difference is from the -0011's greater mission fuel weight.
- The -0011's propulsion pods, pylons and engine systems weigh 37,543 lb. This is 3605 lb more than the -0009A's.
    - For reference, the -0011's total thrust is 96,000 lbf. The -0009A's is 95,000 lbf. The -0011's extra 10.6% propulsion weight is primarily a result of engine weight scaling effects – not the extra 1.1% thrust.
- 9502 lb of the 11,373 lb MTOGW difference is attributed directly to engine and fuel weight increases. The remainder is may be attributed indirectly to these factors.

Table 29. Short Group Weight Statement -0011 Airliner

BWB-0011		
FUNCTIONAL GROUP	WEIGHT (LB)	
WING-BODY	102,803	
Outerwing Box, LE & TE		36,417
Aerodynamic Surfaces		7,086
Nose & Cockpit		1,988
Centerbody		49,702
Afterbody-FIXED		6,628
Outer Wing Lightning Protection Allowance		983
WINGLET/VERTICAL TAILS	2,630	
LANDING GEAR	18,503	
Propulsion Pod	32,751	
Pylons	4,192	
ENGINE SYSTEMS	600	
FUEL SYSTEM	5,696	
FLIGHT CONTROLS	8,302	
HYDRAULICS	1,943	
PNEUMATICS	1,142	
AUXILIARY POWER PLANT	1,423	
ELECTRICAL	4,394	
INSTRUMENTS	1,247	
AVIONICS & AUTOPILOT	3,609	
ANTI-ICING	427	
Non-Cbdy Exterior Paint, Primer & Sealant	874	
Weight Empty	219,118	
Standard & Operational Items*	16,293	
OPERATING WEIGHT EMPTY	235,411	
Mission FUEL	138,161	
PAYLOAD	50,000	
MAX TAKEOFF WEIGHT	423,572	
* Op Items includes 2,400 lbs underfloor container tare (16 containers)		

BWB-0013 is a triple open rotor version of the -0009A twin GTF. A short group weight statement for the -0013 is presented in Table 30. A comparison of the -0013 with the -0009A follows:

- The 419,848 lb MTOGW of the -0013 is 7649 lb heavier than the -0009A's. This difference stems from a 6269 lb greater OEW and 1380 lb more mission fuel.
- 5162 lb of the OEW difference stems from propulsion pod, pylons and engine systems weight – the open rotor engines are heavier than the geared turbofans.
- The remaining OEW weight difference is found in those components sensitive to increased MTOGW – the wing-body, winglet/vertical tails and landing gear.

The -0013 may also be paired with the -0011 tri-GTF for a three-engine to three-engine comparison:

- The 419,848 lb MTOGW of the -0013 is 3724 lb lighter than the -0011's. This difference is comprised of 793 lb greater OEW and 4517 lb less mission fuel.
- The -0013's propulsion pod, pylons and fuel systems are 1557 lb heavier than the -0011's.
- The lower MTOGW of the -0013 results in 764 lb lighter wing-body and landing gear weights. Other weights are unchanged.
- Conclusion: three open rotor engines are slightly heavier than three geared turbofans but provide reduced fuel consumption.

Table 30. Short Group Weight Statement -0013 Airliner

BWB-0013			
FUNCTIONAL GROUP		WEIGHT (LB)	
WING-BODY		102,188	
	Outerwing Box, LE & TE		36,335
	Aerodynamic Surfaces		7,086
	Nose & Cockpit		1,988
	Centerbody		49,169
	Afterbody-FIXED		6,628
	Outer Wing Lightning Protection Allowance		983
WINGLET/VERTICAL TAILS		2,630	
LANDING GEAR		18,354	
Propulsion Pod		33,190	
Pylons		5,310	
ENGINE SYSTEMS		600	
FUEL SYSTEM		5,696	
FLIGHT CONTROLS		8,302	
HYDRAULICS		1,943	
PNEUMATICS		1,142	
AUXILIARY POWER PLANT		1,423	
ELECTRICAL		4,394	
INSTRUMENTS		1,247	
AVIONICS & AUTOPILOT		3,609	
FURNISHINGS & EQUIPMENT		25,983	
AIR CONDITIONING		2,598	
ANTI-ICING		427	
Non-Cbdy Exterior Paint, Primer & Sealant		874	
Weight Empty		219,911	
Standard & Operational Items*		16,293	
OPERATING WEIGHT EMPTY		236,204	
Mission FUEL		133,644	
PAYLOAD		50,000	
MAX TAKEOFF WEIGHT		419,848	

BWB-0015 is a Mach 0.80 version of the Mach 0.85 triple open rotor -0013. A short group weight statement for -0015 is shown in Table 31. Key differences in the -0015 are 2% greater outer wing t/c and 5.4% less installed thrust. A comparison follows:

- BWB-0015's MTOGW is 12,553 lb lighter. This is the result of 6485 lb less OEW and 6068 lb less mission fuel.
- The -0015's smaller engines (propulsion pod, pylons and engine systems) are 2395 lb lighter.
- In the wing-body group, the main difference is the -0015's 3550 lb lighter outer wing box, leading edge and trailing edge. This is primarily a result of the greater outer wing t/c ratio. The -0015's lighter MTOGW is also a factor.
- The remaining significantly different group is landing gear: BWB-0015's gear is 501 lb lighter due to its lighter MTOGW.

Table 31. Short Group Weight Statement -0015 Airliner

BWB-0015			
FUNCTIONAL GROUP		WEIGHT (LB)	
WING-BODY		98,600	
	Outerwing Box, LE & TE		32,785
	Aerodynamic Surfaces		7,086
	Nose & Cockpit		1,988
	Centerbody		49,131
	Afterbody-FIXED		6,628
	Outer Wing Lightning Protection Allowance		983
WINGLET/VERTICAL TAILS		2,630	
LANDING GEAR		17,853	
Propulsion Pod		31,125	
Pylons		4,980	
ENGINE SYSTEMS		600	
FUEL SYSTEM		5,696	
FLIGHT CONTROLS		8,302	
HYDRAULICS		1,943	
PNEUMATICS		1,142	
AUXILIARY POWER PLANT		1,423	
ELECTRICAL		4,394	
INSTRUMENTS		1,247	
AVIONICS & AUTOPILOT		3,609	
FURNISHINGS & EQUIPMENT		25,983	
AIR CONDITIONING		2,598	
ANTI-ICING		427	
Non-Cbdy Exterior Paint, Primer & Sealant		874	
Weight Empty		213,426	
Standard & Operational Items*		16,293	
OPERATING WEIGHT EMPTY		229,719	
Mission FUEL		127,576	
PAYLOAD		50,000	
MAX TAKEOFF WEIGHT		407,295	
* S&O includes 2,400 lbs underfloor container tare (16 containers)			

BWB-0009A NG is a BWB-0009A resized for the NextGen mission described in Section 2.2.2.3. A short group weight statement for -0009A is shown in Table 32. In resizing the airplane, only engine thrust and airframe weights are changed – airplane geometry otherwise remains the same. A comparison between -0009A NG and -0009A is made:

- MTOGW of the -0009A NG is 8269 lb lighter. This results primarily from 6723 lb less mission fuel. Reduced thrust and MTOGW reduce OEW 1546 lb.
- Propulsion weight drops by 903 lb due to 3000 lbf less installed thrust.
- Other changes to OEW are driven by reduced MTOGW. Wing-body weight drops 313 lb and landing gear drops 330 lb.
- All other groups remain the same.

Table 32. Short Group Weight Statement -0009A NG Airliner

BWB-0009A-NG			
FUNCTIONAL GROUP		WEIGHT (LB)	
WING-BODY		101,378	
	Outerwing Box, LE & TE		35,630
	Aerodynamic Surfaces		7,329
	Nose & Cockpit		1,988
	Centerbody		48,821
	Afterbody-FIXED		6,628
	Outer Wing Lightning Protection Allowance		983
WINGLET/VERTICAL TAILS		2,724	
LANDING GEAR		17,719	
Propulsion Pod		28,932	
Pylons		3,703	
ENGINE SYSTEMS		400	
FUEL SYSTEM		5,696	
FLIGHT CONTROLS		8,302	
HYDRAULICS		1,943	
PNEUMATICS		1,142	
AUXILIARY POWER PLANT		1,423	
ELECTRICAL		4,394	
INSTRUMENTS		1,247	
AVIONICS & AUTOPILOT		3,609	
FURNISHINGS & EQUIPMENT		25,983	
AIR CONDITIONING		2,598	
ANTI-ICING		427	
Non-Cbdy Exterior Paint, Primer & Sealant		874	
WEIGHT EMPTY		212,495	
Standard & Operational Items*		15,894	
OPERATING WEIGHT EMPTY		228,389	
Mission FUEL		125,541	
Payload		50,000	
MAX TAKEOFF WEIGHT		403,930	
* Op Items includes 2,400 lbs underfloor container tare (16 containers)			

2.8.1.4 Sizing and Performance Evaluation

Sizing and performance results focus on the six primary BWB designs. Long-wing BWB results are summarized.

2.8.1.4.1 Mission Performance – Primary BWBs

Tabular results for the six primary BWB designs are shown in Table 33, Table 34 and Table 35.

These data permit several pertinent comparisons:

- Geared turbofan versus open rotor (-0009A versus -0013)
- Passenger versus freighter (-0009A versus -0010)
- Two engine versus three engine (-0009A versus -0011)
- Mach 0.85 cruise versus Mach 0.80 cruise (-0013 versus -0015)
- NASA reference mission versus NextGen mission (-0009A versus -0009A NG)

The following comparisons are presented in three blocks, one for each of the three following data tables. Additional comparisons are made in Section 2.10.

- GTF (-0009A) versus OR (-0013): The OR engine results in a MTOGW 1.9% heavier; its OEW is 2.7% heavier; fuel burn is reduced 0.1%. The greater weight of the OR engines practically eliminates the benefit from their increased efficiency.
- Passenger (-0009A) versus freighter (-0010): By design, passenger and freighter MTOGW is the same; the freighter's OEW is 8.5% lighter. On a ton-nm basis the freighter's fuel burn is reduced 48% - this is driven by the freighter's much greater design payload and far shorter design range.

- Two engine (-0009A) versus three engine (-0011): The three engine BWB has 2.8% heavier MTOGW; 2.4% heavier OEW; and 4.7% more fuel consumption. Total thrust is increased by 1.1%. The three-engine BWB is inferior to the twin.
- Mach 0.85 (-0013) versus Mach 0.80 (-0015): The Mach 0.80 airplane MTOGW is 3.0% lighter; its OEW is 2.8% lighter; fuel consumption is down 4.6%. Reduced cruise Mach number provides weight and fuel burn advantages despite the -0015's engines' reduced efficiency (noted in Section 2.10).
- NASA Reference rules (-0009A) versus NextGen (-0009A NG): The NextGen airplane MTOGW is 2.0% lighter; its OEW is 0.7% lighter; fuel burn is reduced 2.8%. NextGen rules are effective at reducing weight and fuel consumption.

Table 33. Sized BWB Configuration Characteristics

		Final-5	Final-5	Final-1	Final-3	Final-1	NextGen-5
Tare weight included in Payload		**ERA-009A-PAX**	**ERA-010-Cargo**	**ERA-011-PAX**	**ERA-013-PAX**	**ERA-015-PAX**	**ERA-009A-NG-PAX**
Reference	**Required**	**2025 BWB**	**2025 BWB**	**2025 BWB**	**2025 BWB**	**2025 BWB**	**2025 BWB**
	Perf.	**Mcr=0.85**	**Mcr=0.85**	**Mcr=0.85**	**Mcr=0.85**	**Mcr=0.80**	**Mcr=0.85**
		PW GTF	**PW GTF**	**PW Tri GTF**	**RR Tri OR**	**RR Tri OR**	**PW GTF**
MTOGW (lb)		412199	412199	423572	419848	407295	403930
OEW (lb)		229935	210395	235412	236214	229719	228389
Payload (lb)	**50k/100k**	50000	100000	50000	50000	50000	50000
Fuel Load at MTOGW (lb)		132264	101804	138160	133634	127576	125541
Range (nm)	**8000/6500**	8000	5841.5	8000	8000	8000	8000
Block Fuel Burned (lb)		121288	91943	126993	121381	115845	117919
nm/lb		0.06596	0.06353	0.06300	0.06591	0.06906	0.06784
NM*PL/LBf		3297.94	6353.39	3149.78	3295.41	3452.89	3392.16
Ton-nm/lbf		1.65	3.18	1.57	1.65	1.73	1.70
Reference Wing Area (sqft)		8048	8048	8048	8048	8048	8048
Wing Aspect Ratio		5.62	5.62	5.62	5.62	5.62	5.62
TO Ref FN @ SL, 0.0, +27F (lbf/eng)		47500	47500	32000	46000	43500	46000
Number of Engines		2	2	3	3	3	2
T/W		0.23	0.23	0.23	0.33	0.32	0.23
W/S		51	51	53	52	51	50
Time to climb to 35000 ft (min)		24.744	24.75	28.824	23.8	24.972	25.302
Dist. to climb to 35000 ft (nm)	**200**	151.72	151.78	184.92	151	154.18	154.69
R/C at 35000 ft (fpm)		661	661	492	456	500	631

Cruise performance of the six airplanes is compared:

- GTF (-0009A) versus OR (-0013): The OR engine increases mid-cruise L/D by 0.3%. Mid-cruise SFC is reduced (improved) by 3.6%. These efficiency gains are practically offset by the OR's increased weight.
- Passenger (-0009A) versus freighter (-0010): Comparison of these airplanes at cruise mid-point is unwise due to the far different cruise leg length. Initial cruise L/D of the two airplanes is practically identical. The freighter's SFC is slightly lower despite practically identical thrust levels, the result of the freighter's reduced engine power and bleed extraction needs. Mid and end of cruise throttle setting is also different.
- Two engine (-0009A) versus three engine (-0011): Initial cruise L/D of the three engine BWB is down 4.9%; mid-cruise L/D is up 0.6%. Cruise SFC of the tri-jet is consistently worse than the twins: mid-cruise SFC is up 1.4%. The triple-GTF has a generally lower L/D and worse SFC than the twin.
- Mach 0.85 (-0013) versus Mach 0.80 (-0015): Flight at Mach 0.80 generally increases cruise L/D. Mid cruise L/D increases 3.1%. At sized cruise operating points, the M 0.80 airplane has a lower SFC: mid-cruise SFC drops by 5.5%. However, propulsion system efficiency drops 0.4% despite the reduced cruise Mach number.
- NASA Reference rules (-0009A) versus NextGen (-0009A NG): NextGen rules permit a cruise-climb at the altitude that provides optimal performance; NASA Reference rules force a

4000-ft step climb, forcing an off-design flight condition for much of the cruise. NextGen rules improve initial cruise L/D by 0.2%; mid-cruise L/D improves 3.7%; final cruise L/D drops by 0.6%. The NextGen airplane has reached 42,479 ft by mid-cruise so by the end of cruise both airplanes have reached the 43,000-ft altitude limit and the NextGen airplane is lighter and slightly less efficient than the geometrically nearly identical -0009A NASA Reference airplane. Propulsion system efficiency is nearly identical for both airplanes.

Table 34. Sized BWB Cruise Performance

		ERA-009A-PAX	ERA-010-Cargo	ERA-011-PAX	ERA-013-PAX	ERA-015-PAX	ERA-009A-NG-PAX
Cruise type		Step-crus	Step-crus	Step-crus	Step-Cruise	Step-crus	Climb-crus
Initial cruise altitude (ft)	**35000**	39000	39000	35000	39000	39000	39763
Initial cruise Mach	**0.85**	0.85	0.85	0.85	0.85	0.8	0.85
Initial cruise L/D		23.924	23.925	22.752	23.936	24.188	23.966
Initial cruise total thrust (lbf)		16862	16865	18283	18191	16499	16499
Initial cruise tau		0.919	0.919	0.822	0.945	0.944	0.965
Initial cruise CL		0.2412	0.2412	0.2052	0.246	0.2693	0.2445
Mid cruise altitude (ft)		39000	39000	39000	39000	39000	42479
Mid cruise Mach	**0.85**	0.85	0.85	0.85	0.85	0.8	0.85
Mid cruise L/D		22.64	23.078	22.768	22.702	23.413	23.478
Mid cruise total thrust (lbf)		15270	15698	15881	15536	14958	14426
Mid cruise tau		0.832	0.855	0.856	0.854	0.855	0.967
Mid cruise CL		0.2067	0.2166	0.2162	0.2109	0.2363	0.2387
Final cruise altitude (ft)		43000	43000	43000	43000	43000	43000
Final cruise Mach	**0.85**	0.85	0.85	0.85	0.85	0.8	0.85
Final cruise L/D		22.38	23.198	22.272	22.491	23.046	22.252
Final cruise total thrust (lbf)		13070	13874	13393	13367	12737	12908
Final cruise tau		0.87	0.924	0.882	0.935	0.912	0.888
Final cruise CL		0.2119	0.2332	0.2161	0.2178	0.2401	0.2081

Takeoff performance is compared below. Landing performance of all six BWBs is about the same since this is driven by aerodynamic and weight considerations rather than propulsion system. All resulting landing field lengths are slightly greater than the 5200-ft target. Landing performance is also similar and all landing approach speeds are well below the 150-kt limit. The one outlier is the -0010 freighter – its approach speed is slightly faster than the others due to its greater landing weight. All six airplanes easily make the 10,500-ft field length requirement – the longest needed is 8916 ft.

- GTF (-0009A) versus OR (-0013): The twin-GTF -0009A takeoff field length is set by balanced field rules; the triple-OR -0013 is set by all-engine rules. The greater relative low-speed thrust of the OR engines reduces takeoff field length by 30.2%.
- Passenger (-0009A) versus freighter (-0010): These airplanes have identical takeoff performance due to their common airframes, MTOGW and engines.
- Two engine (-0009A) versus three engine (-0011): The all-engine field length of the tri-GTF is 6.5% shorter than the balanced field length of the twin-GTF.
- Mach 0.85 (-0013) versus Mach 0.80 (-0015): Takeoff performance is nearly identical: the M0.80 airplane takes off in 0.6% less distance.
- NASA Reference rules (-0009A) versus NextGen (-0009A NG): NextGen rules result in a 0.8% increase in takeoff distance. This may be due to a 1.2% reduction in takeoff thrust divided by MTOGW.

Table 35. Sized BWB Takeoff and Landing Performance

		ERA-009A-PAX	ERA-010-Cargo	ERA-011-PAX	ERA-013-PAX	ERA-015-PAX	ERA-009A-NG-PAX
Balanced field length @ SL, 86 degF (ft)	**10500**	8850	8850	7953	5996	5950	8916
2nd Segment Gradient (%)	**2.4 / 2.7**	2.4	2.4	5.187	8	7.908	2.4
Balanced field liftoff velocity (ktas)		149.75	149.75	147.33	145.1	142.98	149.31
All engine field length over 35 ft. (ft)	**10500**	8749	8749	8278	6179	6141	8800
All engine liftoff velocity (ktas)		157.53	157.53	152.62	151.4	149.15	156.94
Tail scrape angle (deg)		18	18	18	18	18	18
Balanced field liftoff angle (deg)		13.67	13.67	14.27	14.4	14.41	13.5
Flap deflection (deg or setting)		1	1	1	1	1	1
Landing weight (lbm)		291842	321186	297509	299398	292380	286584
Landing ground roll @ SL, Std (ft)		2146.72	2339.41	2190.71	2233	2184.66	2111.2
Landing distance over 50 ft. (ft)		3196.21	3388.89	3240.19	3283	3234.14	3160.68
Landing field length (ft)	**5200**	5327	5648	5400	5472	5390	5268
Landing approach speed (ktas)	**150**	131.38	137.83	132.65	133	131.5	130.19
Top of climb thrust (lbf/eng)		9251	9251	7469	6064	5829	8625.5
Takeoff thrust @ M=0.25 (lbf/eng)		38000	38000	25600	30320	28672	36800
Boeing Equivalent Thrust-BET (lbf/eng)		47690	47690	32128	38052	35983	46184
Engine Reference Thrust (lbf/eng)		51349	51349	34385	45046	45046	51349
Engine Scale Factor		0.9250	0.9250	0.9306	1.0212	0.9657	0.8958
FAR-36 Cutback altitude (ft)	**984 / 853**	1267	1267	1268	2099	1892	1249

Payload-range performance for six airplanes is shown in Figure 57, Figure 58 and Figure 59. These are:

- BWB-0009A passenger
- BWB-0010 freighter
- BWB-0013 passenger
- BWB-0014 – a freighter version of the -0013 not addressed above
- BWB-0009A NG passenger
- BWB-0010 NG freighter – a freighter version of -0009A NG, also not addressed above

Payload-range is shown in solid lines for design payloads and in dashed lines for maximum payloads. Each freighter is a derivative of its passenger "parent". The passenger airplane is sized to take the design payload of 50,000 lb to 8000 nm. Payload-range of the freighter is a fallout and the NASA target freighter mission of 100,000 lb to 6500 nm is indicated by a magenta dot.

For each plot, the long diagonal line represents performance at MTOGW. At a range of about 10,000 nm, the BWB designs reach their fuel volume limit. Payload reductions beyond this point permit no additional fuel to be on-loaded so little additional range is achieved.

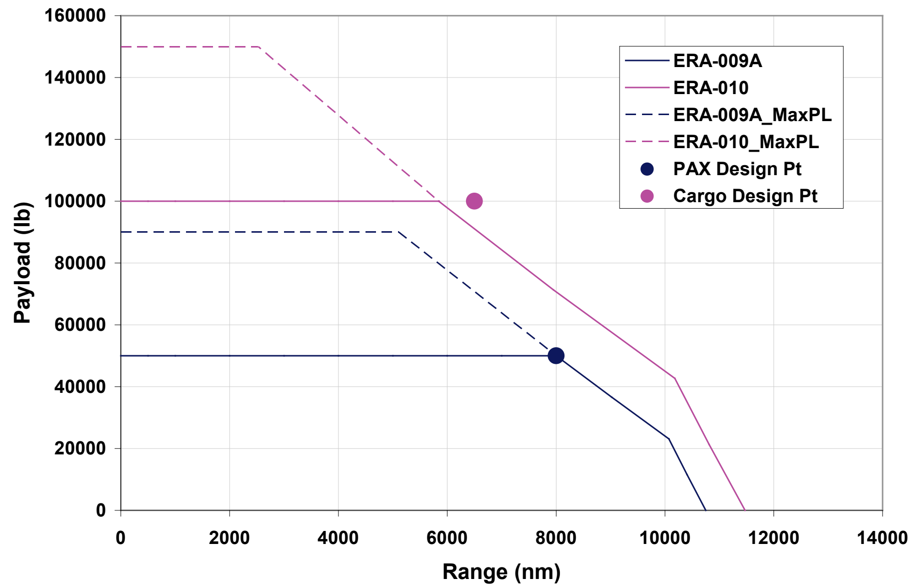


Figure 57. Payload-Range for -0009A Passenger and -0010 Freighter

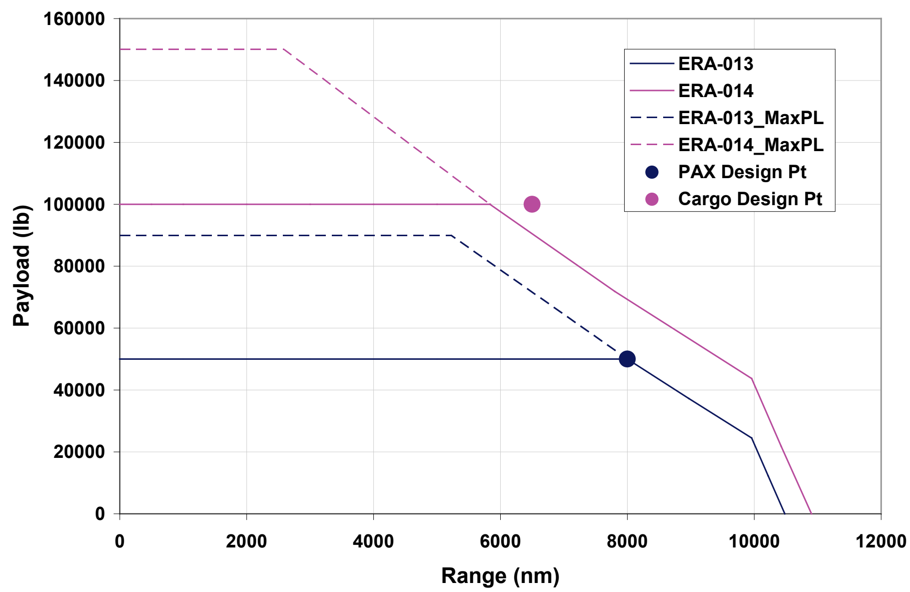


Figure 58. Payload-Range -0013 Passenger and -0014 Freighter

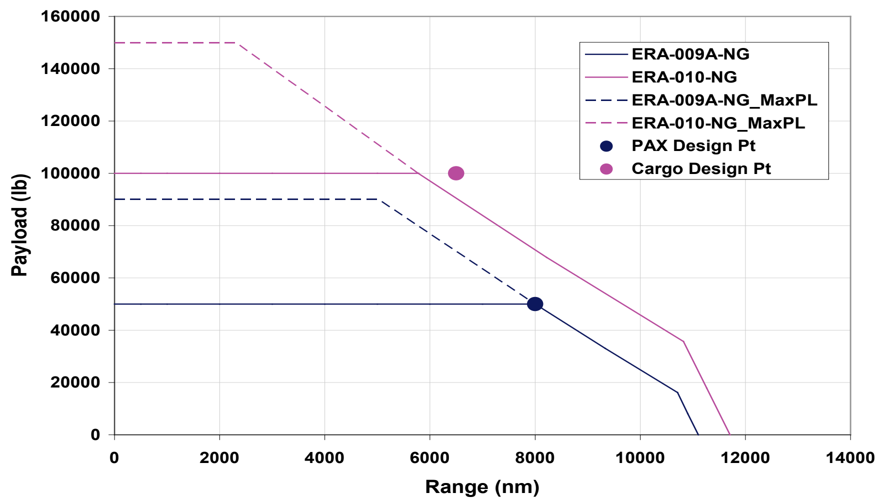


Figure 59. Payload-Range -0009A NG Passenger and -0010 NG Freighter

Fuel efficiency versus range is shown below in Figure 60, Figure 61 and Figure 62 for the six airplanes noted above. Fuel efficiency is quantified as payload times range divided by fuel burned, in the units ton-nm/lb. In the case of the passenger airplanes, payload does not include the tare weight of the cargo containers; for the freighters, tare weight is part of the payload.

For each airplane pair, fuel efficiency of the freighter exceeds that of the passenger airplane because the freighter has a greater payload and less empty weight. Fuel efficiency benefits from increased payload since payload is in the numerator of the fuel efficiency term. At a given payload, fuel efficiency improves moderately as range drops below the design range. At intermediate ranges, the airplane carries less fuel and is more efficient. At short ranges, the fixed overhead of taxi, takeoff and climb fuel outweighs the benefit of reduced fuel during flight. Peak efficiency for the passenger airplanes with design payload occur near 3000 nm range.

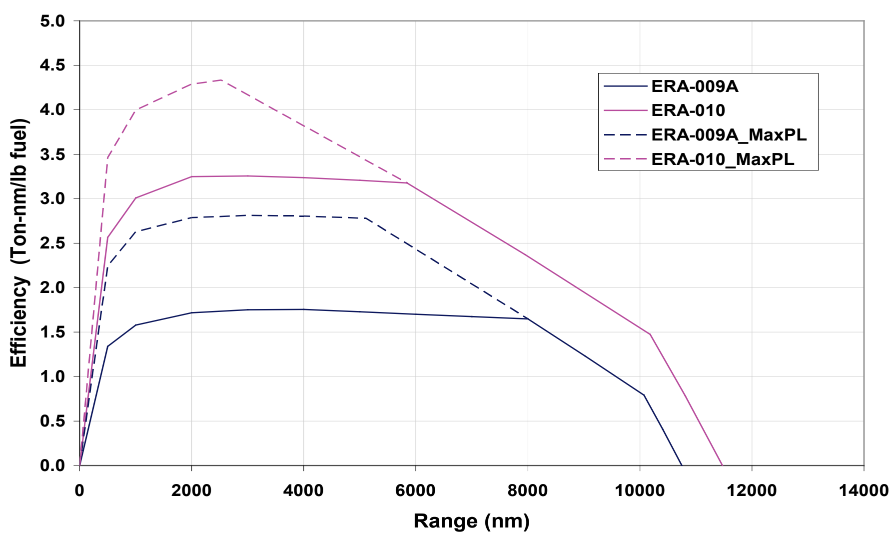


Figure 60. Fuel Efficiency -0009A Passenger and -0010 Freighter

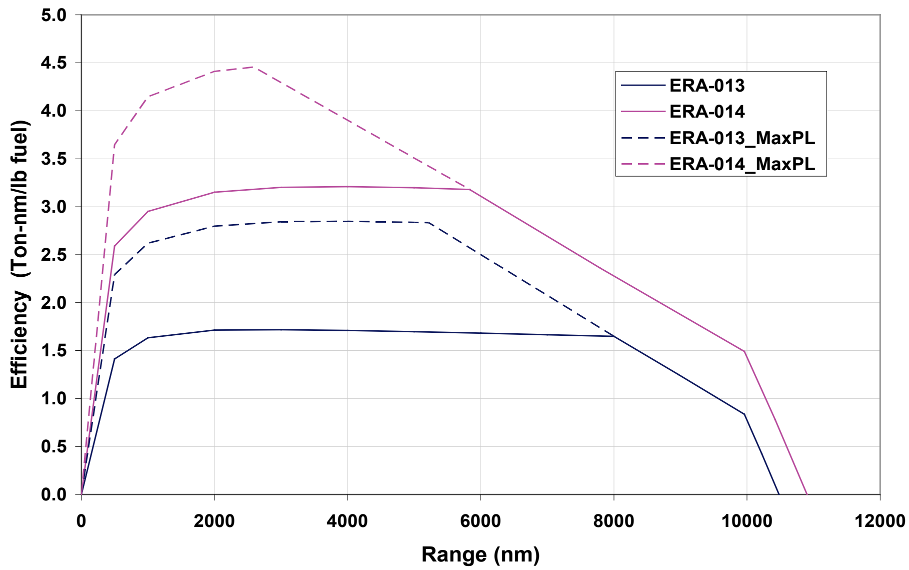


Figure 61. Fuel Efficiency -0013 Passenger and -0014 Freighter

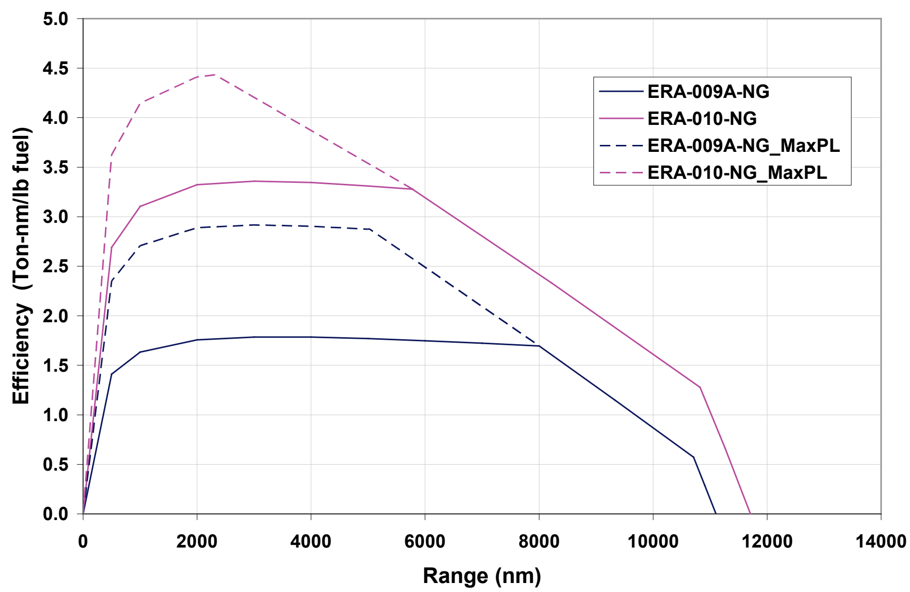


Figure 62. Fuel Efficiency -0009A NG Passenger and -0010 NG Freighter

2.8.1.4.2 Mission Performance – Long-Wing BWBs

Mission performance of the three sized long-wing BWB designs is presented in Table 36, Table 37 and Table 38. Note that these airplanes are evaluated to a somewhat lower level of fidelity that the six primary BWB designs described above.

This data enables comparison among the long-wing passenger BWBs. Additional comparisons are provided in Section 2.10. Comparisons among the long wing models include:

- GTF (-0031) versus OR (-0033)
- Mach 0.85 (-0033) versus Mach 0.80 (-0035)

Configuration characteristics are tabulated in Table 36. In general, similar conclusions are reached for the long-wing airplanes as for the primary BWBs discussed above.

- GTF (-0031) versus OR (-0033): The OR airplane is 1.7% heavier in MTOGW; 1.77% heavier in OEW. The OR airplane also burns 1.5% more fuel. The OR airplane is inferior to the GTF version.
- Mach 0.85 (-0033) versus Mach 0.80 (-0035): Slowing down to M0.80 reduces MTOGW 3.4%; OEW is reduced 2.9%. Fuel burn drops 5.5% to a value 4.1% below that of the GTF version. Slowing down is slightly more beneficial to the long-wing BWB than to the "normal" wing versions (-0013 and -0015).

Table 36. Sized Long-Wing BWB Configuration Characteristics

Tare weight included in Payload		**ERA-031-PAX**	**ERA-033-PAX**	**ERA-035-PAX**
Reference	**Required**	**2025 BWB**	**2025 BWB**	**2025 BWB**
	Perf.	**Mcr=0.85**	**Mcr=0.85**	**Mcr=0.80**
		PW GTF	**RR tri OR**	**RR tri OR**
MTOGW (lb)		427465	434907	420297
OEW (lb)		251063	255489	248198
Payload (lb)	**50k/100k**	50000	50000	50000
Fuel Load at MTOGW (lb)		126402	129418	122099
Range (nm)	**8000/6500**	8000	8000	8000
Block Fuel Burned (lb)		115549	117279	110833
nm/lb		0.06923	0.06821	0.07218
NM*PL/LBf		3461.73	3410.67	3609.03
Ton-nm/lbf		1.73	1.71	1.80
Reference Wing Area (sqft)		8724	8724	8724
Wing Aspect Ratio		6.888	6.888	6.888
TO Ref FN @ SL, 0.0, +27F (lbf/eng)		54500	48000	42000
Number of Engines		2	3	3
T/W		0.25	0.33	0.30
W/S		49	50	48
Time to climb to 35000 ft (min)		17.748	19.542	23.88
Dist. to climb to 35000 ft (nm)	**200**	100.18	115.5	139.09
R/C at 35000 ft (fpm)		1073	757	538

Cruise performance is shown in Table 37. Cruise L/D fluctuates with cruise segment depending on how close the forced 4000-ft cruise altitude step is to the ideal altitude.

- GTF (-0031) versus OR (-0033): Initial cruise L/D of the open rotor is 0.6% greater; mid-cruise L/D is 4.9% worse. Mid-cruise SFC of the open rotor is 2.1% better.
- Mach 0.85 (-0033) versus Mach 0.80 (-0035): Initial cruise L/D of the M0.80 OR is 2.9% greater than the M0.85 version. Mid-cruise L/D is 3.8% better. Mid-cruise SFC is 6.2% better but propulsion system efficiency increases only 0.4%.

Table 37. Sized Long-Wing BWB Cruise Performance

		ERA-031-PAX	ERA-033-PAX	ERA-035-PAX
Cruise type		Step-crus	Step-Cruise	Step-Cruise
Initial cruise altitude (ft)	**35000**	39000	39000	39000
Initial cruise Mach	**0.85**	0.85	0.85	0.8
Initial cruise L/D		25.77	25.913	26.653
Initial cruise total thrust (lbf)		16305	16504	15467
Initial cruise tau		0.774	0.869	0.916
Initial cruise CL		0.2317	0.2359	0.2567
Mid cruise altitude (ft)		43000	39000	39000
Mid cruise Mach	**0.85**	0.85	0.85	0.8
Mid cruise L/D		25.767	24.502	25.444
Mid cruise total thrust (lbf)		14270	15325	14220
Mid cruise tau		0.828	0.807	0.842
Mid cruise CL		0.2458	0.2071	0.2253
Final cruise altitude (ft)		45000	43000	43000
Final cruise Mach	**0.85**	0.85	0.85	0.8
Final cruise L/D		24.88	24.287	25.325
Final cruise total thrust (lbf)		12610	13174	12305
Final cruise tau		0.809	0.883	0.912
Final cruise CL		0.2309	0.2139	0.2351

Takeoff and landing performance is shown in Table 38. Takeoff performance of all three airplanes far exceeds the 10,500-ft requirement. The two-engine airplane's takeoff performance is set by balanced field length; the three-engine versions' are set by all-engine field length over 35 ft. Landing field length of all three airplanes is approximately the same; all slightly exceed the 5200-ft target. Landing speeds are also approximately the same and are ~18 knots under the 150-knot requirement.

Table 38. Sized Long-Wing BWB Takeoff and Landing Performance

		ERA-031-PAX	ERA-033-PAX	ERA-035-PAX
Balanced field length @ SL, 86 degF (ft)	**10500**	7316	5664	6033
2nd Segment Gradient (%)	**2.4 / 2.7**	3.363	8.487	7.092
Balanced field liftoff velocity (ktas)		142.84	141.69	139.99
All engine field length over 35 ft. (ft)	**10500**	7199	5843	6241
All engine liftoff velocity (ktas)		151.57	148.05	145.88
Tail scrape angle (deg)		18	18	18
Balanced field liftoff angle (deg)		14.23	14.42	14.36
Flap deflection (deg or setting)		1	1	1
Landing weight (lbm)		312847	318558	310394
Landing ground roll @ SL, Std (ft)		2091.34	2150.65	2094.56
Landing distance over 50 ft. (ft)		3140.82	3200.13	3144.04
Landing field length (ft)	**5200**	5235	5334	5240
Landing approach speed (ktas)	**150**	130.65	131.84	130.14
Top of climb thrust (lbf/eng)		10614	6327	5628
Takeoff thrust @ M=0.25 (lbf/eng)		43601	30982	27109
Boeing Equivalent Thrust-BET (lbf/eng)		54719	38882	34022
Engine Reference Thrust (lbf/eng)		51349	45046	45046
Engine Scale Factor		1.0614	1.0656	0.9324
FAR-36 Cutback altitude (ft)	**984 / 853**	1661	1776	1776

2.8.1.5 Acoustics Analysis

2.8.1.5.1 Noise Certification Results

2.9 Acoustics Analysis

The NASA N+2 noise goal requires a cumulative margin of 42 dB to the regulative requirement of Stage 4 for the Effective Perceived Noise Level (EPNL), which is a metric for aircraft noise certification measured at the approach, cutback and sideline locations. This is clearly a very aggressive goal, amply illustrated by the fact that the generation of large commercial aircraft currently in service, which is commonly referred to as the Tube-and-Wing (T&W) design, has a cumulative EPNL margin of about 10 dB to the Stage 4 limit. To achieve the approximately 32 dB noise reduction from the levels of the current generation of aircraft, it is apparent that multiple technologies will be required, including advanced engine technologies, unconventional airframe configurations and new flight procedures. This has led to the activities in Blended-Wing-Body (BWB) and Hybrid-Wing-Body (HWB) studies in recent years, especially concerning the integrated effects of airframe, propulsion and acoustics.[7],[8],[9],[10]

It is conceived that advanced engine technologies can reduce the engine noise source amplitudes, while meeting other goals such as fuel savings and emissions. The engine noise radiated to the far field can then be further lowered by utilizing the airframe structure to shield the noise propagation. This is the concept studied in this report; three airframe designs, the conventional T&W, the BWB, and an advanced T&W, are combined with various propulsion options to reveal the acoustic characteristics of the airframe/propulsion integration. Engine noise shielding can be achieved by both the BWB design and the advanced T&W configuration. The latter has the engines mounted on the fuselage above the wings, which utilizes the wing and the fuselage for shielding, respectively for inlet noise and for jet and aft fan noise.

Due to practical constraints in aircraft design such as aerodynamic performance and propulsion efficiency, engine installation is likely to be limited to the vicinity of the airframe/wing trailing edges. The efficiency of engine noise shielding in this case is then correspondingly limited, and shielding alone is not likely to be enough to achieve the NASA 42 dB noise goal. As a very low fidelity estimate, noise shielding for practical aircraft would probably have a maximum benefit of about 15 dB for the cumulative engine noise levels, far from the NASA goal. The actual reduction will of course depend on the detailed designs. For the BWB/HWB configuration, for example, the engines will not likely to be installed much further than one fan diameter upstream of the trailing edges, due to other constraints in the aircraft system design, including the aerodynamic performance, stability and control, and propulsion efficiency. This puts an upper bound on the noise shielding benefit because the propagation to the aft quadrant is not significantly shielded. Thus, engine noise source amplitude reduction will also have to play a large role in achieving the NASA noise goal. Of course, advanced engine technologies will also be needed to achieve other goals such as fuel savings and emissions. This is why various engine options are studied here, including the Geared Turbofan (GTF), the Advanced Turbofan (ATF) and the Open Rotor (OR) engine, to select the best combination for the goals. Again as a very low fidelity estimate, the advanced engines may contribute about 12 dB to the cumulative engine noise reduction.

By combining these two aspects of noise reduction, namely, engine noise source amplitude reduction and shielding, the engine noise component for the BWB configuration and the advanced T&W design can be expected to be significantly lower than that of current generation of engines on conventional T&W aircraft, probably to the maximum of about 27 dB. This significant reduction in engine noise greatly helps the acoustics of the advanced design concepts reported here; as will be discussed in detail in subsequent sections, both the BWB design and the advanced T&W can achieve cumulative EPNL margins of more than 30 dB to the Stage 4 limit, an achievement that is significant by any practical standard but is short of the NASA goal. It will also be shown that the NASA N+2 goal of 42 dB margin to Stage 4 becomes feasible only with substantial development of further noise reduction on airframe noise components, with acoustic optimization on both local and system level, and/or with low noise operation procedures. None of these needed technologies is trivial and all of them are in very low Technology Readiness Level (TRL), highlighting the difficulties of the challenge of achieving the NASA N+2 noise goal.

The reason for this conclusion is that the significant engine noise reduction cannot be directly translated into the same amount of EPNL reduction for the total aircraft noise, because as the engine noise is reduced, the airframe noise components will become comparable to or larger than the engine noise, diminishing the benefits of shielding and engine noise technology to the total aircraft noise levels. This really should not come as a surprise, because the aircraft is a system of multiple components and the total noise is usually dominated by a few of them. When noise reduction is achieved on these few components, they may or may not still be the dominant components. In the latter case where the noise reduction is significant enough so that they are not the dominant component any more, some other components become the dominant contributors to the total noise, and further noise reduction can only be effective if the reduction is on the new dominant components. For the configurations studied here, it will be shown that the engine noise reduction has reached a plateau so that efficient further reduction will have to come from the airframe noise components. For the BWB design, these are the main landing gears and the leading edge slats, while for the advance T&W, they are the flap side edges and the slats, the reasons for which will be given in later sections. It will be shown that for the BWB design, reductions in the main landing gear and the slat component can lead to total noise reductions that meet the NASA N+2 noise goal, though it should be pointed out that the required component noise technologies are mostly in development and still face many significant hurdles before they can be considered implementable on real aircraft.

2.9.1 Scope of Acoustic Analysis

2.9.1.1 Configurations

Acoustic analyses are performed on 7 aircraft configurations with various airframe designs and propulsion systems. These are summarized in Table 39, listing the configuration number, the airframe design, the engine type and number, and the maximum takeoff weight (MTOW).

Table 39. Summary of Configurations for Acoustic Analysis

ID	Airframe	Engine	MTOW (lb)
0005	T&W	Twin GTF	449,852
0007	T&W	Twin ATF	428,624
0009	BWB	Twin GTF	412,199
0011	BWB	Tri GTF	423,572
0013	BWB (M=0.85)	Tri OR	419,848
0015	BWB (M=0.8)	Tri OR	407,295
0027	ATW	Twin ATF	456,089

These are summarized here for the convenience of reference in the acoustic analyses, while the design details of each configuration are described in other parts of the report. The first two configurations are conventional T&W design with the turbofan engines mounted under the wing. Both the geared turbofan and the advanced turbofan engines are studied for this conventional design, respectively the configuration 0005 and 0007. The next two configurations are the BWB design with the geared turbofan engines with the configuration 0009 and 0011 respectively for the twin and tri engine design. The next two configurations in Table 39 are also BWB, but with open rotor engines as the propulsion system. Both these configurations have three engines with the configuration 0013 and 0015 respectively designed for cruise Mach number of 0.85 and 0.8. The two BWB types are illustrated in Figure 63 with the upper diagram for the twin engine design and the lower diagram for the open rotor design. The last design in Table 39, the configuration 0027, is an advanced tube and wing with the engines mounted on the fuselage above the wing. This is illustrated in Figure 64, which also shows that the fuselage has a double deck layout.

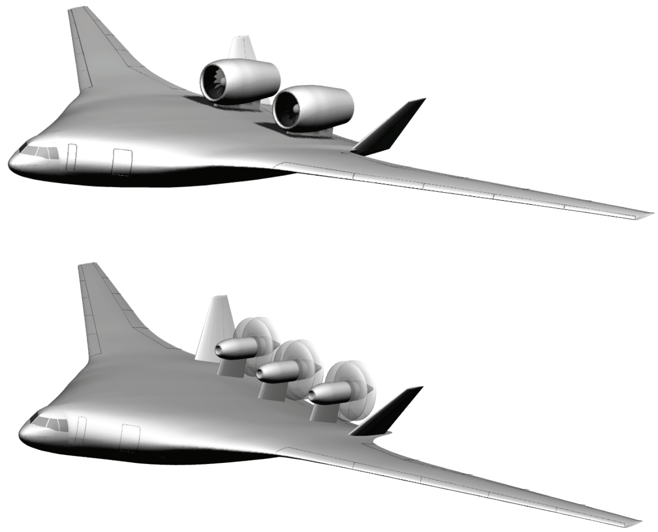


Figure 63. BWB configurations with turbofan (upper) and open rotor (lower) engines

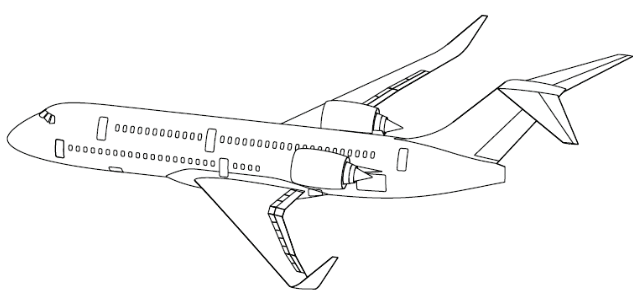


Figure 64. Advanced tube and wing design with turbofan engines

2.9.2 Overall Summary of Acoustic Results

The baseline configurations of the 7 designs discussed in Section 2.9.1.1 are analyzed for the three aircraft noise certification conditions with the results summarized in Table 40. The table gives the EPNL results for each configuration together with the corresponding Stage 3 limits and the corresponding margins, given at the individual conditions as well as the cumulative results. To facilitate easy comparisons, the results are regrouped and given in Table 41 for the EPNL results only. From Table 39, it is clear that all the configurations have comparable maximum takeoff weight, so that the Stage 3 noise limits are also comparable for all the configurations at approach and sideline conditions, respectively about 104 and 100 dB. The EPNL limits at cutback conditions depend on the number of engines, in addition to the maximum takeoff weight. Thus, at cutback conditions, the twin-engine designs all have the limit of approximately 97 dB, and the limit for the tri-engine configurations is approximately 100 dB.

Table 40. Summary of Acoustic Analysis Results

	Approach	Cutback	Sideline	CUM
0005 Stage 3 EPNL Limits	103.9	97.3	100.5	301.8
0005 EPNL	90.1	88.1	85	263.2
0005 Margin to Stage 3	13.8	9.2	15.5	38.6
0007 Stage 3 EPNL Limits	103.8	97	100.3	301.1
0007 EPNL	92	86.7	89.4	268.1
0007 Margin to Stage 3	11.8	10.3	10.9	33
0009 Stage 3 EPNL Limits	103.6	96.8	100.2	300.6
0009 EPNL	92.3	83.5	80.9	256.7
0009 Margin to Stage 3	11.3	13.3	19.3	43.9
0011 Stage 3 EPNL Limits	103.7	100	100.3	304
0011 EPNL	94.5	85.1	83.1	262.7
0011 Margin to Stage 3	9.2	14.9	17.2	41.3
0013 Stage 3 EPNL Limits	103.7	99.9	100.3	303.9
0013 EPNL	95.3	84.4	88.5	268.2
0013 Margin to Stage 3	8.4	15.5	11.8	35.7
0015 Stage 3 EPNL Limits	103.6	99.8	100.1	300.5
0015 EPNL	94.8	84.8	88.6	268.2
0015 Margin to Stage 3	8.8	15	11.5	32.3
0027 Stage 3 EPNL Limits	104	97.4	100.6	301.9
0027 EPNL	92.1	85	82.8	259.9
0027 Margin to Stage 3	11.9	12.4	17.8	42

Table 41. Summary of EPNL

Configuration	Approach	Cutback	Sideline	CUM
0005	90.1	88.1	85.0	263.2
0007	92.0	86.7	89.4	268.1
0009	92.3	83.5	80.9	256.7
0011	94.5	85.1	83.1	262.7
0013	95.3	84.4	88.5	268.2
0015	94.8	84.8	88.6	268.2
0027	92.1	85.0	82.8	259.9

These results are also plotted in Figure 65 and Figure 66, with Figure 65 for the three individual conditions Figure 66 for the cumulative levels. For the approach condition, the top diagram in Figure 65 shows that the conventional tube and wing designs (0005 and 0007) are not noisier than the other configurations. For designs with turbofan engines, the low engine noise renders the airframe noise the dominant contributor to the total noise, for which the BWB and the T&W design have comparable amplitude, even though the airframe structures for the two are very different. This will be analyzed in detail in a later section, and is mainly due to the high main landing gear noise for the BWB design and the high flap side edge noise for the T&W design. The approach noise for the BWB configuration with open rotor engines is the highest in the group because engine noise is still a major component for this type of engines. By comparing the top diagram with the other two in Figure 65, which are respectively for the cutback and sideline conditions, the trends seems to reverse; the BWB design shows now noticeable advantages, especially for the designs with the geared turbofan engine. This is the benefit of noise shielding. At cutback and sideline conditions, engine power settings are high so that engine noise can be significant without shielding, as in the conventional T&W design. Thus, higher noise levels for the configuration 0005 and 0007 are seen in the middle diagram of Figure 65 at cutback conditions because the rest of the group has the benefit of shielding, including the advanced T&W design 0027. The shielding effects are less at sideline conditions for the BWB configurations powered by the open rotor engines, as seen in the bottom diagram of Figure 65, both because of the less effective shielding of the tri-engine design and due to the less efficient shielding of low frequency tones from the open rotors.

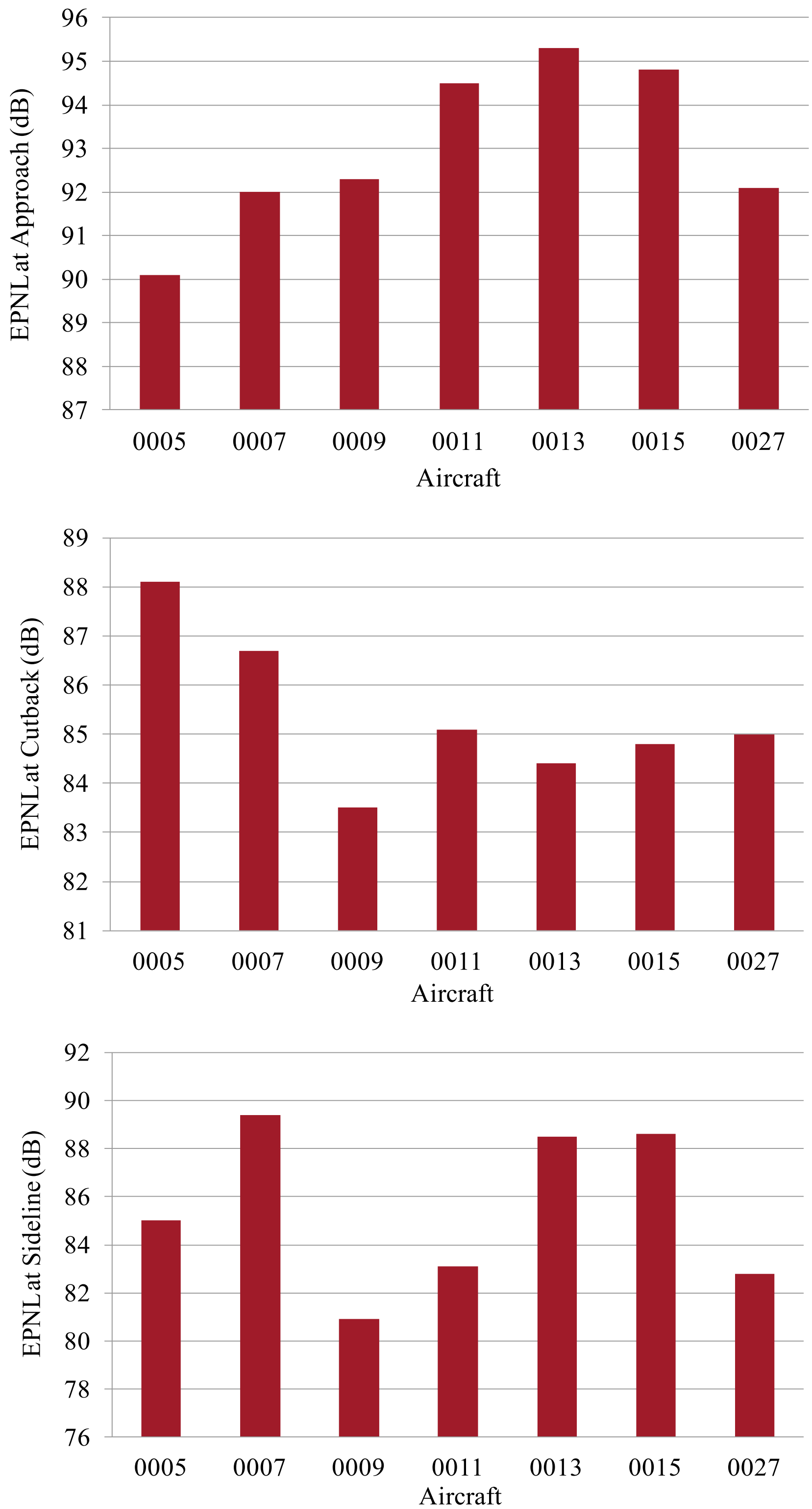


Figure 65. EPNL at approach conditions for baseline configurations

By adding the EPNL numbers for the three conditions together, the cumulative EPNL is shown in Figure 66. Due to the low levels of noise source amplitude of the geared turbofan engines and the significant shielding of the BWB design, the configuration 0009 has the lowest cumulative EPNL, followed by the advanced T&W design that also benefits from the shielding effects. It is also interesting to note that the BWB designs with the open rotor engines are not quieter than the conventional T&W designs, even though the former benefit from shielding. This highlights the importance of the quiet engine technologies; the open rotor engines have higher noise levels that essentially cancel the benefits of shielding, in comparison with conventional T&W designs with turbofan engines.

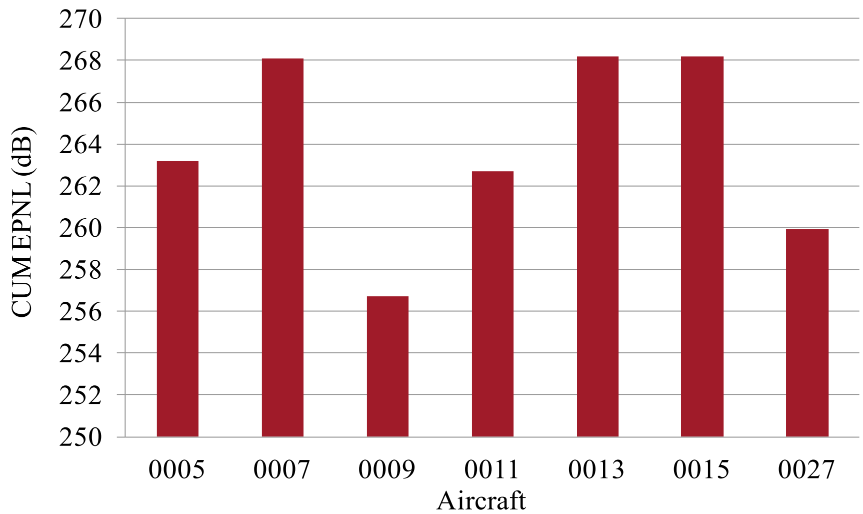


Figure 66. Cumulative EPNL for baseline configurations

To see how the above results compare with the NASA N+2 noise goal, the results summarized in Table 40 and Table 41 are plotted in Figure 67 in terms of the EPNL margin to Stage 3, together with the NASA goal. Clearly, all the configurations have large margins to Stage 3 but they do not reach the NASA goal. This is also clearly shown in Figure 68, which plots the cumulative margins in reference to Stage 4. The numbers in this feature indicates that the configuration 0009, which is a BWB design with geared turbofan engines, has the largest cumulative margin, of about 34 dB.

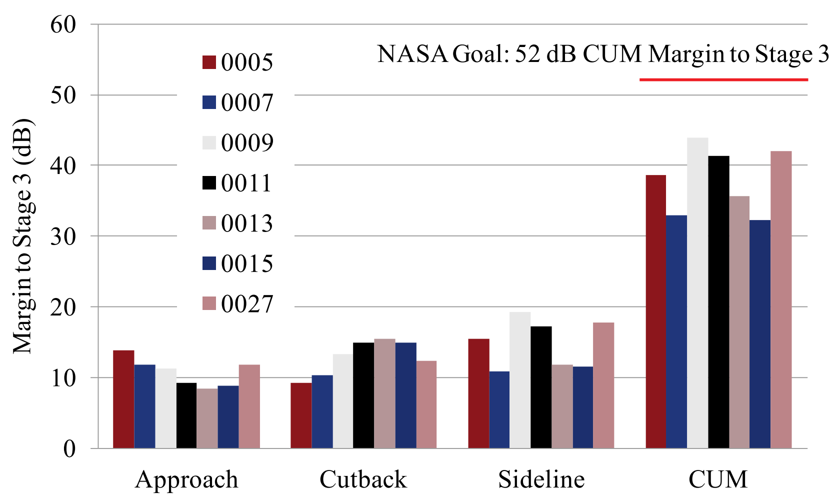


Figure 67. EPNL margin to Stage 3 for baseline configurations

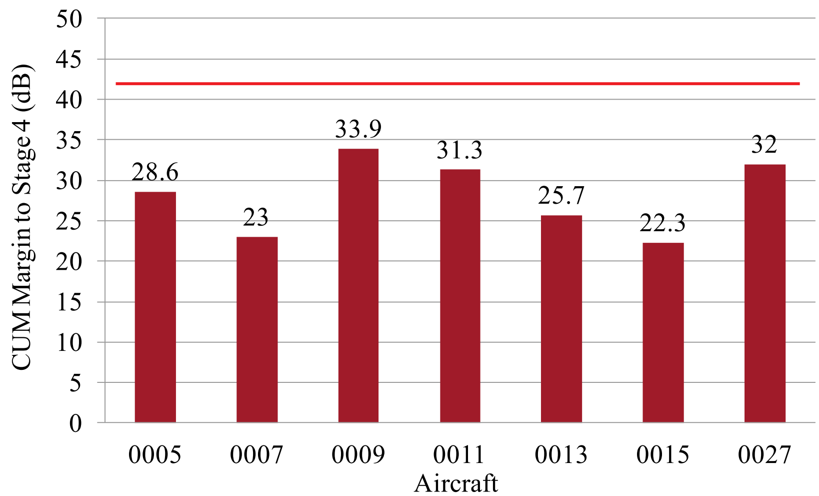


Figure 68. Cumulative EPNL margin to Stage 4 for baseline configurations

2.9.3 Further Noise Reduction

The baseline configurations discussed in the previous sections all have significant EPNL noise margins to the Stage 4 limits, but they do not meet the NASA N+2 noise goal. The best configuration is 0009, which is selected to be the PSC design, and has a noise margin of about 34 dB to Stage 4, which is about 8 dB short of the NASA goal. Thus, further noise reduction is needed for the baseline configurations. Supporting detailed studies point to the directions of these further noise reductions. Primarily, the noise from the main landing gears and the slats are holding up the total noise. In addition, further noise reductions are possible in airframe noise and low noise flight operations. The former may include the reduction of component noise source amplitudes and the attenuation of the noise generated by the components, while the latter may aim at reducing the flight approach speed and maximizing takeoff altitudes, both in turn leading to lower airframe noise.

In summary, both the BWB design (-0009) and the advanced T&W design (-0027) can achieve cumulative EPNL more than 30 dB below the Stage 4 limit. With further optimization of the engine/airframe integration and further development of component noise reduction technologies, both configurations have the potential of achieving the NASA N+2 noise goal of 42 dB below Stage 4. This is significant compared with aircrafts currently in service whose cumulative EPNL is in the range of 10 to 15 dB below Stage 4. Even for new designs that are planned to enter service in the next few years, the cumulative EPNL is expected to be only about 20 dB below Stage 4.

As is well-known, a change in aircraft configuration, from T&W to BWB for example, involves many aspects, most of which is not acoustic, or even technical, such as the economy of the new design and regulatory issues. These are clearly important, but are not the focus of discussions here in this section. Instead, it is appropriate to list some recommendations which are specifically related to the aircraft configurations studied here and are critical in achieving the NASA N+2 noise goal.

- **Noise Shielding of Ducted Fan:** The noise shielding databases used and discussed in this report consist of broadband point sources, open rotor fan noise sources and jet noise sources, but not duct fan noise sources, which are relevant to advanced turbofan engines with very high bypass ratio with fan tones dominating the other components. To fill this gap, tests are needed that can realistically simulate the ducted fan noise and its shielding by the airframe body or wings. Realistic conditions will need to include flight effects and accurate measurements need to be free of distortions to the tone frequencies and amplitudes. With the large engine sizes due to the very high bypass ratio, the low frequency coherent nature of the tones, and the practical limitations of the engine installation, the shielding characteristics of ducted fan sources can be expected to be different from others such as the incoherent jet noise sources, which makes the studies of noise shielding of ducted fan sources a critical step in future development of acoustic research for advanced aircraft configurations.

- **Airframe Noise Reduction:** As seen in the previous sections, airframe noise is a major contributor to the total aircraft noise for the configurations studied here, and in many cases, such as approach conditions, it is the dominant component. In fact, the baseline PSC failed to reach the NASA N+2 noise goal because the airframe noise is holding up the noise levels. Thus, a crucial step to achieve the NASA goal is to reduce airframe noise. For the PSC design, the main landing gears and the slats are the major airframe noise components. From the analysis given in the previous section, the landing gear noise needs to be reduced by at least 5 dB and the slat noise by more than 3 dB in order for the PSC to achieve the NASA noise goal. It should also be pointed out that airframe noise reduction also has immediate benefits to the T&W design, and can help lower the noise levels of aircraft currently in service or planned to enter the aircraft market in the near future. This dual-use objective is feasible for component technologies that do not rely any particular aircraft overall design.
- **Flight Test Demonstration:** The assessment of system noise for unconventional aircraft, such as the BWB design, has so far largely relied on empirical predictions of component noise and individual features. While this has been the accepted approach for conventional T&W configurations, its application to unconventional aircraft has never been validated and demonstrated. Thus, it is important to have flight test demonstrations to validate the system noise prediction process, and hence, to demonstrate the feasibility and potential of achieving the NASA N+2 noise goal. The flight tests can be at reduced scales but need to have all the essential acoustic features, such as realistic engines and high lift systems.
- **Prediction Tool Development:** As seen in the previous sections, the system noise assessment for unconventional aircraft is largely empirical, both in defining the noise source amplitudes and in predicting the shielding effects. It is a very time-consuming and tedious process to assemble the appropriate databases and to integrate all the individual elements to perform the final assessments. While this can be feasible for a limited number of configurations, it is clearly not sufficient in parametric and optimization studies where many variations in configuration and flow conditions need to be considered. This is why no acoustic optimization is done in the present study. Thus, tool development is needed in two directions. The first is further maturing the predictions of components and individual features so that the predictions are more physics-based and less relying on empirical database. The second is to automate and streamline the prediction on the system level to enable parametric studies and optimization. The lack of acoustic optimization in the work reported here shows that the lack of sufficient tools has already started to slow down the progress of achieving the NASA N+2 noise goal.
- **Engine Noise Shielding Enhancement:** To achieve significant engine noise shielding, the first intuitive concept is to use a large portion of the shielding surface, by placing the engines well upstream of the BWB trailing edge, for example. This, however, may not always be acceptable due to other constraints in aircraft design, such as propulsion efficiency that needs to place the engines away from the high speed flows on the top of the airframe. Thus, engine noise shielding enhancement is likely needed in practical designs that strike a balance between acoustics and other requirements. This may become especially important for very high bypass ratio engines whose low frequency tones are difficult to shield. The shielding enhancement can include nozzle shapes to redistribute the jet noise sources, vertical tails to redirect far field radiation, local surface treatments to absorb sound, and utilization of trailing edge devices such as elevons to effectively increase the shielding surface.

- **Acoustic Optimization:** Acoustic optimization includes both system levels studies and local optimization. For the former, the overall aircraft design can be optimized for low noise through engine locations, component designs (vertical tails, elevons, slats), and flight profiles (approach speed, cutback altitude, etc). For the latter, local components can be redesigned to achieve lower noise. An example of this is the local surface contour of the BWB lower surface in the vicinity of the main landing gear. The main landing gears have very high noise levels because of the high speed local flows, which result from the rapid surface contour transition from the BWB center body to the outer wings. The surface contour can be redesigned to lower the local flow speed and hence lower the landing gear noise.

2.10 Comparison of Aircraft

In this section, the airplanes described above are first compared in terms of configuration geometry, aerodynamics, mass properties, and propulsion system characteristics. This is followed by comparisons in the objective metrics of this study: fuel burned, noise and LTO NO_x.

2.10.1 Configuration

Three basic configurations are examined in this study: a conventional tube-and-wing; a double-deck tube-and-wing; and a blended wing body. The conventional tube-and-wing is studied at two technology levels: 1998 and 2025. In configuration, the 2025 technology level manifests as a higher aspect ratio wing. The 2025 tube-and-wing and the double deck airplane have common wing technology levels; the BWB has outboard wing airfoils that are less aft-cambered but are otherwise similar.

Four key airplanes are illustrated in Figure 69. From the left, these are:

- A representative 1998 airplane, the -0003. The -0001 is similar but has about 10% more wing area and 5% more span.
- The 2025 T&W-0005. The 2025 airplane with the largest wing.
- The 2025 T&W-0007. The 2025 airplane with the smallest wing.
- 2025 BWB-0009A. Representative of all of the primary BWBs. A comparison of the -0009A with a long-wing BWB is shown in Figure 56.

Figure 70 illustrates the -0007 and -0009A on either side of the -0027A double-deck configuration.

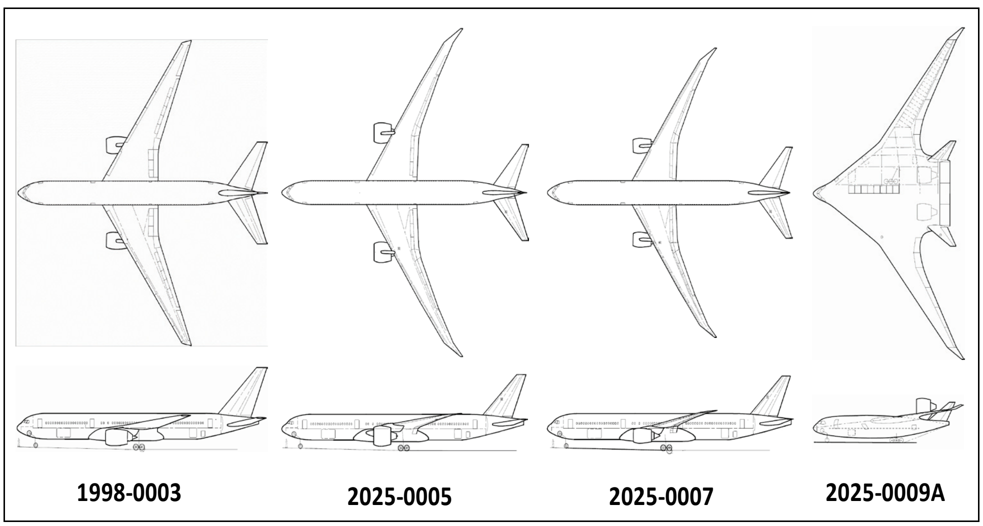


Figure 69. Top and Side View Comparison of -0003, -0005, -0007 and -0009A

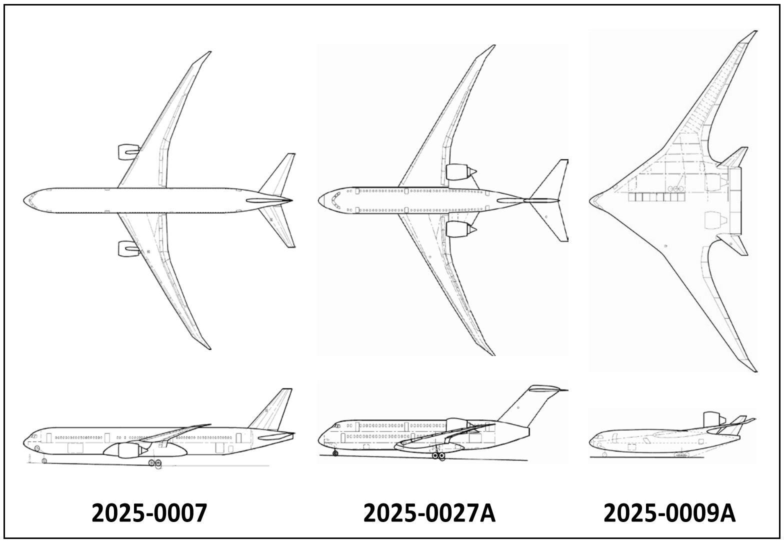


Figure 70. Top and Side View Comparison of -0007, -0027A and -0009A

2.10.2 Performance to NASA's Goals

Design goals for this study pertain to fuel consumption, airport noise and landing and takeoff oxides of nitrogen (LTO NO_x).

2.10.2.1 Fuel Burned, with OEW and DOC

The design goal for fuel consumption is to reduce fuel burned by 50% relative to a representative 1998-technology airliner. The 1998 T&W-0001 is selected as the baseline from three candidate airplanes. The T&W-0001 is sized using NASA Reference rules. The two other candidates are considered less representative: the 1998 T&W-0001 OP and the 1998 T&W-0003. Although sizing the -0001 OP with "Operational" mission rules is more consistent with 1998 airliner practice than using NASA Reference rules, the "Operational" rules result in an airplane (-0001 OP) that burns 11.2% more fuel than the NASA reference airplane (-0001). On the other hand, the RRNA-powered T&W-0003 burns 6.5% less fuel than the P&W-0001. So, the T&W-0001 is selected as the most representative (or best compromise) of the three candidates.

Figure 71 presents a multi-dimensional plot of key airplane characteristics for selected study airplanes. The vertical axis is fuel burned relative to the 1998 baseline (-0001). The horizontal axis is OEW, also relative to the -0001. Lastly, contours of equal direct operating cost (DOC) are overlaid on the plot in dashed cyan lines. DOC is estimated only on the basis of OEW and fuel burned. The object of the plot is to characterize the airplane in terms of the NASA fuel consumption goal while also addressing considerations of commercial interest. At the level of detail of this study, these considerations include OEW and DOC. DOC is shown here based on a fuel price of $4.00 per gallon. Greater fuel prices tend to flatten and compress the contours – as fuel prices increase, the contours move towards horizontal, with the "DOC Ratio" contours aligning with the relative fuel consumption lines. As fuel prices tend towards zero, the contours become more vertical and widely spaced.

Figure 71 is an overview showing the airplanes in three groups: 1998 T&W; 2025 T&W; and 2025 BWB. Performance of the three 1998 airplanes is described above. The Operational rules add about 7% to DOC; the -0003 reduces DOC by about 6%.

The 2025 T&W airplanes reduce fuel burn approximately 45% - just short of the NASA goal. OEW is reduced ~17% and DOC drops ~30%.

The 2025 BWB airplane reduce fuel burn about 52% - each BWB design exceeds the NASA goal. Empty weight is reduced some 20% and DOC drops ~35%.

All of the 2025 airplanes provide a major commercial advantage when compared to the 1998 baseline airplane – any could be operated profitably in competition with 1998-technology airplanes.

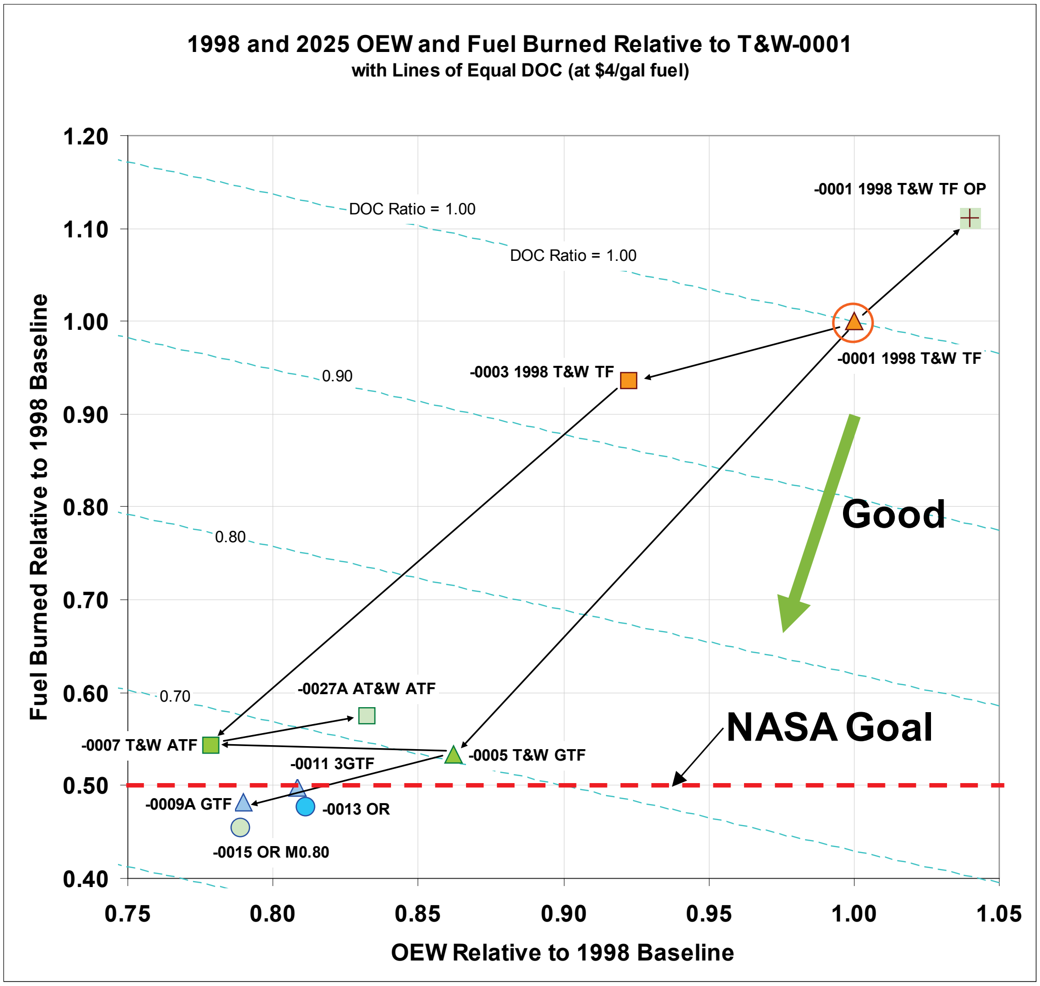


Figure 71. Overview – Relative Fuel Burned and OEW

Figure 72 is a blow-up of Figure 71 showing only 2025 airplanes. (Additional detail and description is provided in the following figures, so a complete description is not provided here.)

Four 2025 T&W airplanes are shown. These airplanes are related in several ways:

- T&W-0007 and AT&W-0027A share wing and engine technology but differ in fuselage configuration.
- T&W-0007 and T&W-0005 share everything but engine type. The -0007 has lightweight but less-efficient advanced turbofans. The -0005 has more efficient but heavier geared turbofans.
- The T&W-0005 and T&W-0005 NG share everything but mission rules. The -0005 is sized with NASA reference rules; the -0005 NG is sized with NextGen rules.

The T&W-0007 is the lightest airplane, 22.1% lighter than the baseline. This compares with the 16.8% reduction provided by the AT&W-0027A. The -0007 also burns less fuel than the -0027A: respectively 54.3% versus 57.4% of the baseline's fuel consumption. In terms of DOC, the -0007 provides a substantial benefit over the less efficient and heavier -0027A: 67.8% versus 71.4% relative DOC, respectively. From a pure fuel burn or DOC perspective, the -0027A is inferior to the -0007. However, as described in Section 2.9 and below, the -0027A provides substantial noise benefits that may increase its commercial attractiveness.

The T&W-0007 is far lighter than T&W-0005, but burns somewhat more fuel. The -0007 is again 22.1% lighter than the baseline; the -0005 is 13.8% lighter. The -0007 burns more fuel than the -0005, with relative fuel burned of 54.3% and 53.4%, respectively. In terms of DOC, the -0007 provides a clear advantage due to its low weight. Its relative DOC is 67.8%; the -0005's is 70.3%. So although the -0007 burns more fuel, its DOC is some 3.6% lower than that of the -0005, a substantial commercial advantage.

Application of NextGen rules to T&W-0005 reduces weight, fuel burned and DOC. Relative weight drops from 86.2% to 84.7%. Relative fuel burned drops from 53.4% to 51.5%. Relative DOC drops from 70.3% to 68.9%. Clearly, NextGen rules are beneficial.

Eight 2025 BWBs are shown in Figure 72. These permit numerous comparisons, some of which are deferred to Figure 74 below. Here the general relationship between the "primary" BWBs and the "long-wing" BWBs is described.

Three long-wing BWBs are created: -0031 geared turbofan; -0033 open rotor with Mach 0.85 cruise; and -0035 open rotor with Mach 0.80 cruise. These correspond to shorter-wing versions -0009A, -0013 and -0015. Comparison of each corresponding pair shows that the long-wing versions provide a modest fuel burned reduction in exchange for a substantial increase in weight. For example, the shorter-wing -0009A may be compared with the long-wing -0031. Relative OEWs are 79.0% and 86.2%, respectively, a 9.1% increase in OEW. Relative fuel burn is 48.2% and 45.3%, respectively, a 6.0% drop. Relative DOC increases from 65.0% to 66.1%, a 1.7% jump. Although the fuel burned reduction of the long-wing BWB attends to NASA's goal, the increased DOC and nearly 80-meter wingspan are commercially unattractive. For this reason, the long-wing BWBs are eliminated for consideration as the preferred system concept.

A direct comparison of T&W and BWB airplanes is possible. The T&W-0005 and BWB-0009A share technologies and engines – only their configurations are different. The BWB design burns less fuel, is lighter and has a lower DOC. Relative fuel burned drops from 53.4% to 48.2%, a 9.7% reduction. OEW drops from a relative 86.2% to 79.0%, an 8.4% reduction. DOC drops from a relative 70.3% to 65.0%, a 7.5% reduction. In terms of fuel burned, OEW and DOC the BWB configuration provides a substantial advantage.

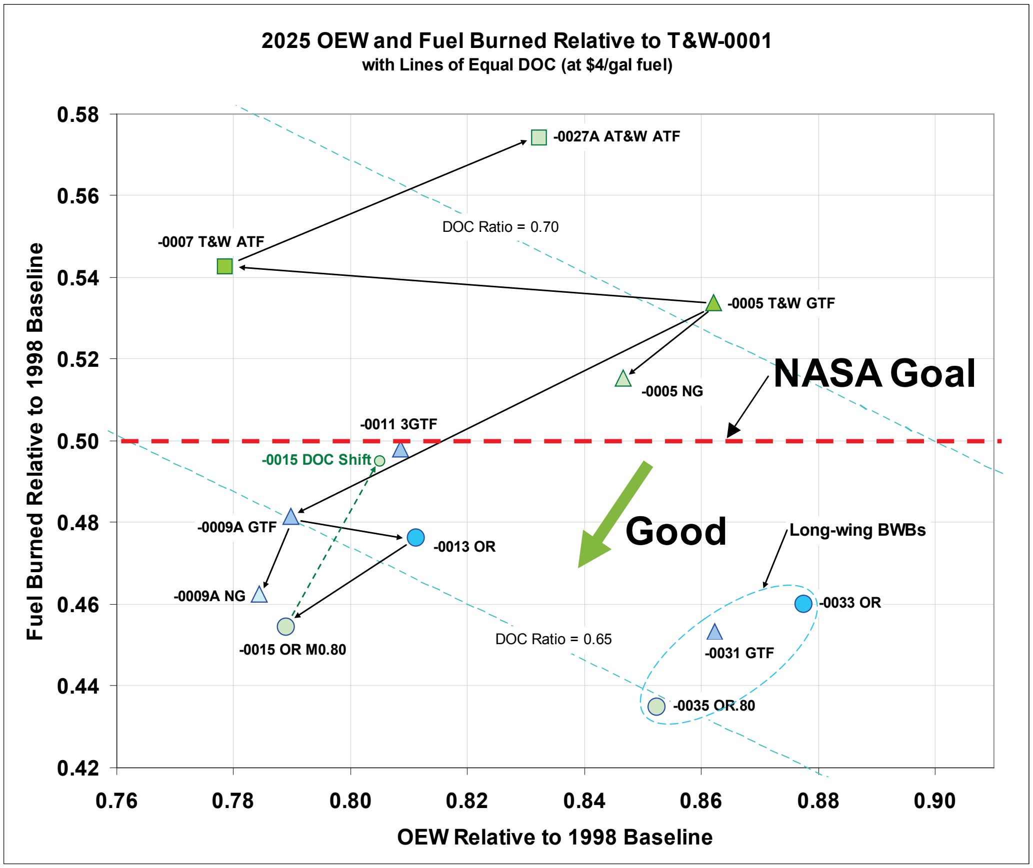


Figure 72. Relative Fuel Burned and OEW for 2025 Passenger Airplanes

Figure 73 is a blowup of Figure 72, showing only the 2025 T&W passenger airplanes. One airplane is added – the AT&W-0027. This is an advanced version of the -0027A with higher aspect ratio wing, large winglets and alternate drag estimation methods. These combine, resulting in an airplane both lighter and more fuel efficient than the -0027. It is also more fuel efficient than any other 2025 T&W design and nearly as light as the T&W-0007, also with advanced turbofan engines. The AT&W-0027 provides a relative fuel burned of 50.8%, just shy of the 50% NASA goal.

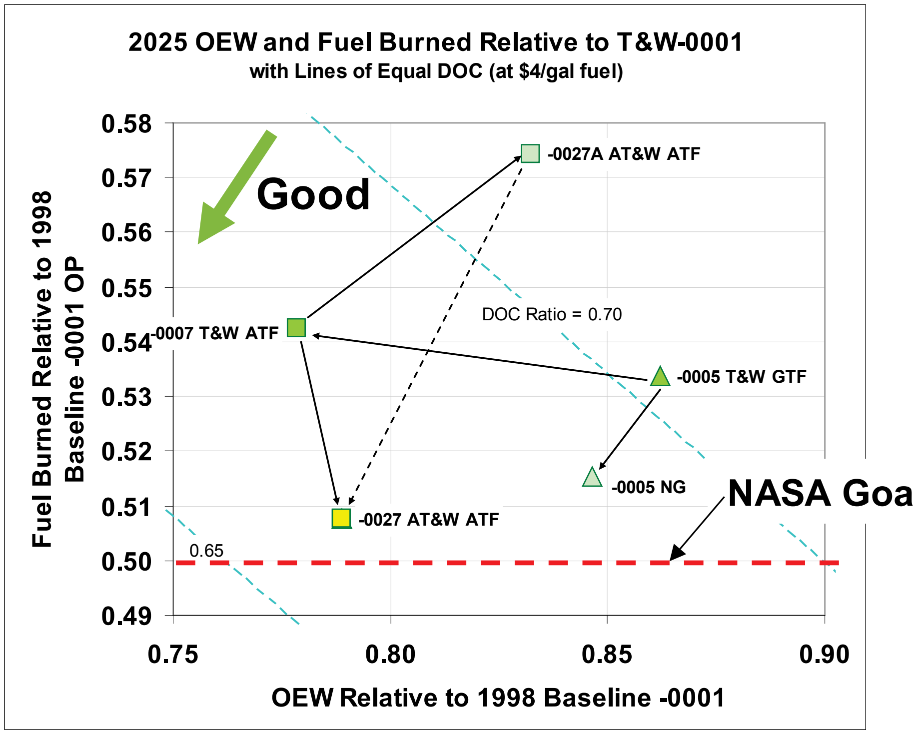


Figure 73. Relative Fuel Burned and OEW - 2025 Tube-and-Wing Passenger Airplanes

Figure 74 facilitates a discussion of the primary BWB designs. The study design permits several comparisons with BWB-0009A serving as the focal point:

- Geared turbofan compared to open rotor (-0009A versus -0013)
- Twin GTF compared to triple GTF (-0009A versus -0011)
- NASA Reference rules compared to NextGen rules (-0009A versus -0009A NG)
- Mach 0.85 cruise compared to Mach 0.80 cruise (-0013 versus -0015)
    - Effect on DOC of reduced cruise speed.

Comparing the GTF BWB-0009A with the OR BWB-0013 shows that changing to the open rotor reduces fuel burned slightly while increasing weight and DOC. Fuel burned drops from a relative 48.2% to 47.6%, a 1.2% reduction. Weight increases from a relative 79.0% to 81.1%, an increase of 2.7%. DOC increases from a relative 65% to 65.6%, a 0.9% increase.

Comparing the twin-GTF -0009A with the triple GTF -0011 shows that the tri-jet burns more fuel, is heavier and has an increased DOC. The triple GTF is clearly inferior to the twin.

NextGen rules provide a clear-cut benefit relative to NASA Reference rules. Relative to the -0009A, the -0009A NG reduces fuel burn by 3.9%; OEW drops 0.8%; DOC drops 1.8%.

A reduction in cruise Mach number reduces fuel burn and OEW but DOC is increased. In slowing down, fuel burned drops from a relative 47.6% to 45.4%, a 4.6% reduction. Relative OEW drops from 81.1% to 78.9%, a 2.7% drop. DOC of the M0.80 airplane may not be read from the plot's contours. These contours are based on airplane productivity derived from a M0.85 cruise speed. In slowing down, the airplane is less productive and its effective ownership cost (per ton-nm per year) is increased. A point labeled "-0015 DOC Shift" appears on Figure 74. This point is "shifted" from the OEW and Fuel Burned point onto the estimated correct spot on the DOC contour scale. In slowing from M0.85 to M0.80, DOC increases from a relative 65.6% to 66.1%, a 0.8% jump. The commercial appeal of reduced fuel burn in exchange for increased DOC and reduced speed on an 8000-nm mission is uncertain.

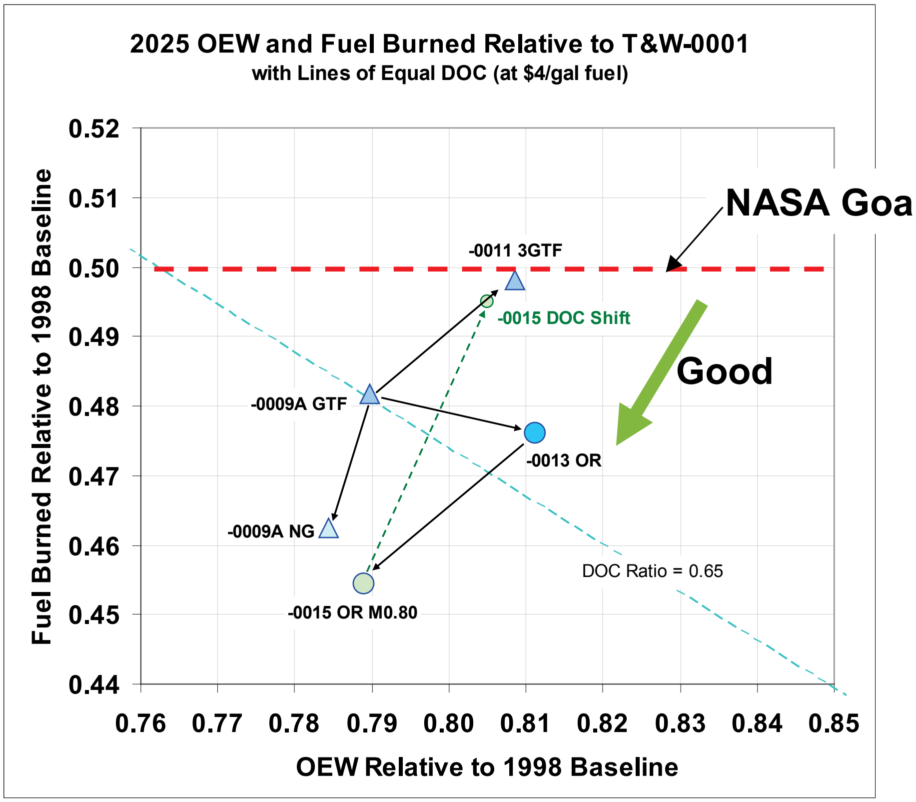


Figure 74. Relative Fuel Burned and OEW – BWB Passenger Airplanes

2.10.2.2 Acoustics

Figure 75 presents cumulative airport noise margins for seven of the study airplanes. These results are described in depth in Section 2.9. These results permit summary comparisons of engine type and configuration:

- The geared turbofan provides a noise benefit relative to the advanced turbofan (-0005 versus -0007).
- The BWB configuration provides a noise benefit via shielding. (-0009A versus -0005).
- The advanced tube-and-wing (double deck) configuration provides a noise benefit via shielding (-0027A versus -0007).
- Three smaller GTF engines are noisier than two larger GTFs (-0011 versus -0009A).
- Open rotor engines are noisier than geared turbofans (-0013 versus -0009A).

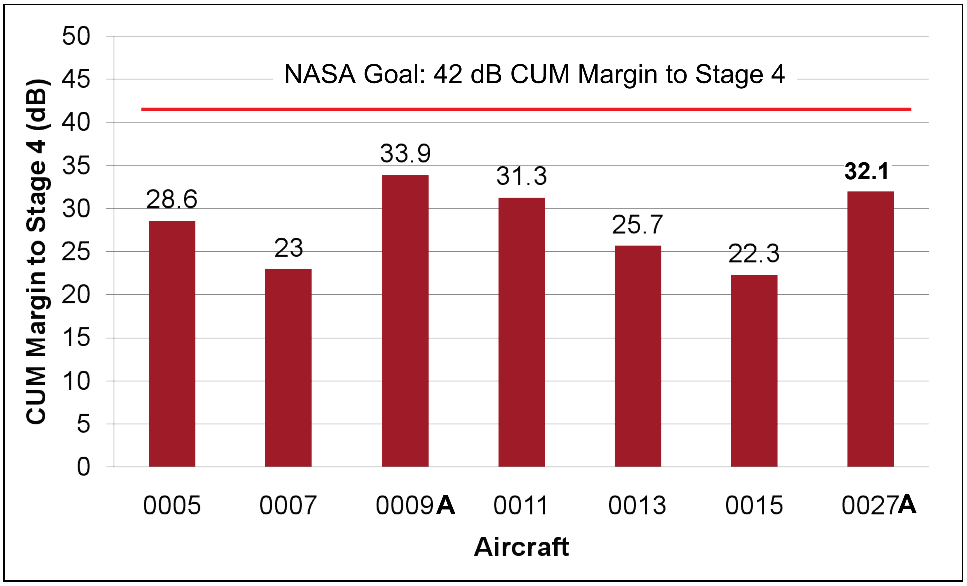


Figure 75. Noise Margin to Stage 4

Figure 76 combines the noise results shown in Figure 75 with the fuel burned reductions reported in Figure 72 to show in a two-dimensional sense how the configurations compare in terms of noise and fuel efficiency. (Note that the fuel burned scale is reversed in this plot – the axis is fuel burned reduction relative to the baseline – what was 55% in the prior figures is 45% in this figure.)

The NASA goal of 50% fuel burned reduction and 42 dB margin to Stage 4 noise is shown by dashed red lines; their intersection is shown as a yellow dot. Airplanes in the upper-right portion of the plot best address the combined NASA goals. The lower-left corner is the farthest from the goal.

Considered in this way, the BWB-0009A provides the best combination of fuel burned reduction and noise margin. Despite its disappointing fuel burned performance, the triple GTF BWB-0011 is also attractive. Of the T&W airplanes, the T&W-0005 and AT&W-0027A are most attractive. Unanswered by this study is the performance of a GTF version of the -0027A double-deck, rear-engine airplane. The combination of acoustic shielding provided by the configuration with the quieter GTF engines of the -0005 may be attractive.

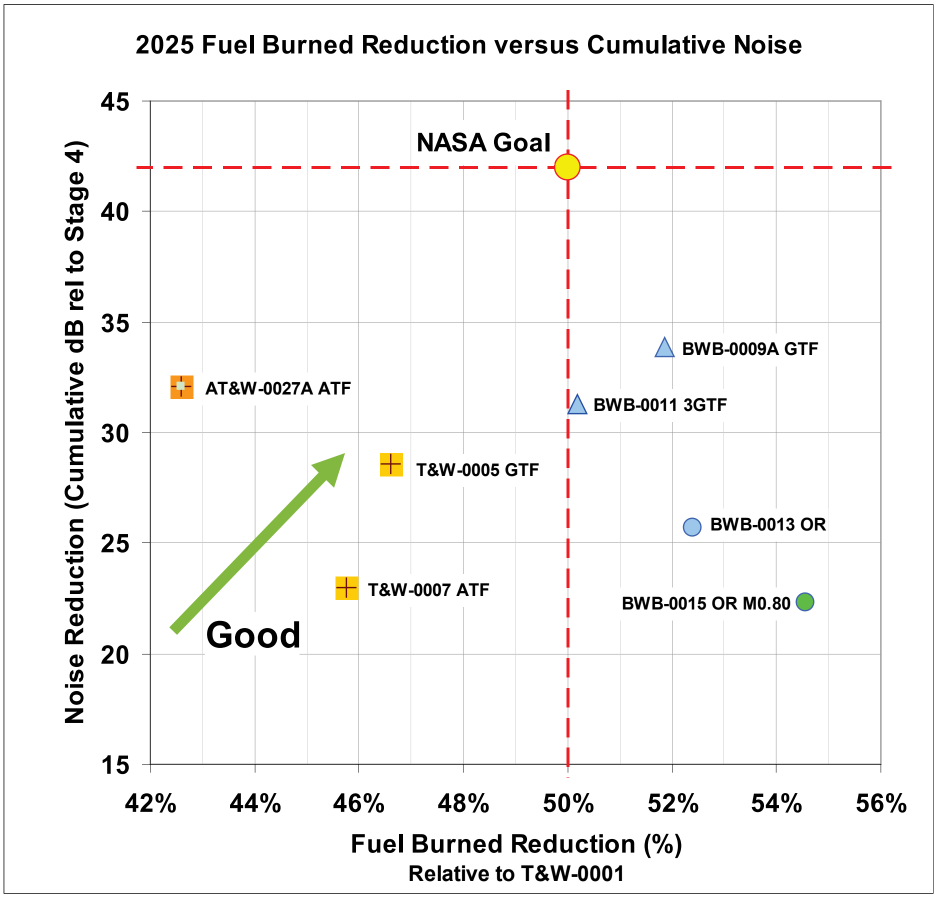


Figure 76. Noise and Relative Fuel Burned Reduction

2.10.2.3 Landing and Takeoff NO_x

A comparison of engine LTO NO_x is presented for all study engines in Figure 77. Comparison of 2025-technology engines is presented in Figure 78.

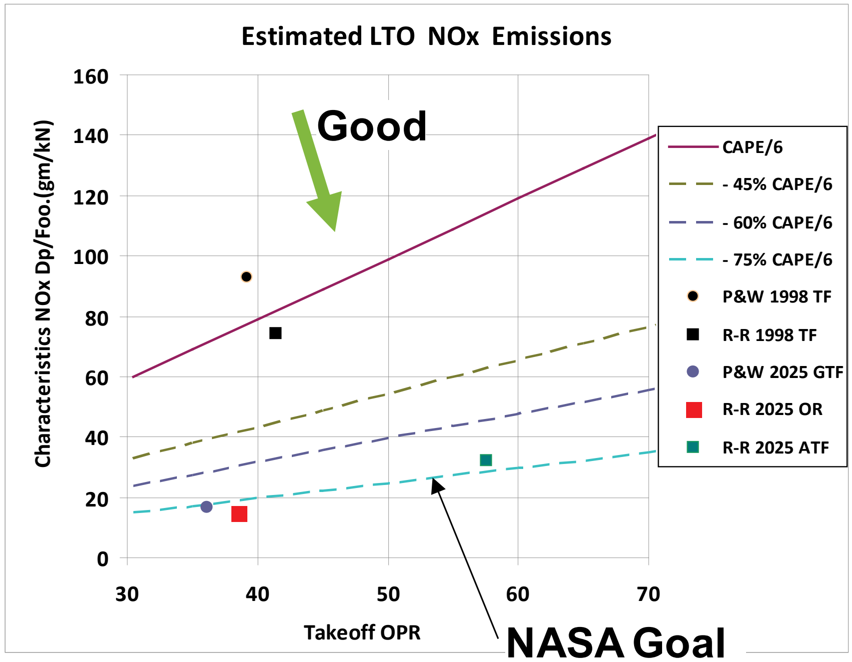


Figure 77. LTO NO_x Emissions versus Overall Pressure Ratio

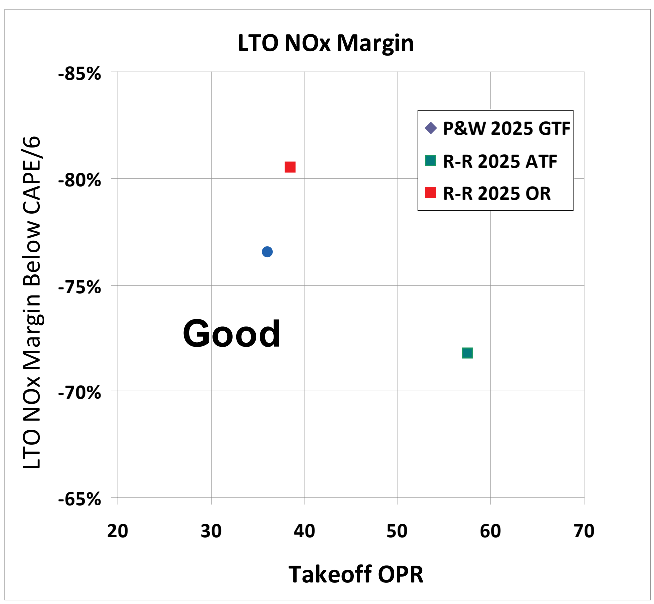


Figure 78. LTO NO_x Margins

2.10.2.4 Mission Rules

Figure 79 shows relative fuel burn, OEW and DOC for three pairs of airplanes. Each pair is the same except for their mission rules. The plot is annotated to show the change in fuel burned due to rules, technology level and configuration type.

Using the 1998 T&W-0001 OP as the base, changing to NASA Reference rules reduces fuel burned by 10.7%.

With conventional configurations, changing from Operational rules to NextGen rules reduces fuel burned by 13.9%. Changing both the rules (from OP to NextGen) and technology levels (from 1998 to 2025), fuel burned drops 53.6%.

Applied to BWB configurations, changing from OP rules to NextGen reduces fuel burned by 13.9%. Changing the rules (OP to NextGen) and technology levels (1998 to 2025), fuel burned drops 58.4%.

In all cases, advancing from OP rules to NASA Reference rules to NextGen rules also results in a reduction in airplane OEW as well as in DOC.

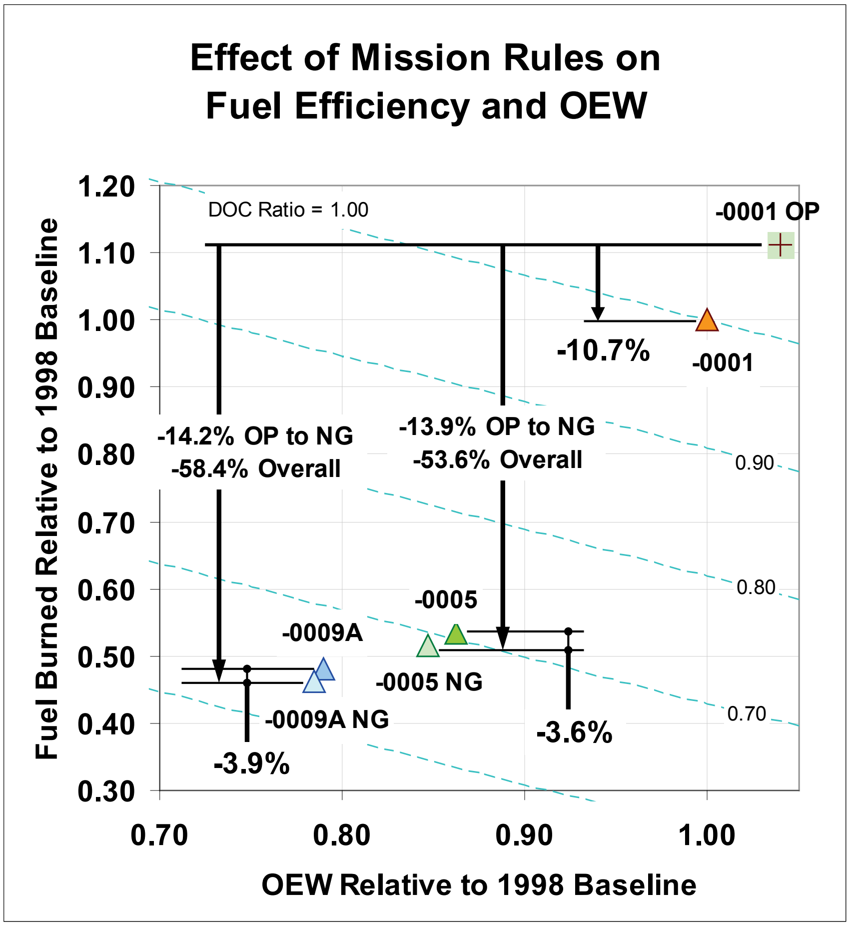


Figure 79. Effect of Mission Rules on Fuel Burned and OEW

2.11 NextGen

The work covered under this section includes defining a future NextGen scenario that the PSC aircraft will most likely be operating within at and beyond the 2025 timeframe, and providing a description of the process used to define the scenario. The scenario was used to define a NASA N+2 sizing mission. A similar approach was undertaken for the NASA N+3 SUGAR study.[3] The current study includes developing a set of requirements to optimize the operational performance characteristics of the sized PSC vehicle in the NextGen environment. These requirements will exploit improved departure and climb-out performance for airport noise reduction; optimal cruise, arrival, and landing speeds for fuel savings; and optimized departure, arrival, and approach noise-abatement procedures.

The PSC was also evaluated for an airport operation scenario derived from previous Boeing Air Traffic Management (ATM) and marketing studies at a typical airport where long-range transports represent a large fraction of daily operations.

The Joint Planning and Development Office (JPDO) is the interagency office planning for NextGen beyond the 2018 timeframe. Therefore, the work being conducted by the JPDO was deemed the best source of information to evaluate what the NextGen system would look like for the PSC 2025 EIS aircraft.

2.11.1 ERA Alignment with NextGen

2.11.1.1 NextGen Vision for 2025

Since 2005, the Boeing Advanced Air Traffic Management organization has been a key part of an integrated team of contractors working with the Interagency Portfolio and System Analysis (IPSA) group under JPDO on a task order under FAA contract DTFAWA-06-C-00015. The BCA Avionics ATM Group's mission is to help define future requirements for avionics, based on requirements being developed by NextGen and SESAR. This includes participating in the development of NextGen scenarios to be analyzed in FY2011, perform NAS-wide airport capacity modeling to support benefits analysis for NextGen being performed by the JPDO IPSA division, and to coordinate and integrate results with other JPDO IPSA team members, JPDO divisions and working groups, FAA & other agencies. The end goal is to support JPDO NextGen business case that has been requested by the Office of Management & Budget (OMB).

The activity within JPDO has led to a set of NGOps levels, as shown in Figure 80 below. NGOps levels were designed for communications purposes since it has proven difficult to effectively describe NextGen in terms of the macro set of operational improvements and enablers. NGOps levels provide a way to discuss portfolios (reference points) that are a subset of NextGen as defined by the Integrated Work Plan. These levels are a portfolio of operational ATM CNS improvements with a set of enablers that provide a set of benefits within a range of risks and costs that represent an implementable architecture. Generally, with increasing NGOps level the costs and risks go up, the performance improves, and the IOC date is further out into the future.

The Goal of NextGen is to increase capacity, reduce delay and environmental impact, while maintaining or improving safety. Hence NextGen will evolve from today (NGOps-1,2) to NGOps-6. And while the FAA is responsible for NextGen through NGOps-3; JPDO, partner agencies, and industry are working to define concepts for NGOps-4 to -6. NGOps-4 includes ADS-B In; concepts mostly demonstrated, but significant research is needed to prove safety and cost effectiveness of these concepts. NGOps-5 requires a major change in operational concept which includes more automation on the ground and in the aircraft. These concepts have not been validated; and a large amount of research is needed to analyze failure modes, mixed equipage, and off-nominal events. NGOps-6 involves a paradigm shift from today's operation and requires fully automated ground-based 4D Traffic Flow Management and Air Traffic Control, and Gate to gate Trajectory Based Operations. In NGOps-6, automation provides the primary means of control and separation and the human controller's function is more to provide monitoring and fail-safe services. NGOps-6 also includes Unmanned Aircraft Systems (UAS). There is little validation of these operational concepts, and much research is needed to define performance requirements for ground automation and avionics. To achieve higher NGOps levels and ultimately NGOps-6, the federal government needs to increase the funding to the JPDO partner agencies and accelerate the implementation of NextGen.

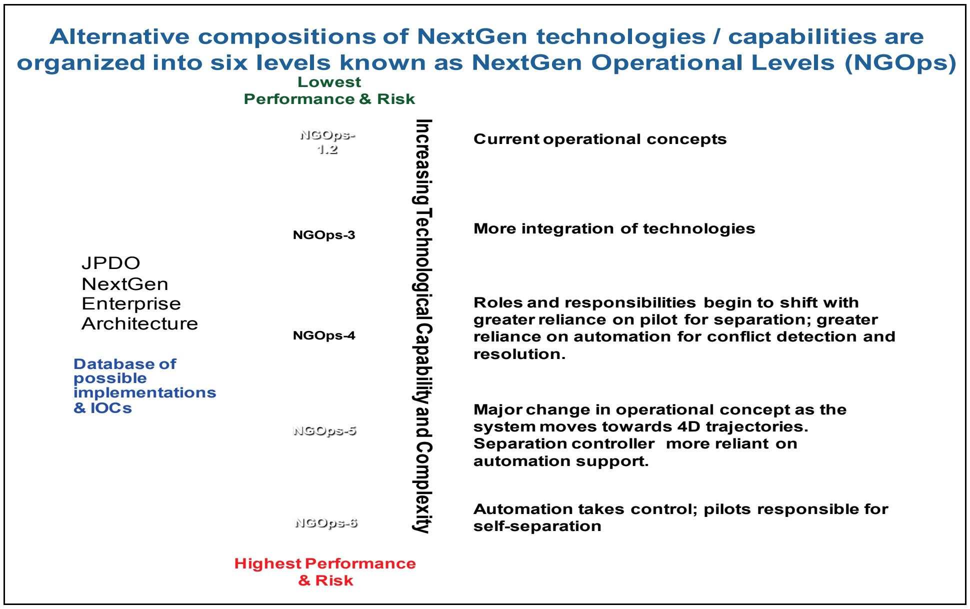


Figure 80. NextGen Operational Performance Levels

2.11.1.2 Defining PSC Requirements for NextGen

In this study, a Reference, Operational, and NextGen mission have been defined, as described in detail in sections 2.2.1 – 2.2.3. With respect to NGOps levels, the NextGen mission has been defined for NGOps-6. For convenience, the NextGen mission is provided again in Figure 81, including highlights of the changes/improvements.

The ERA NextGen mission is similar in concept to the 2030 mission of the SUGAR study.[3] Table 42 shows a comparison between the 2008 Operational Mission, the 2030 SUGAR mission and the ERA 2025 NextGen mission. Comparisons are shown for each phase of flight for the mission and reserves. In brief, future missions have reduced hold times, elimination of loiter, optimized climb and descent, and reduced fuel reserves (~40%).

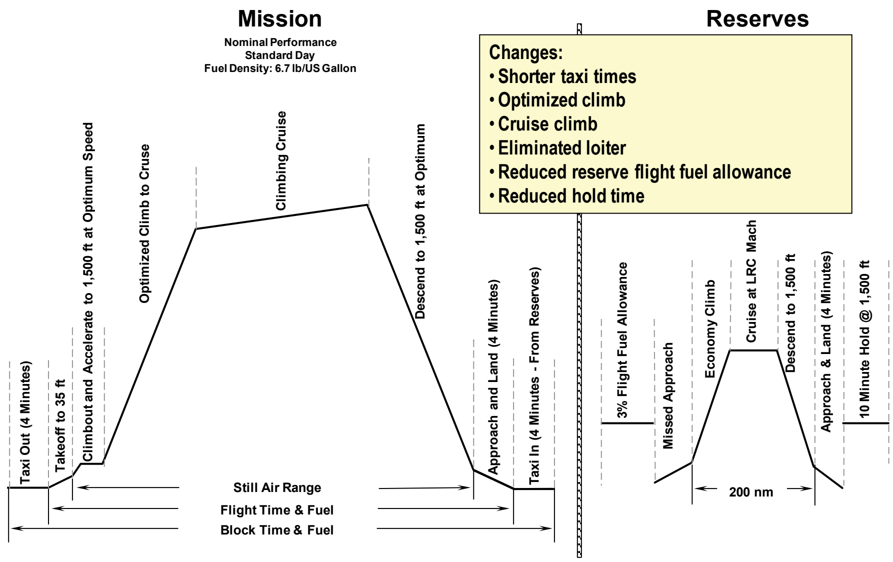


Figure 81. ERA NextGen Mission (NGOps-6 is assumed)

Table 42. Comparison of Mission Profiles

Mission Segment	2008 Mission Profile (Operational)	2030 Mission Profile (SUGAR)	2025 Mission Profile (ERA)
Mission			
Taxi Out	Airport congestion and queues at runways increase airplane idle time while waiting to takeoff. Assumed 16 minutes of idle power.	Better Ground Traffic Management allows airplane to taxi directly from gate to runway. Assumed 4 minutes of idle power.	Same as SUGAR
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.	Same as SUGAR
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 optimize real-time airplane altitude and speed in 4D to minimize track distance and fuel burn while maintaining safe separation distances	Same as SUGAR
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. No loiter	Full 4D tailored arrivals might not be achieved at congested airports by 2025. No loiter
Taxi In	Airport congestion and waiting for gates to clear increases time airplane idles while waiting to unload	Better Ground Traffic Management allows airplane to taxi directly from runway to gate	Same as SUGAR
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%	Same as SUGAR
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	Same as SUGAR
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	Same as SUGAR
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	Same as SUGAR
Note: Segments not listed indicate no change between profiles			

2.11.2 Airport Selection for Operational Noise Analysis

2.11.2.1 Candidate Airports

Based on all the selection/criteria above, a list of candidate airports was compiled. The list entailed Atlanta (ATL), Los Angeles (LAX), San Francisco (SFO) and Miami (MIA). Table 43 lists each candidate airport with respect to the criteria. Clearly there are other busy, significant, and large-market airports, however, they were not considered due to lack of radar data.

Table 43. Candidate Airports Based On Selection Criteria

Criteria	Airport Candidates
Radar Data	ATL , LAX , MIA , SFO
Forecast Models	ATL , LAX , MIA , SFO
EIR / Noise Models	LAX
NextGen Involvement	LAX , SFO
Noise Criticality	LAX , SFO
Metroplex Aspects	LAX , SFO
Fleet Mix	ATL , LAX , MIA , SFO

2.11.2.2 Selection of LAX

It is evident in Table 43 that LAX s the only airport that met all the criteria; hence it was the leading candidate. The final verification for selecting LAX was assuring it was ranked highest in airport operations amongst the other candidates. The specific metrics for evaluating operations are referenced in The Airports Council International and FAA databases and they are:

- Number of Domestic Passengers & International Passengers
- Total Number of Passengers
- Tons of Domestic Cargo & International Cargo
- Total Tons of Cargo
- Total Movements (divide by 2 to get departures and arrivals)

Using these metrics, the four candidate airports, were compared and ranked for the year 2009. The weighted rankings are shown in Figure 82. Indeed, as illustrated, LAX consistently ranks 2nd in all the metrics, namely passenger volume, cargo volume, and total movements. Accordingly, LAX ranks 1st (highest) in airport operations, in an aggregate sense (Total and Average metrics).

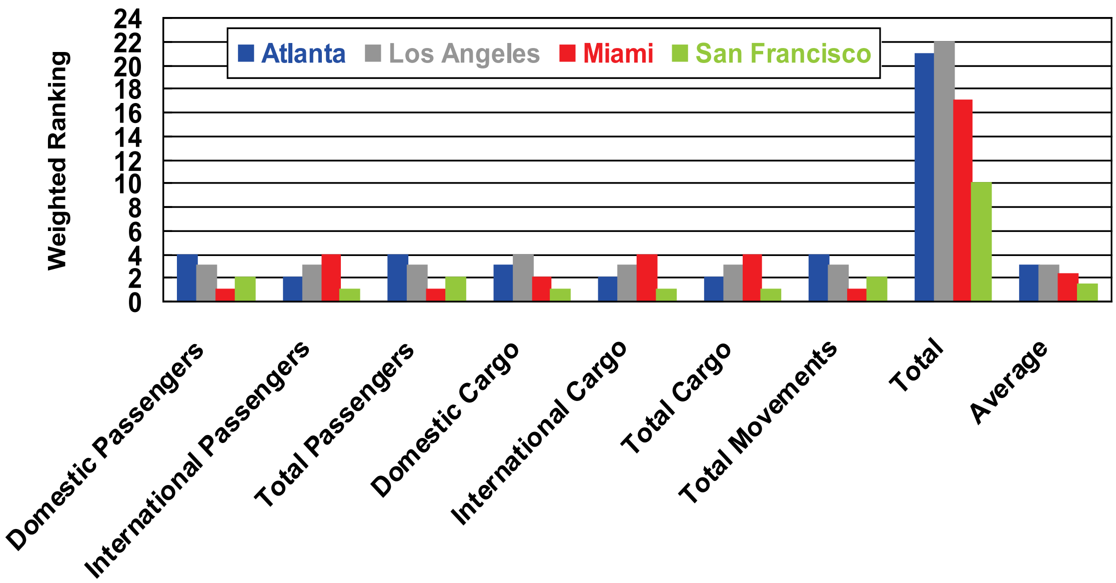


Figure 82. Airport Candidates Based on Airport Operations Metrics

It is worth noting how busy LAX is in terms of absolute levels. In 2009, LAX ranked:

- 3rd in North America and 7th in the world with 56,520,843 PAXs
- 13th in the world with 1,509,236 tons Cargo
- 4th in the world with 634,383 movements

Hence, based on all selection criteria above and airport operations metrics, it was clear that LAX was the right choice of airport for operational noise analysis for the ERA study.

2.11.3 Development of LAX Airport Operations Models

2.11.3.1 Radar Database

Radar data exists in several formats, namely, ACATS, ANOMS8, PDARS, and CMSIM. The sources of these radar data types are, respectively, flight data, the airport, FAA, and NASA. ANOMS8 data covers a range of 50 Nautical Miles out from the airport. If a longer range is required, CMSIM data can be utilized, which extends out to 200 Nautical Miles. This study utilized ANOMS8 radar data collected for LAX under another NASA contract. Data was available from July 2009 – January 2011. The data provided information on LAX airport operations and flight tracks. Since the data covered the recent 2 ½ years, it was deemed sufficient in quantity and relevant in time to provide pertinent information.

2.11.3.2 Development of LAX Current Operations Model

2.11.3.2.1 Current Operational Tracks & Routes

During a typical day, there are many arrivals and departures at LAX, as shown in Figure 83. Arrivals are noted in red, and departures are noted in green. With too many tracks to model individually, representative daily routes were created. Arrivals tracks were simulated with routes denoted in black. Departure tracks were simulated with routes denoted in blue. Tracks to other airports such as Long Beach and Ontario are shown (diagonal cross-lines). These did not impact the analysis. In this study, a simplification was made, in which departures or arrivals on a given runway were dispersed equally on the routes of that runway. No attempt was made to determine which routes were loaded more, nor which specific aircraft flew on which specific route.

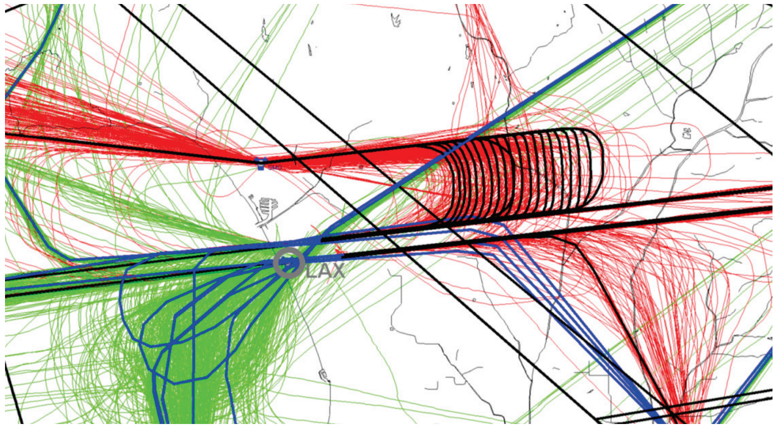


Figure 83. Typical Day LAX Airport Operations (Departures & Arrivals)

2.11.3.2.2 Current Operations Statistics

As noted above, the ANOMS8 radar database was utilized in this study. The range of data spanned 2 ½ years, from July 2009 through January 2011. In the revised methodology, the radar data was synthesized into departures and arrivals on daily basis, sorted by INM aircraft model, runway, time period, and route patterns. The focus in this study was on daily operations; nonetheless, it is worth reviewing in brief, the operational statistics for the entire time period.

Over the 2 ½ year period, the radar database indicated that there were 445,135 departures at LAX. This excludes helicopters and unidentifiable aircraft types. Runway usage for all the departures (departures sorted by runways 06L, 06R, 07L, 07R, 24L, 24R, 25L, 25R) is depicted in Figure 84. The associated percentage of departures by runway (with respect to total departures) is depicted in Figure 85. Clearly, as shown, runways 25R and 24L handled most of the departures.

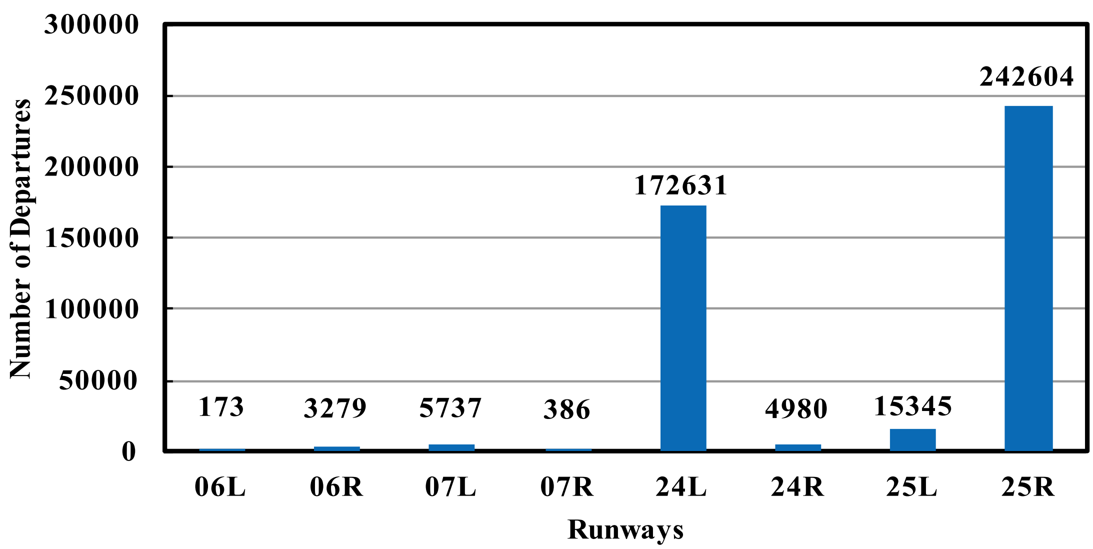


Figure 84. Total Departures at LAX by Runway (Rwy Usage) for 2 ½ Year Period

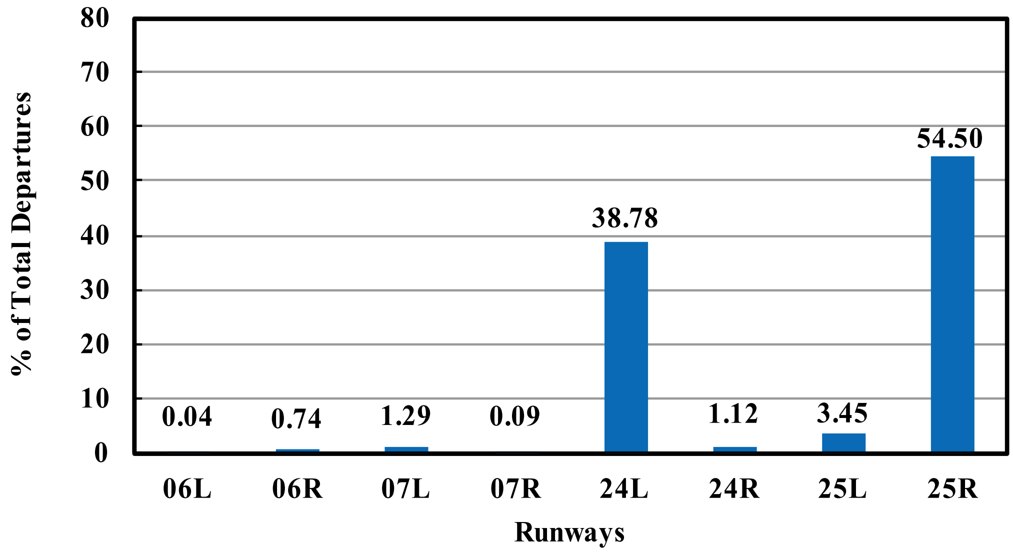


Figure 85. Runway Usage in Percent for All Departures at LAX for 2 ½ Year Period

Similarly, the radar database indicated that there were 439,831 arrivals over the 2 ½ year period. This excludes helicopters and unidentifiable aircraft types. Runway usage for arrivals, i.e. arrivals sorted by runway is shown in Figure 86. The associated percentage of arrivals by runway is depicted in Figure 87. For arrivals, the dominant runways were 24R and 25L.

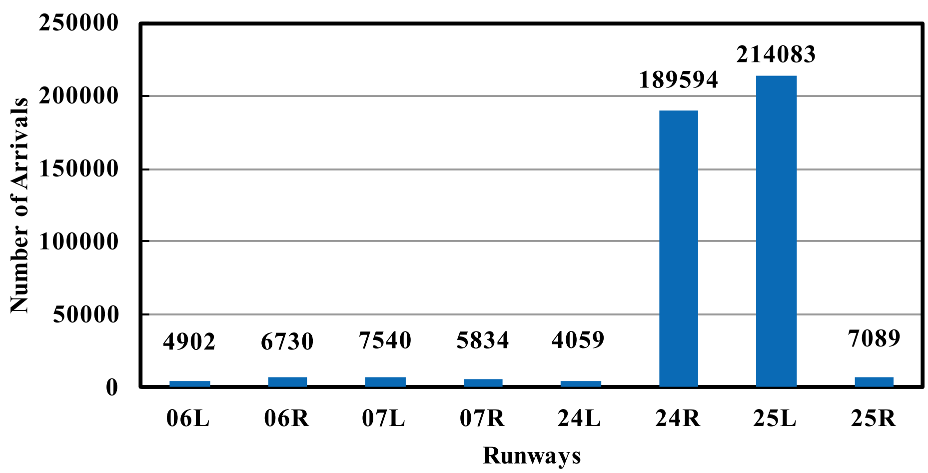


Figure 86. Total Arrivals at LAX by Runway (Rwy Usage) for 2 ½ Year Period

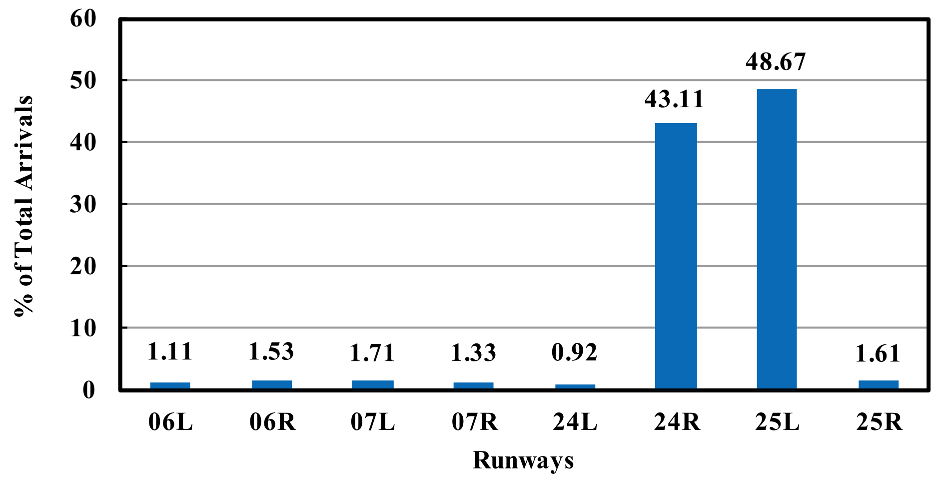


Figure 87. Runway Usage in Percent for All Arrivals at LAX for 2 ½ Year Period

The runway usage shown in Figure 85 and Figure 87 are for the total operational levels over 2 ½ years, irrespective of time of day. Hence, the data was further subdivided into total operations during periods of the morning (12 AM – 7 AM), daytime (7 AM – 7 PM), evening (7 PM – 10 PM), and nighttime (10 PM – 12 AM). For brevity, the data breakdown is not included herein; however, it was similar to the overall percentages shown in Figure 85 and Figure 87. The only difference is that arrivals in the morning exhibit a distribution more uniform than in Figure 87.

The data was also analyzed for breakdown of total departures and arrivals by airplane type across all runways. It was found that there are 239 unique airplanes departing or arriving into LAX. For brevity the data is not shown herein. In brief, over the 2 ½ year period, the most prevalent airplanes for departures and arrivals were the 737 Classic, 757-200, A320, B737-800, E120, E135, and A319. Further breakdown by most prevalent aircraft during each of the specific time periods was also found but is not of high importance to this study.

Having discussed briefly the total operations statistics for the 2 ½ year time period; focus shifts to daily operations statistics. The latter is the basis for operational airport noise analysis. To derive daily operational levels, the normalization factor of 579 was selected, which is the total days for the 2 ½ year time period. The total departures sorted by runway, (data in Figure 84), when normalized to daily levels, yields the data in Figure 88. Similarly, the total arrivals sorted by runway, (data in Figure 86), when normalized to daily levels, yields the data in Figure 89. Note that the normalization for all runways is the same, hence the daily runway usage in percentages is the same as before (Figure 85 for departures and Figure 87 for arrivals).

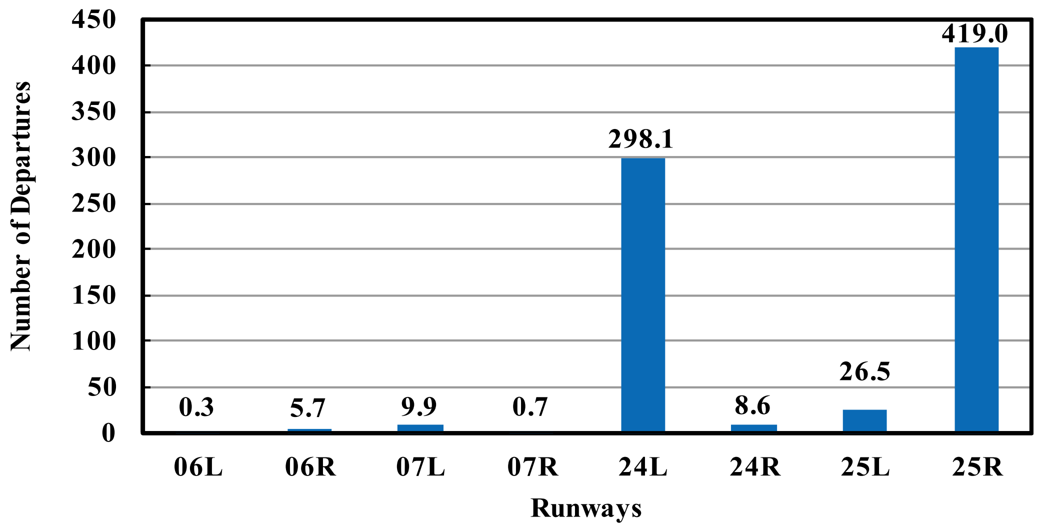


Figure 88. Daily Departures at LAX by Runway (Rwy Usage for 24 HR Period)

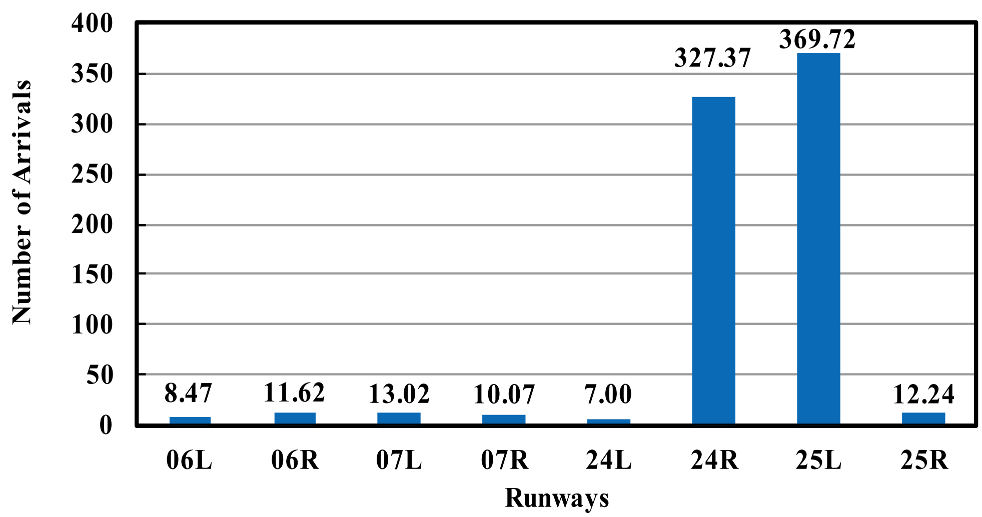


Figure 89. Daily Arrivals at LAX by Runway (Rwy Usage for 24 HR Period)

It is important to note that the figures above show, in some instances, fractions of operations. This is because there might have been fewer than 579 operations on a given runway over the 2 ½ year period. Hence when normalized by 579, the data yields daily values < 1. Note that summation of the levels in Figure 88 yields 769, which is the total daily departures at LAX. Similarly, adding the levels in Figure 89 yields 760, which is the total daily arrivals at LAX.

The total daily operations were further sorted by operations during the morning, daytime, evening and nighttime periods. This data can be presented on an absolute level basis, i.e. number of departures/arrivals; however, the data will instead be presented in percentages with respect to the total operations during the specific time period. Figure 90 shows the percent runway usage for daily departures during the daytime period, i.e. 7 AM to 7 PM. The daily percent runway use for the other time periods, i.e. morning (12 AM – 7 AM), evening (7 PM – 10 PM), and nighttime (10 PM – 12 AM), is provided in Table 44. Note that the percentage values for the runways are different for the 4 time periods, yet the relative rankings of the runways and the most prevalent runways are the same for all time periods.

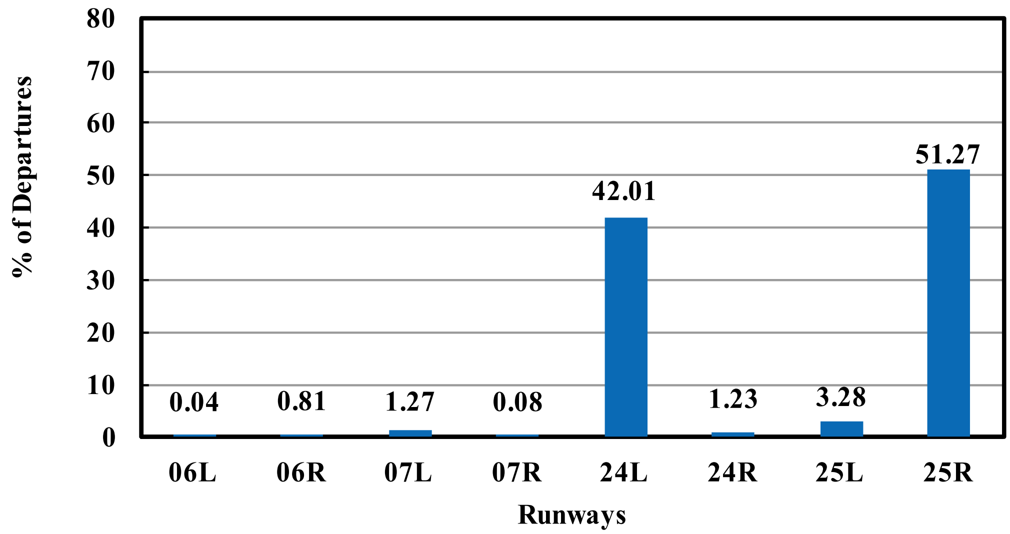


Figure 90. Runway Usage in Percent for Daytime Departures at LAX (Daily 7AM-7PM)

Table 44. Daily Departures in Percent by Runway and Time Period

Runway	Morning	Day	Evening	Night
06L	0.02	0.04	0.02	0.03
06R	0.38	0.81	0.73	0.57
07L	1.69	1.27	1.03	1.28
07R	0.18	0.08	0.07	0.07
24L	18.50	42.01	45.80	28.30
24R	1.26	1.23	0.61	0.71
25L	4.01	3.28	4.76	2.15
25R	73.95	51.27	46.98	66.89
SUM	100	100	100	100

Similarly, the percent runway use for arrivals during the daytime period is illustrated in Figure 91 below. The percent runway use for daily arrivals during the morning, evening, and nighttime periods is provided in Table 45. Again, the percentage values are different for the 4 time periods, yet there is some similarity in trends. The daytime, evening, and nighttime periods exhibit the same runway rankings and most prevalent runway. The morning period arrivals are distinct in that they exhibit a more uniform runway distribution.

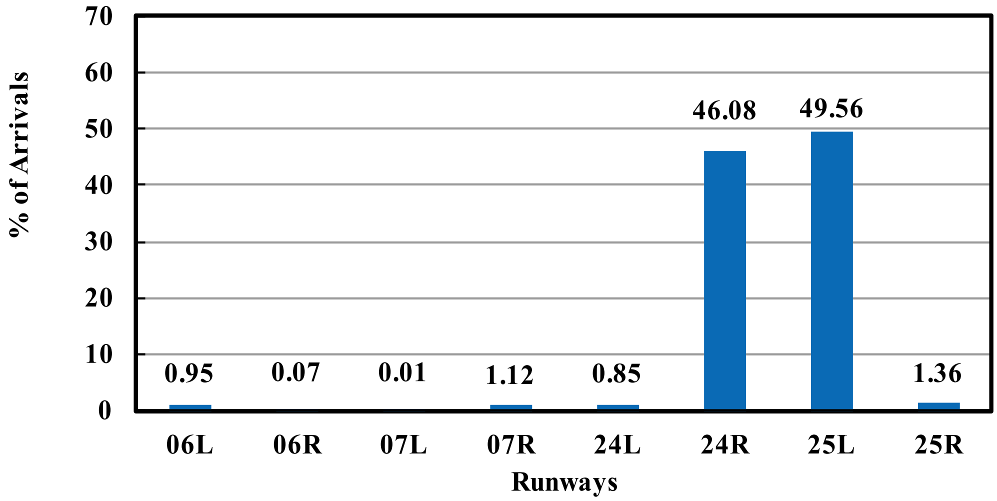


Figure 91. Runway Usage in Percent for Daytime Arrivals at LAX (Daily 7AM-7PM)

Table 45. Daily Arrivals in Percent by Runway and Time Period

Runway	Morning	Day	Evening	Night
06L	3.80	0.95	0.78	0.89
06R	20.23	0.07	0.01	0.34
07L	23.63	0.01	0.02	0.02
07R	4.48	1.12	0.89	1.20
24L	0.36	0.85	1.49	0.63
24R	11.97	46.08	45.93	39.16
25L	33.87	49.56	48.20	56.76
25R	1.67	1.36	2.68	1.00
SUM	100.0	100.0	100.0	100.0

So far, discussion has focused on sorting daily operations by runway and time period. However, daily operations were also sorted by airplane type and time period. Figure 92 (a) shows the daily departures over a 24 HR period sorted by airplane type. Departures across all the runways were included. As noted in the figure, the top 10 most prevalent aircraft are the 737-700, 757, 737-800, A320, EMB120, CRJ9, A319, EMB145, 737-300, and 747-400. These aircraft account for 536 of the 769 daily departures, or 70%. Similarly, Figure 92 (b) depicts the daily arrivals over a 24 HR period sorted by airplane type. Arrivals across all the runways were included. Again, the same aircraft are most prevalent aside from the 747-400 being replaced with the CL601 aircraft. Of the 760 total daily arrivals, 531or 70% were flown by the 10 most prevalent aircraft. Note that for both departures and arrivals, there is an "Other" category which is a collection of all the aircraft with less than 1 departure or 1 arrival. The other category is mostly insignificant since it only amounts to 1.5% of the total daily arrivals or departures.

Aside from the 24 HR time period, daily departures and arrivals during the morning, daytime, evening, and nighttime periods were also sorted by airplane type. Departures and arrivals across all runways were included. For brevity the data is omitted. It should be noted, that some of the top 10 prevalent aircraft in the 24 HR period were also prevalent in each of the time periods. There were, however, some differences in aircraft type and relative rankings.

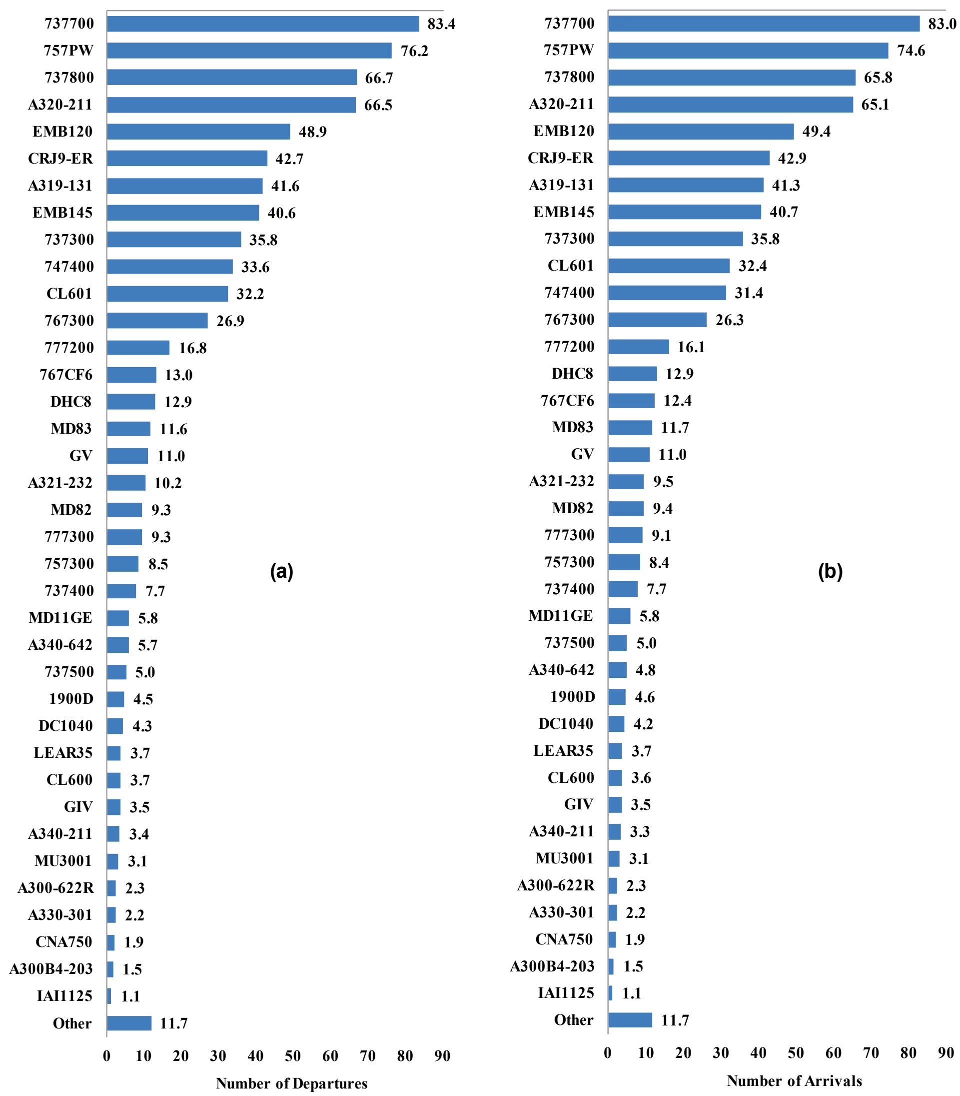


Figure 92. (a) Daily Departures in LAX by Airplane Type (All Runways / 24 HR) (b) Daily Arrivals in LAX by Airplane Type (All Runways / 24 HR)

Aside from operations across all runways, operations on each runway were also analyzed. Daily departures and arrivals for each runway were sorted by aircraft type. Moreover, for each runway, daily departures and arrivals during the morning, daytime, evening and nighttime periods were also sorted by aircraft type. Accordingly, the most prevalent departure and arrival aircraft were found for each runway and for each time period on a given runway. For completeness, this synthesis has been mentioned, but the results are omitted, since they are of low importance.

Having discussed above, sorting of data by airplane type, it is important to understand what set of aircraft were utilized. Examining closely Figure 92, it should be noted that there is a reduced set of aircraft. In fact, all daily departures and arrivals were sorted by the 88 INM aircraft models, and not by the original and extended set of 239 unique aircraft. This is because the daily operations were derived after the unique aircraft were already grouped into the 88 aircraft models (step 6 after step 5 of the revised methodology). This is not viewed as a lack of fidelity since the INM aircraft models are viewed as representative aircraft categories, with a noise signature that simulates well, the noise of all the aircraft within the specific category.

Thus far, various operational statistics were shown. The focus now is on the most critical statistics and the adjustments that were applied to develop the LAX current airport operations model. Recall that the daily operations were divided into daily departures and arrivals, sorted by INM aircraft, by runway, and by time period. Recall also that the time period included day, evening, nighttime, and morning. For the first adjustment, the nighttime and morning periods were combined (10PM–12AM + 12AM–7AM) to form a new extended nighttime period (10PM – 7AM). This was necessary to be consistent with the extended nighttime period assumed by the DNL airport noise analysis metric. Accordingly the departures for the nighttime and morning were added together. Similarly, the nighttime and morning arrivals were added together. In both instances the aircraft and runway sorting was preserved. The second adjustment entailed weighting of operations for noise annoyance. In specific, the departures and arrivals sorted by INM aircraft, by runway and by the new time periods were adjusted as follows:

Day operation x 1 , Evening operation x 3 , Extended Nighttime operation x 10

Hence, aside from the day operations, each operation in the evening and nighttime was considered multiple times. In other words, the penalty, was to make even a few operations in the later hours of the day seem like there were many more operations. Hence the noise of only a few operations gets multiplied many times over, resulting in a greater noise impact. The reason for the skewed weighting is because there is greater sensitivity to noise later in the day.

Having derived the "adjusted" operations by accounting for the new extended nighttime period and also for the annoyance weighting, one last regrouping was required. The day evening and nighttime periods were all combined into a single time period. This is standard procedure for INM airport noise analysis. Accordingly the weighted day, evening and nighttime operations were summed together. Note that the aircraft and runway sorting was preserved. Hence, for both departures and arrivals, the input into INM was one single dataset of operations for each runway, albeit, still sorted by INM aircraft model.

Within INM, the final set of daily operations data was sorted by runway irrespective of aircraft, and by aircraft irrespective of runway. The latter is shown in Table 46 (a) for departures and in Table 46 (b) for arrivals. This data includes all weightings, adjustments, and regroupings. Note that total weighted daily departures are ~2271 vs. the actual 769, and total weighted arrivals are 2028 vs. the actual 760. Ordering by most to least operations, it is clear that the top 10 departure aircraft are: A320, 737-800, 757, 747-400, 737-700, A319, EMB120, CRJ9, 767-300, and CL601. The top 10 arrival aircraft are: 757, 737-800, 737-700, A320, A319, EMB120, 747-400, CRJ9, 767-300, and EMB145. There are differences in rankings in Table 46 as compared to Figure 92. This is because the departures and arrivals herein are weighted levels. Thus, any aircraft with high evening and/or nighttime operations scores higher in the weighted scale as compared to the non-weighted scale, i.e. gains in relative ranking when weighting is applied.

The data in Table 46 provides each and every INM aircraft used as input. To understand later on, which aircraft will be replaced with the PSC, all the aircraft were assigned to the overall aircraft categories of: Single Aisle, Twin Aisle, General Aviation and Commuter, and Out-of-Production. The distribution of aircraft across these categories is shown in Figure 93. As shown, of the 60% of Single Aisle aircraft operating today at LAX, 8% are smaller type (EMB145, CRJ9), 39% are medium type (A319, 717200), and 13% are larger type single aisle aircraft (A321, 757). Similarly, of the 24% of Twin Aisle aircraft, 7% are smaller type (767, A300), 8% are medium type (A330, DC10), and 9% are larger type twin aisle aircraft (747400, A380). Of the 14% General Aviation and Commuter aircraft, <1% are smaller type (CNA172), 7% are medium type (LEAR25), and 7% are larger type (GV) aircraft. The remaining 6% of operations at LAX today are out of production smaller and larger freighter aircraft (DC8, 747200).

Table 46. (a) Weighted Daily Departures in LAX by Airplane Type (All runways / 24HR); (b) Weighted Daily Arrivals in LAX by Airplane Type (All runways / 24HR)

(a)

Aircraft	Weighted Departures
A320-211	224.6840
737800	214.9810
757PW	211.0536
747400	196.8221
737700	183.4870
A319-131	144.2314
EMB120	120.7306
CRJ9-ER	102.6615
767300	88.8325
CL601	80.9499
EMB145	74.2746
737300	62.7029
777200	62.1019
777300	52.7876
767CF6	45.5268
A321-232	45.0121
757300	29.7306
MD11GE	29.4681
DC1040	25.4197
DHC8	25.3074
A340-642	24.9603
GV	20.6978
MD83	20.2280
MD82	16.4767
1900D	16.2107
A300-622R	15.2090
A300B4-203	13.0155
737400	12.9810
737500	10.0207
A340-211	9.3696
A380-841	9.3489
GIV	9.0121
LEAR35	8.5389
CL600	7.8964
MU3001	6.5112
A330-301	6.2073
747100	5.4059
747200	4.8808
CNA750	3.8705
DC870	3.4715
IA1125	2.4491
DHC6	2.4128
MD9025	2.3713
GII	2.1883
74720B	1.9309
CNA441	1.6218
CNA500	1.5803
CIT3	1.5026
GIIB	1.2539
A310-304	1.1710
LEAR25	1.1295
BEC58P	1.0155
FAL20	1.0104
GASEPV	0.7547
727200	0.7340
ECLIPSE500	0.5181
767400	0.4732
CNA208	0.4197
HS748A	0.2297
CNA182	0.1848
GASEPF	0.1675
CNA206	0.1537
DC930	0.1330
727100	0.1209
747SP	0.1209
A330-343	0.1174
CNA172	0.1123
717200	0.1071
CNA510	0.0915
BAC111	0.0898
737D17	0.0829
PA28	0.0691
DO328	0.0449
707320	0.0328
PA31	0.0311
707	0.0242
MD81	0.0242
SD330	0.0190
DC910	0.0104
L1011	0.0069
DC950	0.0052
BAE146	0.0052
DHC830	0.0052
DC860	0.0035
DC8QN	0.0035
DC3	0.0017
Sum	**2271.6131**

(b)

Aircraft	Weighted Arrivals
757PW	263.5769
737800	194.0726
737700	193.8463
A320-211	191.5630
A319-131	125.8670
EMB120	110.0173
747400	103.1433
CRJ9-ER	95.8100
767300	93.1796
EMB145	73.1848
CL601	66.1105
737300	62.4145
767CF6	48.3368
MD11GE	35.8290
777200	35.4473
757300	29.3938
MD83	29.0743
DC1040	28.3385
GV	26.4560
A321-232	23.4663
DHC8	18.1278
MD82	16.6822
777300	16.4318
A300-622R	13.7288
737400	11.0501
737500	10.7789
A300B4-203	10.2539
A330-301	9.8221
GIV	8.3731
LEAR35	8.1123
CL600	7.9914
1900D	7.2798
A340-642	6.6390
MU3001	6.1986
A310-304	4.8791
747100	4.5337
A340-211	4.4387
DC870	3.9326
CNA750	3.8221
747200	3.6442
GII	2.1192
IA1125	2.0846
DHC6	1.7617
MD9025	1.7392
CIT3	1.4698
CNA500	1.4542
CNA441	1.0484
GIIB	1.0449
FAL20	1.0328
74720B	1.0225
LEAR25	1.0035
A380-841	0.9706
BEC58P	0.9568
GASEPV	0.6995
727200	0.6269
ECLIPSE500	0.5838
767400	0.5734
HS748A	0.2573
CNA208	0.2228
CNA182	0.2176
CNA206	0.1554
CNA172	0.1364
727100	0.1261
DC930	0.1157
717200	0.1088
A330-343	0.1088
CNA510	0.1071
747SP	0.0933
707320	0.0881
GASEPF	0.0812
737D17	0.0674
DO328	0.0656
MD81	0.0570
BAC111	0.0449
DC950	0.0363
L1011	0.0259
PA31	0.0121
SD330	0.0104
PA28	0.0086
DC8QN	0.0069
DC910	0.0052
DC3	0.0035
DC860	0.0035
Sum	**2028.2055**

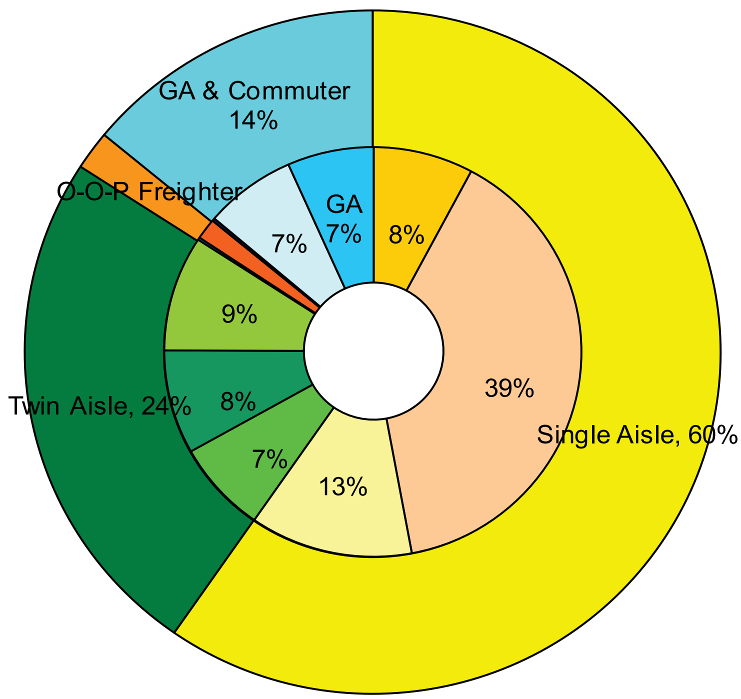


Figure 93. LAX Daily Operational Fleet Mix

The final data sorted by runway, irrespective of aircraft, is depicted in Table 47 (a) for departures and in Table 47 (b) for arrivals. Again, this data includes all weightings, adjustments, and regroupings. Table 47 also shows, for each runway, the associated routes that were used in the baseline operations model. Note the equal distribution of operations for a runway with multiple routes. For example, runway 25R has equal distribution of departures on the 5 departure routes.

Table 47. (a) Weighted Daily Departures in LAX by Runway (All aircraft / 24HR); (b) Weighted Daily Arrivals in LAX by Runway (All aircraft / 24HR)

(a)

Runway	Weighted Departures	Departure Routes
06L	0.7	SNGO5
06R	13.1	SNGO5A
07L	31.8	SNGO5B
07R	2.5	SNGO5C
24L	227.1	CASTA
	227.1	KARVR3
	227.1	LOOP6
24R	23.2	PERCH9B
25L	77.7	HOLTZ9
25R	288.2	CARDI5
	288.2	JEDDD1
	288.2	LOOP6B
	288.2	OSHNN3
	288.2	PERCH9
Sum	**2271.6**	

(b)

Runway	Weighted Arrivals	Arrival Routes
06L	33.8	ILS06L
06R	112.9	ILS06R
07L	129.5	ILS07L
07R	40.6	ILS07R
24L	16.2	ILS24L
24R	710.2	ILS24R
25L	952.1	ILS25L
25R	33.1	ILS25R
Sum	**2028.2**	

So in review, this section has focused on statistics of present day departures and arrivals at LAX. Statistics were shown in absolute values and percentages for: (a) 2 ½ years worth of operations, (b) daily normalized operations, (c) operations dispersed by runway (runway usage), (d) operations sorted by time period, and (e) operations sorted by aircraft type. The statistics and discussions provided overall insight into the operations at LAX. In addition, the statistics formed the basis for development of the LAX baseline operations model.

2.11.3.3 Development of LAX 2030 Operations Model

2.11.3.3.1 Airport & Market Forecasts

In order to determine the LAX airport forecasts, as well the overall airline industry market forecasts, several sources of information were referenced, namely the Airport Councils International (ACI) databases, the FAA growth databases and the Boeing Current Market Outlook. ACI published a report in 2005 with forecast from 2005-2020. The overall comments were that with unconstrained growth, passenger traffic would grow over 15 years by 4.1 % through 2020. Similarly, freight would grow by 5.4 %. For North America the predicted average annual passenger growth rate 2004 -2020 would be 2.7 % for domestic and 3.1 % for international. The average annual growth for freight was 3.5 %. This data was based on information from 273 ACI member airports, of which LAX is a member airport.

Using a more recent source, the Boeing Current Market Outlook (CMO) predicts 3.6 % annual growth rate worldwide. The distribution of the worldwide aircraft fleet by Large, Twin Aisle, Single Aisle, and Regional Jet categories is shown in Figure 94 (a). The 2010 distribution is the inner rings and the project 2030 distribution is the outer rings. Similarly Boeing CMO predicts 1.7 % annual growth in North America. The distribution of the North America fleet by Large, Twin Aisle, Single Aisle, and Regional Jet categories is shown in Figure 94 (b). Again, the 2010 distribution is the inner rings and the project 2030 distribution is the outer rings.

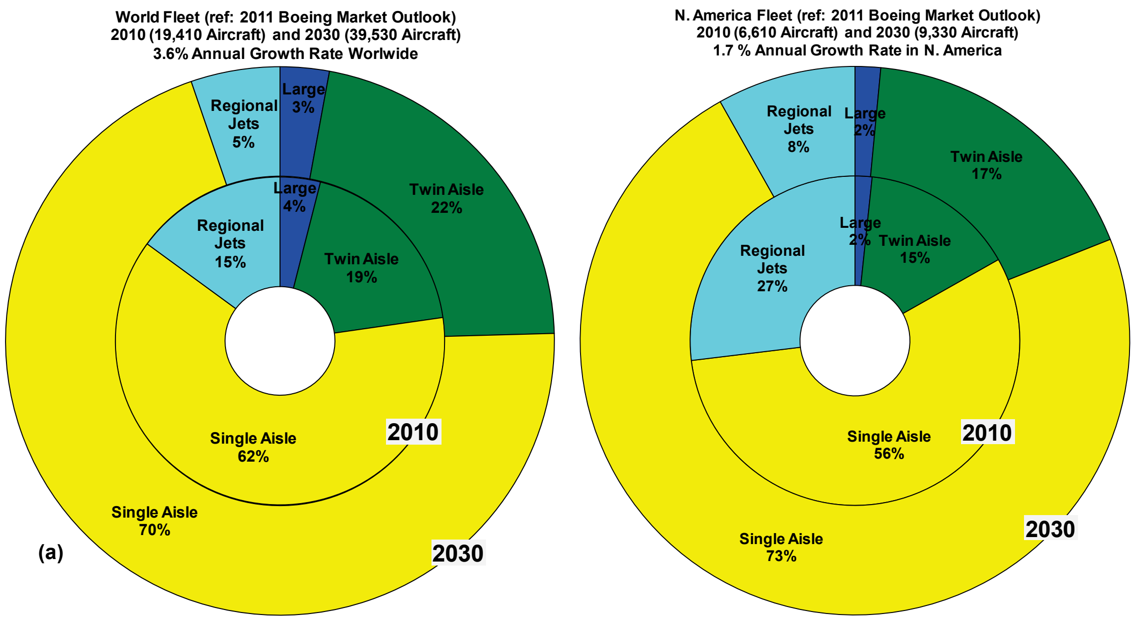


Figure 94. (a) Boeing Current Market Outlook Forecast for Worldwide Fleet; (b) Boeing Current Market Outlook Forecast for North America Fleet

Using the source above as a basis for comparison the FAA airport growth database was used for LAX specific growth forecast information. There, it was cited that 452,198 air carrier operations occurred in LAX in 2010. For 2030, projections indicated there would be 836,733 operations. Using the compound annual growth rate equation:

$$c = e^{\left[\frac{Ln\frac{Final\ Value}{Initial\ Value}}{Time\ Period}\right]} - 1$$

the annual growth rate for LAX was determined to be 3.12%. With this annual growth rate, the growth factor to the year 2030 would be $(1.0312)^{(2030\text{-}2009)} = 1.906$. Hence 2030 would have nearly double the current day operations.

2.11.3.3.2 2030 Operations Statistics

Since the FAA forecast database sited LAX airport specific information, hence 3.12 % compound annual growth rate was utilized. With this growth rate the growth factor of 1.906 was used to adjust the current operations model to 2030 levels. In specific, the weighted departures and arrivals by aircraft shown in Table 46 were multiplied by the growth factor. The total dialy operations were adjusted as shown in Table 48. Recall that aircraft types, aircraft distributions, and runway usage were all not changed from the baseline model. Hence much of the statistics shown previously are valid for the 2030 operations model.

Table 48. LAX Current and 2030 Daily Operations

Daily Operations	Current	2030
Departures	769	1422
Arrivals	760	1405

2.11.4 Development of PSC INM Model

2.11.4.1 Performance Aspects for NextGen Missions

The INM contains a database of aircraft performance and noise-power-distance (NPD) maps for existing commercial, military and general aviation aircraft, which is needed for an airport noise analysis. In addition the model allows the user to create performance and noise data for new aircraft such as the PSC to assess the impact of current or future operations on airport noise. NPD maps were created for the PSC using the same methods as used to estimate certification noise levels. In Figure 95 the noise levels of the 777-200 / GE90 and the PSC are compared. At approach power the PSC noise curve is 5 EPNdB below the corresponding 777-200 approach noise curve. At full power this difference is on the order of 23 EPNdB.

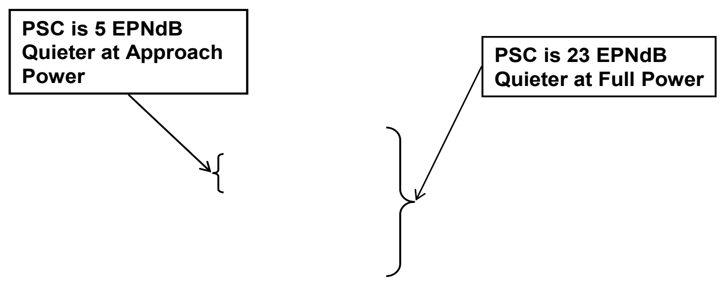


Figure 95. INM Model – Noise Power Distance Data

The aircraft performance data of the PSC for the NextGen sizing mission was adapted for use in the airport noise study. Typically airport studies make use of aircraft performance data at conditions representative of normal airport operations and flight procedures. In the case of the 777-200 the INM data is provided at a 70% load factor condition for nine different stage lengths which correspond to different takeoff weight and flight ranges. The 777-200 takeoff performance data is shown in Figure 96 for a standard departure procedure. Altitude, speed, and thrust are shown as a function of distance along the flight path.

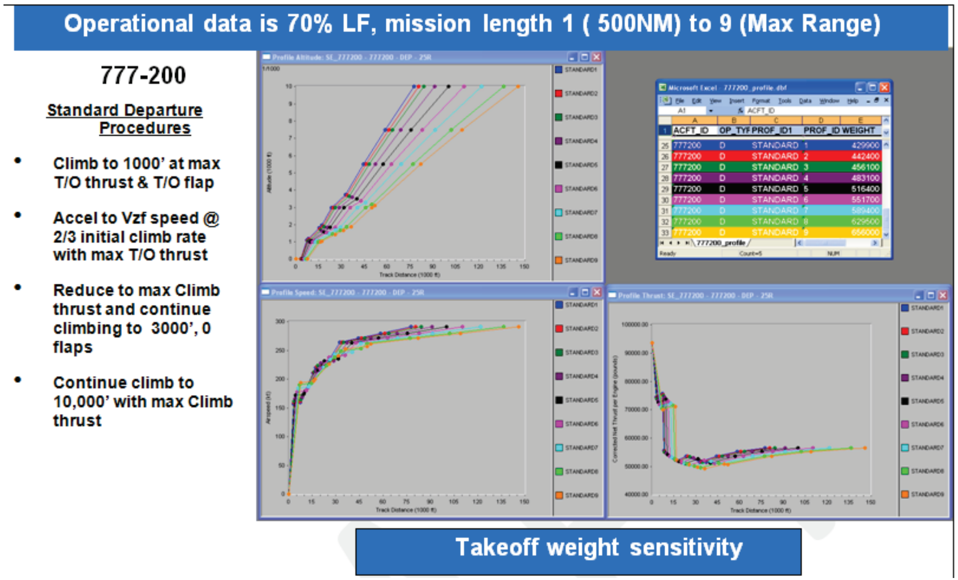


Figure 96. INM Model – Aircraft Performance Data

Besides the standard takeoff procedure, the INM also provides data for a close-in noise abatement departure procedure (NADP) and a distant NADP at the various stage lengths. Figure 97 compares these procedures for the stage length 1 which is a 500NM mission with a takeoff weight of 429,900 lbs for the 777-200. The procedure affects the altitude, speed, and thrust of the aircraft over communities located 10 to 40 NM from the airport.

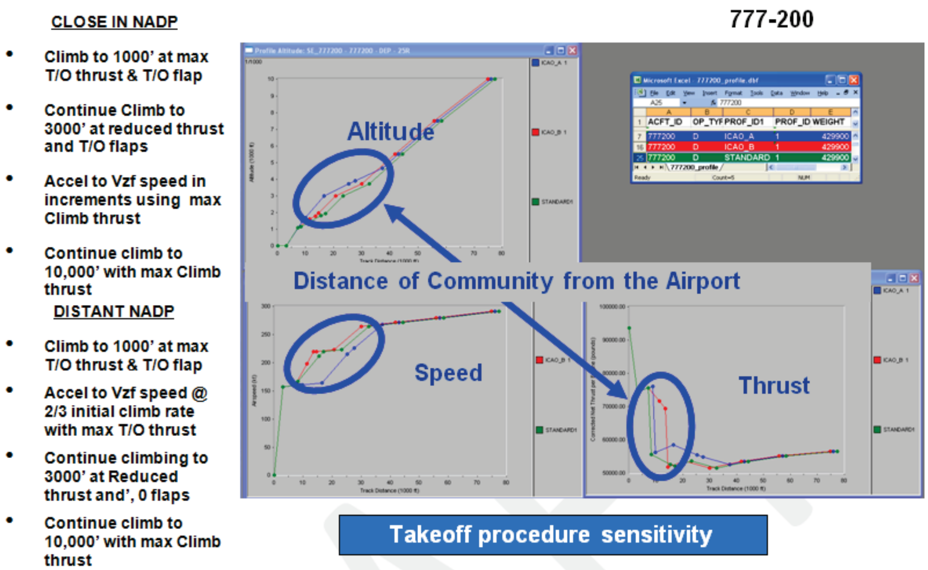


Figure 97. Noise Abatement Departure Procedure (NADP)

Noise Abatement Departure Procedures (NADP) essentially trade altitude and thrust in the climb and acceleration segments.

2.11.5 Noise Contour Results

2.11.5.1 PSC Single Event Noise Analysis

The PSC performance and NPD data were used in INM to generate single event noise contours. The reach technology NPD was generated by applying a 3 EPNdB reduction to the slat noise and a 5 EPNdB reduction to the landing gear component noise sources to meet the NASA noise certification goal as discussed in Section 2.9.3. The resulting noise contours are shown in Figure 98 for a single westerly departure and arrival. These are Sound Exposure Level (SEL) noise contours in 5 dB increments ranging from 75 dB (blue) to 95 dB (red). The performance data used here was the NextGen sizing mission which included certification cutback takeoff procedure and a 3 degree stabilized approach.

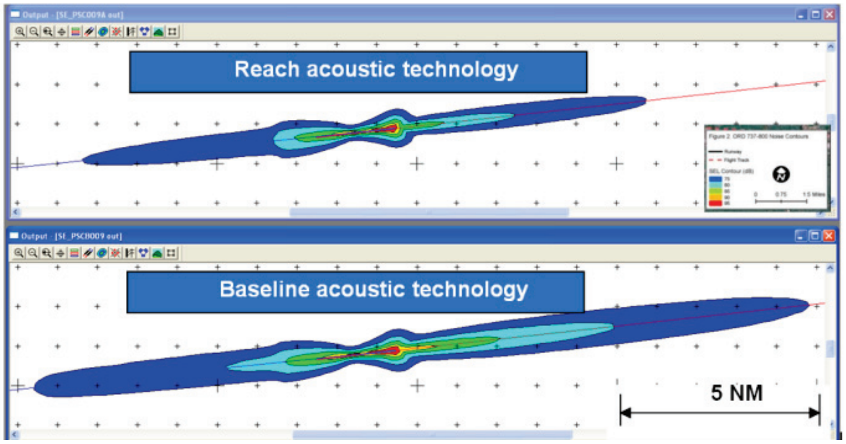


Figure 98. PSC Single Event Noise Contour Results - Operational performance (certification cutback then restore to max climb power at 3000' altitude)

The comparison is repeated in Figure 99 for an operational NADP where the cutback is only to max climb power, which results in slightly fatter but noticeably shorter contours under the departure. The portion of the noise footprint under the arrival is the same as in Figure 98.

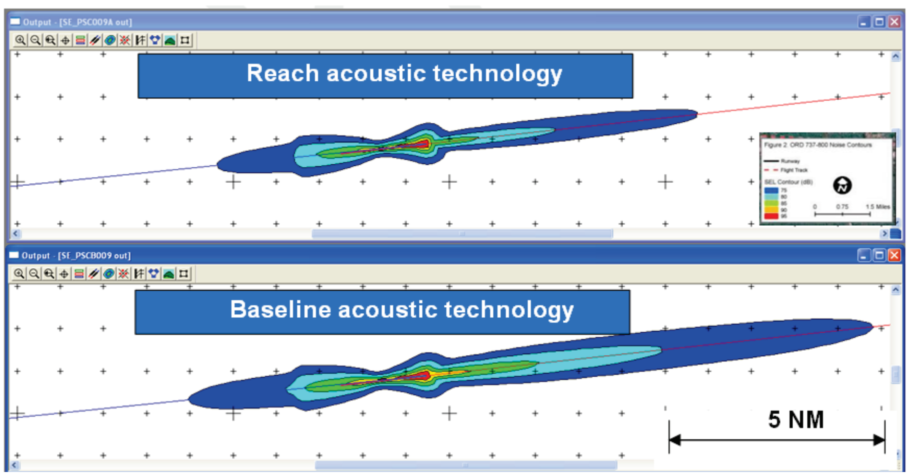


Figure 99. PSC Noise Contour Results - Operational performance (cutback to max climb at 1500')

The PSC is clearly sized to perform the mission of today's twin aisle aircraft, however the technology developed for the PSC will also be applied to the single aisle replacement aircraft. In the NASA Subsonic Ultra Green Aircraft Research (SUGAR) project N+2 and N+3 levels of technology were evaluated. These denote two and three generations beyond the current transport fleet, respectively, which studied aircraft that might enter service out to the 2030 to 2035 time frame.[3] The class of aircraft evaluated in SUGAR technology maturation study was a single aisle replacement. SEL noise contours are shown in Figure 100 for a 737-800 and aircraft designed with N+2 and N+3 levels of technology, which bracket the PSC reach level of technology.

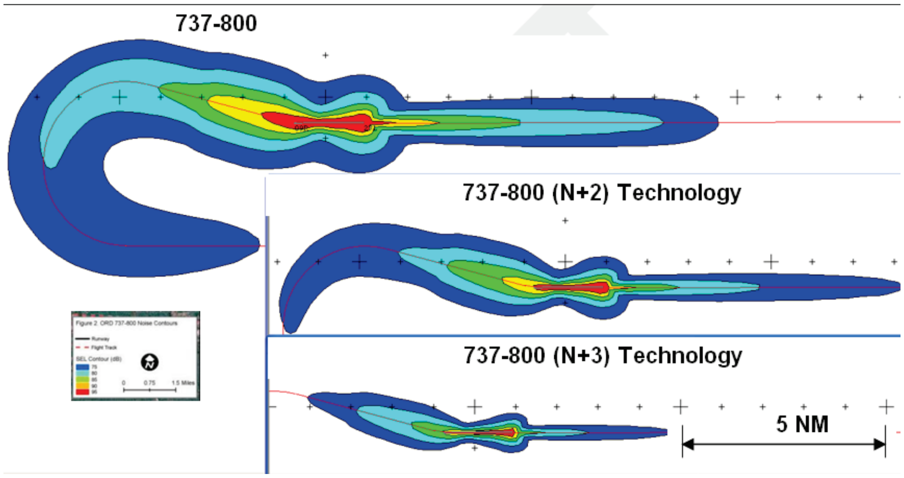


Figure 100. Previous Noise Analysis for Single Aisle ref. – SUGAR study

Another way to compare the noise of different aircraft is to overlay the contour of a single noise level for each aircraft type. In Figure 101 the 85 dB SEL contour of a 747-400, a 777-200, the PSC with baseline, and the PSC with reach acoustic technology are shown. The noise footprint of the baseline PSC covers less than a quarter the area of these twin aisle aircraft.

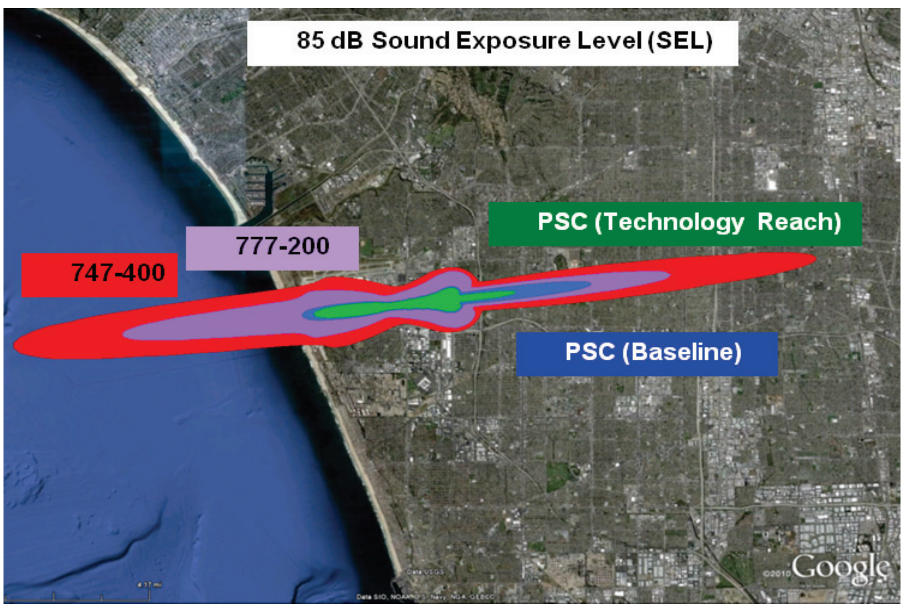


Figure 101. Single Event Noise Comparisons

The 85 SEL contours of a few other aircraft that will likely be operating along side the PSC in the future are shown in Figure 102. Again the PSC noise contour shown here is either a quarter or an eighth the size of today's aircraft depending on the acoustic technology level (baseline or technology reach).

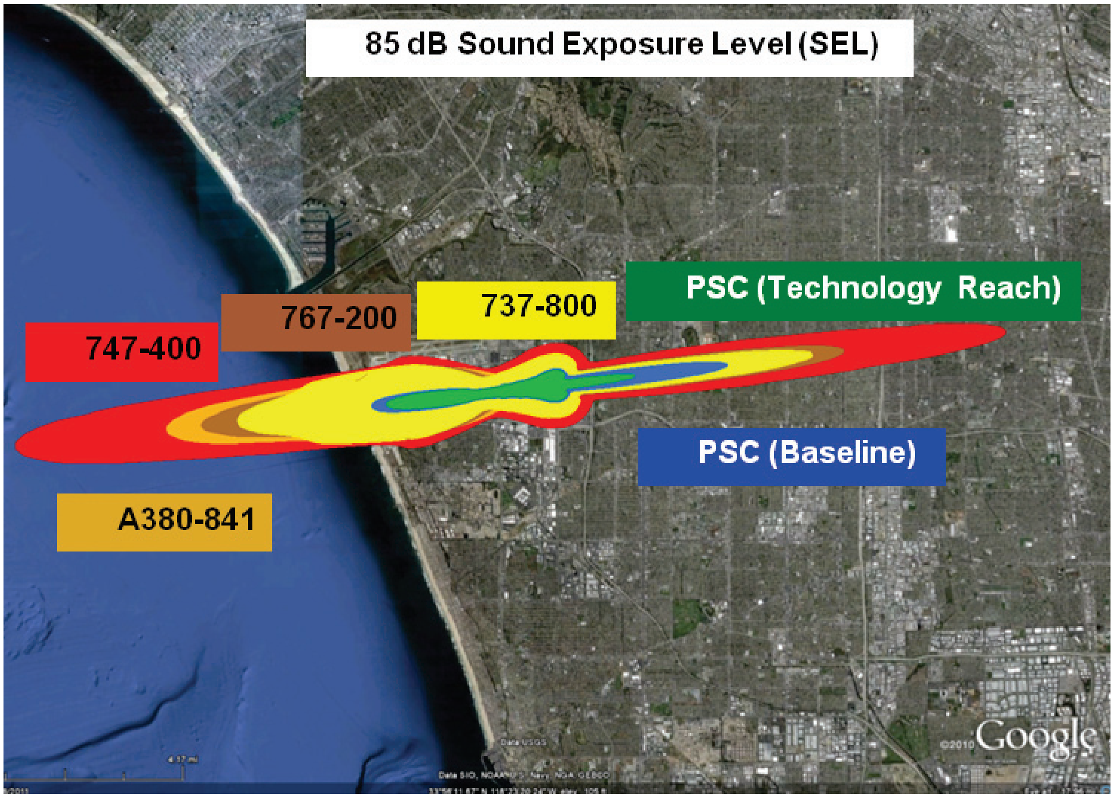


Figure 102. Single Event Noise Comparisons, Cont.

2.11.5.2 LAX Current (2010) & 2030 Cumulative Noise Analysis

INM models of LAX operations in 2010 and 2030 were developed from flight procedures and airspace design information of previous NASA air traffic management studies to evaluate NextGen technologies. The INM models for LAX operations in 2010 and a projection of operations for 2030 (based purely on a growth factor of 1.906 as described in 2.11.3.3.1), were used to generate community equivalent sound level (CNEL) noise contours. The results show that in twenty years time, operations will nearly double and if this growth were to be handled with additional flights of the same aircraft in use today the CNEL noise exposure area would grow by 65-70%, with noise from departures effecting communities west of the airport to the coast and arrivals mostly impacting communities east of the airport under the final approach patterns to LAX. The 65, 70, and 75 CNEL contours for both 2010 and 2030 are shown in Figure 103. In another scenario all twin isles operations were replaced with the PSC (technology reach) aircraft. This resulting 65, 70, and 75 CNEL noise contour area was reduced by 15-20%. This data is shown in Figure 104.

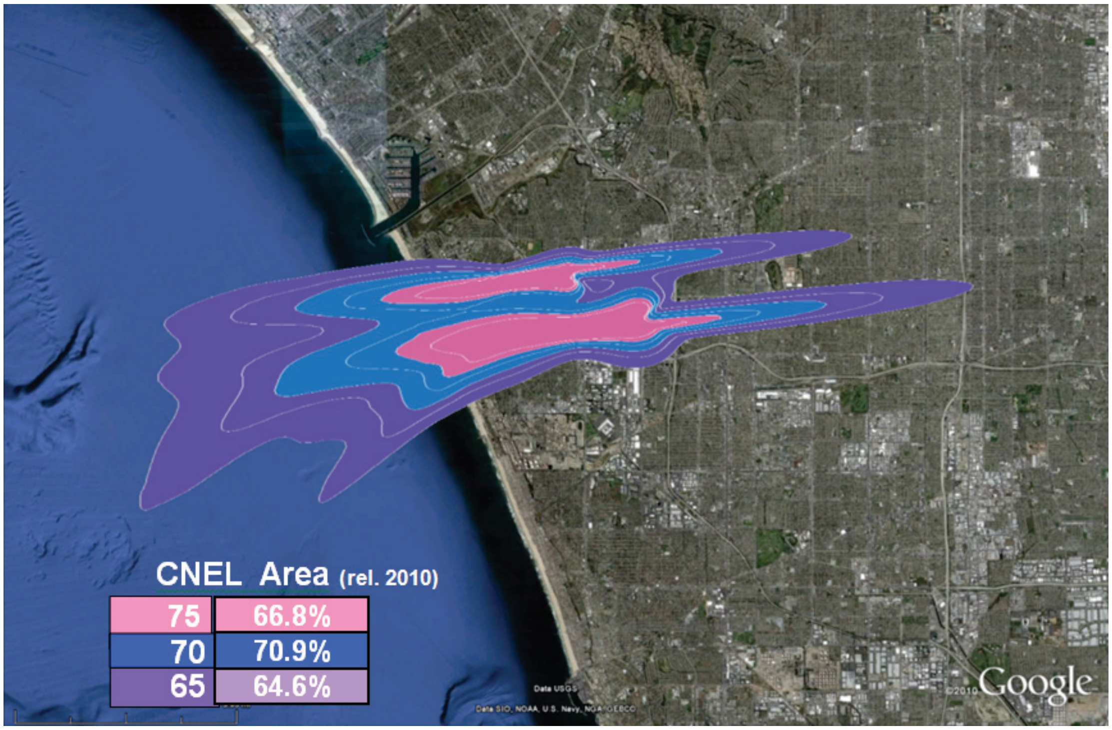


Figure 103. 2010 & 2030 CNEL Noise Contours

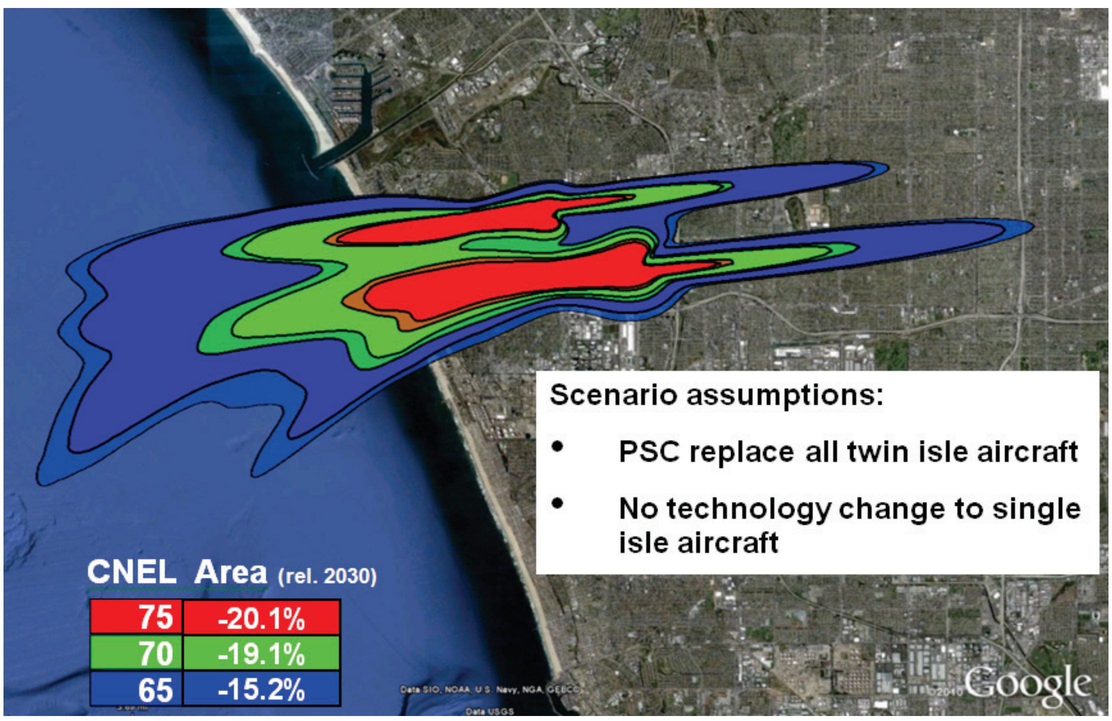


Figure 104. 2030 CNEL Noise Contours with PSC (Technology Reach) Aircraft

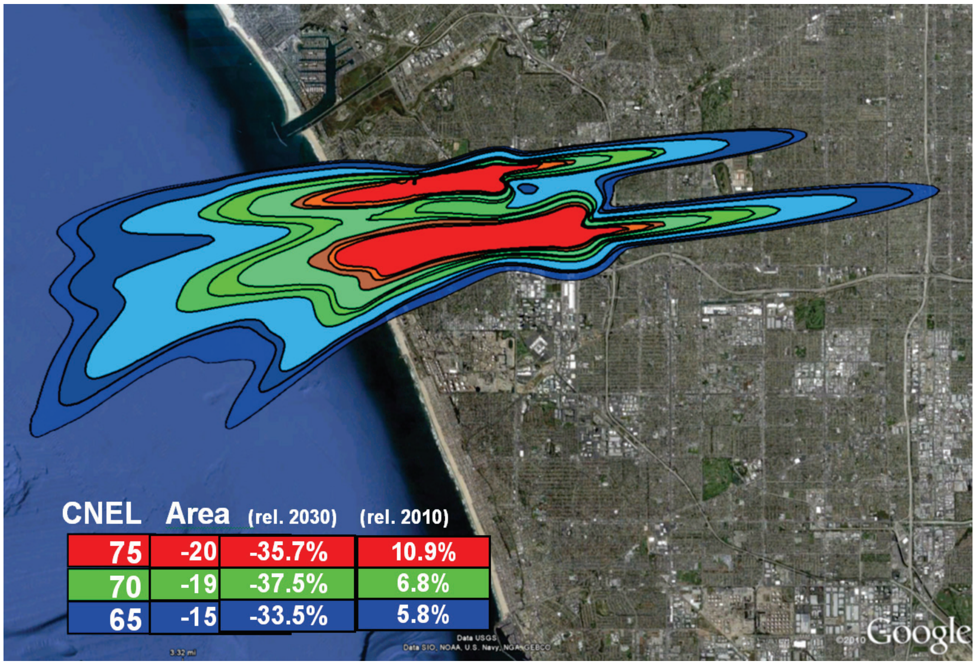


Figure 105 shows a comparison of noise contours for three scenarios: a) 2030 operations model, b) a model with all twin aisle aircraft replaced with PSC technology reach aircraft, c) a best scenario model with twin aisle aircraft replaced with PSC technology reach aircraft and PSC technology applied to all single aisle aircraft. As shown in the figure the CNEL noise contour areas are reduced by 30 – 40% relative to the 2030 scenario. Additionally the areas are brought within 5 to 10% of the original 2010 CNEL noise contour areas.

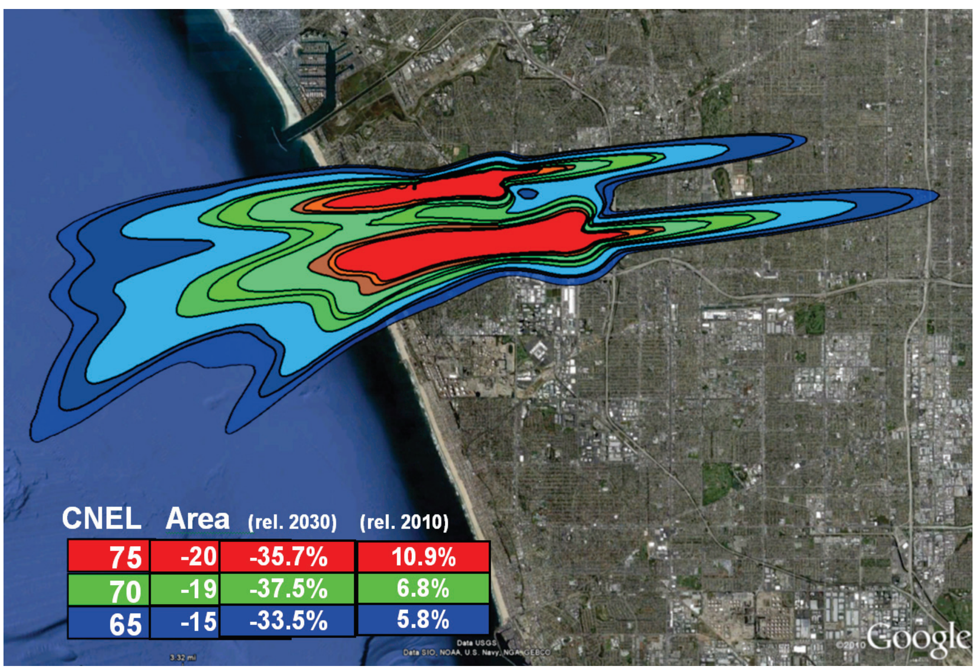


Figure 105. Noise Contour Comparison for 3 Scenarios in 2030

Figure 106 gives a clear view of the CNEL noise contours in the scenario where PSC and PSC technology is applied to all twin and single aisle aircraft. In this figure it is apparent that the 75 CNEL noise contour is essentially contained within the airport boundary outlined in bold white.

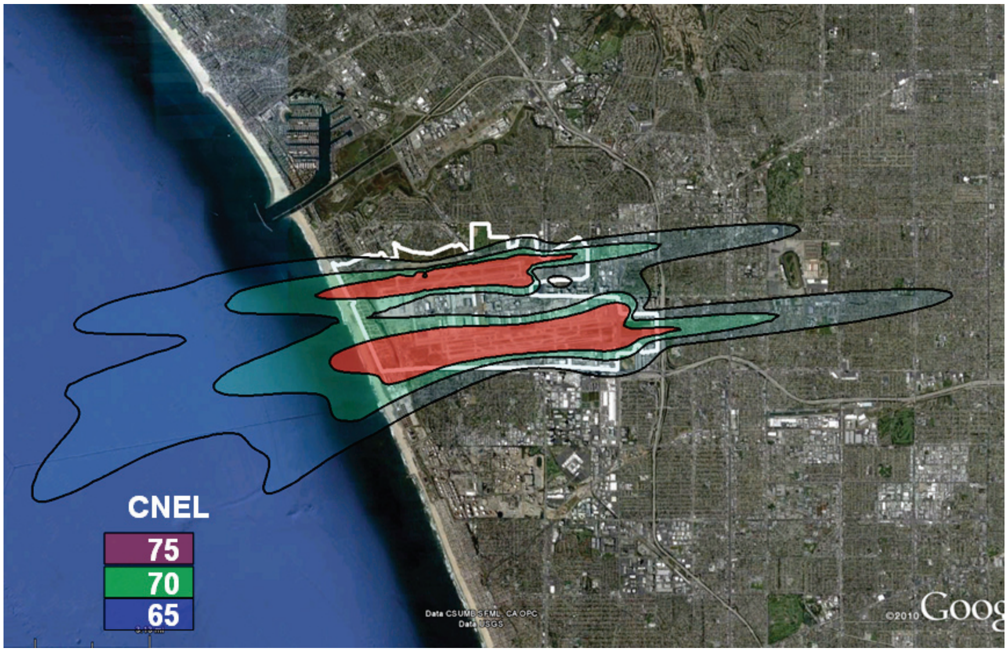


Figure 106. Best Scenario LAX 2030 Contours

2.11.6 Local Emissions (NOx) and Greenhouse Gas (CO2) Results

LTO NO_X data for all engines of the 1998 EIS conventional configurations, the 2025 EIS conventional and advanced conventional configurations, and the 2025 EIS Blended Wing Body configurations are included in the performance package. As an example, Table 49 shows the landing and takeoff (LTO) NO_x ICAO engine exhaust emissions coefficient data for the geared turbofan engine (GTF) of the PSC and for the PW4090, the engine of one of the 1998 EIS conventional configurations. Relative to the CAEP/6 NO_x standard the PW4090 is over by 9.2% whereas the GTF is below by 23.5%.

Table 49. Local Emissions & Greenhouse Gas

ICAO ENGINE EXHAUST EMISSIONS						
Engine Identification:	GTF				*Bypass Ratio:*	20.2
Unique ID Number:	XXXXXX				*Pressure Ratio (πoo):*	36.1
Engine Type:	GTF				*Rated Output (Foo) (kN):*	256.2
Regulatory Data						
Characteristic Value	*NOx*					
Dp/Foo (g/kN)	16.7					
As % of Original Limit	14.9%					
As % of CAEP/2 Limit	18.6%					
As % of CAEP/4 Limit	21.1%	Goal(-75%)				
As % of CAEP/6 Limit	23.5%	-76.54%				
Estimated Data	*Power*	*Time*	*Fuel Flow*	*NOxEI*		
Mode	*% Foo*	*Minutes*	*kg/s*	*gm/kg*		
Take-Off	100	0.7	1.29	26.52		
Climb Out	85	2.2	1.07	11.62		
Approach	30	4.0	0.35	3.11		
Idle	7	26.0	0.11	4.00		
LTO Total (kg or gm)			417.21	3724		
Number of Engines				3		
Number of Tests				-		
Average Dp/Foo				14.54		
Sigma				---		
Range				---		
Atmospheric Conditions					*Fuel*	
Barometer (kPa)	101.325				*Spec*	Jet-A
Temperature (K)	288.9				*H/C*	1.92
Abs Humidity (kg/kg)	0.00634				*Aromatics (%)*	XX

ICAO ENGINE EXHAUST EMISSIONS						
Engine Identification:	PW4090				*Bypass Ratio:*	6
Unique ID Number:	10PW099				*Pressure Ratio (πoo):*	38.9
Engine Type:	TF				*Rated Output (Foo) (kN):*	408.3
Regulatory Data						
Characteristic Value	*NOx*					
Dp/Foo (g/kN)	83.8					
As % of Original Limit	71.2%					
As % of CAEP/2 Limit	88.9%					
As % of CAEP/4 Limit	98.8%	Goal(-75%)				
As % of CAEP/6 Limit	109.2%	9.20%				
Estimated Data	*Power*	*Time*	*Fuel Flow*	*NOxEI*		
Mode	*% Foo*	*Minutes*	*kg/s*	*gm/kg*		
Take-Off	100	0.7	3.926	57.52		
Climb Out	85	2.2	2.996	41.17		
Approach	30	4.0	0.979	12.74		
Idle	7	26.0	0.338	4.48		
LTO Total (kg or gm)			1323	31122		
Number of Engines				2		
Number of Tests				4		
Average Dp/Foo				76.22		
Sigma				---		
Range				---		
Atmospheric Conditions					*Fuel*	
Barometer (kPa)	101.1-102.5				*Spec*	Jet-A
Temperature (K)	275.5-302.5				*H/C*	1.85-1.92
Abs Humidity (kg/kg)	).0033-0.0112				*Aromatics (%)*	17

The total fuel burned, NO_x and CO_2 (green house gas) emissions for a complete LTO cycle for the PSC and 1998 EIS conventional aircraft are shown in Figure 107. The fuel burn benefit of the NextGen mission which requires an allowance of only 10 minutes for holding at end of mission rather than 30 minutes results in 1,093 lbs less fuel (3,432 lbs less $C0_2$). The combination of a lower NO_x producing engine and a shorter duration LTO cycle results in 74 % less NO_x and 42 % less fuel and CO_2 produced by a PSC aircraft than that produced by a 1998 EIS aircraft.

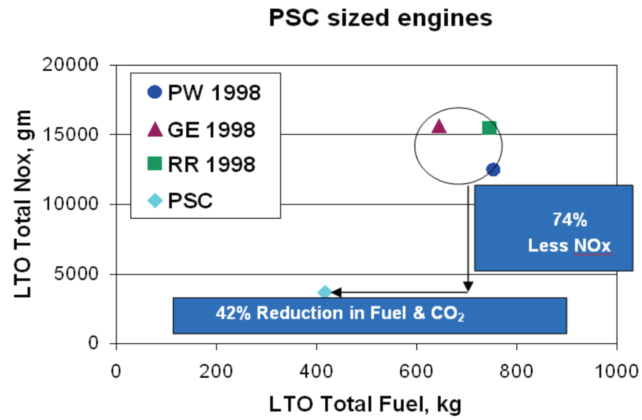


Figure 107. Total LTO Fuel Burn, NO_x & Greenhouse Gas

2.11.7 Summary of NextGen Related Work (Cranfield Aerospace)

Two topics of research pertaining to NextGen were completed by Cranfield Aerospace for Boeing in 2011. They included a study on the integration of unmanned aircraft systems (UAS) into U.S. and European Airspace and a study on the environmental characterization of conceptual aircraft emissions. The executive summary is provided in Appendix E.

2.12 Selection of Preferred System Concept

Selection of the Preferred System Concept (PSC) is based on criteria including:

- Aircraft performance towards NASA's goals for fuel efficiency, noise and LTO NO_x.
- Commercial considerations including direct operating cost (DOC) and airport compatibility.

As shown in Figure 72, several airplanes meet NASA's fuel consumption goals with significant margin. These are:

- BWB-0009A with twin geared turbofans
- BWB-0013 with three open rotors
- BWB-0015 with three open rotors, with Mach 0.80 cruise
- Long-wing versions of the three BWB designs above (BWB-0031, -0033, -0035)

Of these, the long-wing versions are eliminated due to their reduced commercial value resulting from increased DOC and reduced airport compatibility. As shown in Figure 72, their DOCs are some 2% greater than their shorter-wing predecessors, a large margin in commercial operations. Also, their ~80-meter spans (the same as the Airbus A380) are in conflict with the need to serve intermediate-size airports now served by Boeing 767 and 787 airplanes – airplanes with equivalent capacity to those of this study.

The superior fuel consumption of the BWB-0015 is more than offset by its substantially increased noise (as shown in Figure 76) and by the reduced productivity resulting from its slower cruise speed. This results in a DOC that is approximately 1% worse than the BWB-0009A geared turbofan (as shown in Figure 72).

The BWB-0013 open rotor design provides slightly less fuel burn than the BWB-0009A geared turbofan, but is noisier (as shown in Figure 76) and has a greater DOC (as shown in Figure 72).

From the above, the twin geared turbofan blended-wing-body configuration (BWB-0009A) is selected as the Preferred System Concept. It provides the best combination of fuel efficiency, noise, LTO NO_x, DOC and airport compatibility.

2.13 Performance of PSC in 2025 Operating Context

Performance of the Preferred System Concept in the 2025 operating context is represented by the BWB-0009A NG. This is the BWB-0009A PSC slightly resized for and operated using the NextGen rules described in Section 2.2.2.3.

Performance of this airplane is described in many of the figures and tables in Section 2.8 and Section 2.10. To summarize, the BWB-0009A NG:

- Reduces fuel consumption by 53.7% from the 1998 baseline, exceeding NASA's fuel consumption goal.
  - Fuel consumption is reduced 58.4% from the 1998 baseline airplane resized and flown with realistic 1998 mission rules.
- With advanced acoustic features, meets NASA's noise goal.
- Meets NASA's landing and takeoff emissions goal.

2.14 Summary and Conclusions

The effect of advanced technologies, configurations and operating rules on fuel efficiency, noise and emissions is examined. Numerous comparable designs enable conclusions to be made.

In summary, a combination of advanced technologies, configuration and operating rules permit 2025-technology airplanes to meet or surpass NASA's challenging goals and improve commercial appeal.

- NASA's goals are met only with a combination of advanced technology and configuration. The twin geared turbofan powered BWB-0009A with advanced noise reduction features meets fuel, noise and emissions goals. The BWB-0009A NG reduces fuel consumption by 53.7% from the baseline 1998 airplane.
- No conventional or advanced conventional configuration meets NASA's fuel consumption or acoustic goals
- The BWB configuration enables a 9.7% fuel consumption reduction relative to the most efficient 2025 conventional configuration. Acoustic shielding provided by the BWB configuration also provides a 5.3 dB cumulative noise margin from Stage 4.

2.14.1 Effect of Advanced Technologies and Operating Rules

Advanced technologies combine to provide major improvements towards NASA goals. 2025 technologies applied to conventional configurations reduce fuel consumption 46.6%. Cumulative noise is reduced roughly 24 dB compared to PW4000-powered Boeing 767 certification levels. Absolute LTO NO_x emissions are reduced by some 85% due to cleaner engines and reduced thrust requirements.

Advanced operating rules provide substantial improvements towards NASA goals. Advancing from 1998-level operating rules to NextGen can provide ~14% fuel burn reductions for aircraft designed to NextGen rules. The effect of NextGen on existing fleet fuel consumption is not addressed in this study.

2.14.2 General Characteristics

This study illuminates certain general airplane characteristics that are important to performance for all four species examined: 1) 1998 conventional configurations, 2) 2025 conventional configurations, 3) a 2025 advanced conventional configuration and 4) 2025 BWB configurations.

A strong correlation between airplane wetted aspect ratio (AR_{wet}) and cruise L/D is demonstrated. Accounting for improvements provided by HLFC and riblets, this correlation applies across all four species.

For each airplane species, wetted aspect ratio increases with span along a trend line. Each species has its own trend line. For a given span, the 1998 conventional configuration has the lowest AR_{wet}. The advanced conventional configuration provides an AR_{wet} boost relative to the 2025 conventional configuration due to its compact fuselage. The BWB configuration provides a significantly greater AR_{wet} per span than the other species. Additionally, the BWB configuration increases AR_{wet} more rapidly with increased span than do the other species. Conclusion: BWB configurations provide increased AR_{wet} and L/D for a given span.

For each airplane species, operating empty weight (OEW) increases with AR_{wet} along a different trend line for each species. 1998 airplanes are the heaviest, and increase weight most quickly with AR_{wet}. 2025 conventional and advanced conventional configurations follow a common trend line between the 1998 airplanes and the BWBs. Their weight also increases more gradually with AR_{wet}. BWB designs follow a very shallow trend line that is considerably lighter than that of the conventional and advanced conventional airplanes. Conclusion: BWB designs are considerably lighter for a given AR_{wet}.

AR_{wet} and weight increase with span. This creates a tension between aerodynamic efficiency (L/D) and light weight that is resolved in the sizing process. Conclusion: Of the 2025 airplanes, BWB configurations tend to optimize at increased span and AR_{wet} resulting in a superior combination of aerodynamic performance (L/D) and light weight (OEW).

2.14.3 Engine Characteristics

Three 2025 engine types are examined. These trade weight, complexity and efficiency. Each provides ~20% of the fuel burn reduction or more. However, the geared turbofan with its low noise signature combined with the BWB shielding had the lowest noise of any of the configurations. The engine for the PSC is the geared turbofan with the lowest noise and comparable fuel burn to the open rotor. Potential improvements in engine cycle - airplane matching and optimization could improve the results and potentially result in a different preferred engine.

2.14.4 Acoustics

Cumulative noise margins are influenced by technology level, operating rules, engine type and airplane configuration.

As noted above, 2025 technology levels provide substantial noise reductions from a combination of quieter engines and reduced airplane weight and thrust. Improved operating rules provide modest acoustic gains via reductions in airplane size, weight and thrust.

Engine type influences noise margins by effects from fan pressure ratio, nacelle acoustic effects and interference effects between rotating and static components. The geared turbofan engine of the T&W-0005 provides a Stage 4 noise margin 5.6 dB greater than that of the advanced turbofan powered T&W-0007. This includes the effect of lighter weight and reduced thrust needed for the T&W-0007. The geared turbofan BWB-0009A is 8.2 dB quieter than the open rotor powered BWB-0013. Conclusion: The geared turbofan engine is the quietest; the open rotor is the noisiest. It is important to note however that all 2025 airplanes meet Stage 4 requirements with a margin of 22 dB or more – even the noisiest engine is far quieter than near-term future noise requirements.

Configuration plays an important part in noise margin. Acoustic shielding of the engines is important. Other sources, including leading edge devices and landing gear become crucial once engine noise is shielded. The double-deck, mid-engine AT&W-0027A provides acoustic shielding of the engine with its tall fuselage and nearby wing. This results in a 9.1 dB advantage over its conventional cousin, the T&W-0007. The BWB configuration also provides acoustic shielding. It is 5.3 dB quieter than the T&W-0005 which has the same engines. BWB noise is compromised by its higher approach speed – acoustic treatment of the landing gear and Krueger flap can pay substantial dividends in noise reduction.

2.14.5 NextGen

The Nextgen air traffic management system in 2030 is expected to rely much more heavily on integrated automation tools than the ATM system of today in order to accommodate the forecast growth in air travel. The ATM system of 2030 was assumed to be what JPDO has characterized as NGOps-6 which allowed the 2030 EIS configurations, PSC included, to be sized with a more efficient NextGen mission. This essentially reduced the flight time and fuel required per flight to meet the range and payload requirement.

The PSC was evaluated at LAX because it was an airport representative of typical PSC operations. Community noise was assessed using both single events and cumulative noise metrics. The cumulative noise assessment included development of baseline (2010) & forecast (2030) operation models for LAX. The INM performance & noise models were also developed for the PSC to assess various PSC market penetration levels, specifically replacing all twin aisle operations with PSC aircraft, and then applying PSC technology to all single aisle aircraft.

The results indicate that PSC technology is required in order to meet growth demand and environmental constraints. PSC alone replacing noisier twin isles reduces contour areas by 15-20%.

Applying PSC technology to both single & twin aisles reduces contour areas by 30 – 40% and contains the noise within airport boundary. NOx is reduced by 74% and greenhouse gas (CO_2) is reduced by 42%

2.14.6 Improvements

The BWB configuration is not mature; design methods are evolving. Designs developed in this study appears to have significant room for improvement.

A freighter-specific BWB design is not created in this study. Design of a pure freighter may yield a better suited and even more efficient design.

3 Technology Maturation Plans

3.1 Introduction

The Preferred System Concept (PSC) aircraft conceived in this study will require a significant amount of technology development. With its Blended Wing Body (BWB) configuration, the PSC is dependent on technology development needed to enable the BWB. The PSC employs additional technologies that enhance its performance. Development of the complete set of BWB-enabling and BWB-enhancing technologies is expected to provide the PSC with the capability of achieving the Environmentally Responsible Aviation (ERA) goals.

Technology maturation plans were developed in this study with the goal of demonstrating technology readiness sufficient to authorize starting Engineering and Manufacturing Development (EMD) or the equivalent commercial aircraft development process for a production PSC. Recent U.S. Government acquisition regulations aimed at limiting overruns and schedule slippage in Department of Defense (DOD) production programs require major defense acquisition programs to demonstrate adequate maturity for critical technologies prior to award of EMD. Following the defense acquisition guidelines (Reference 11) to assess technology readiness, a Technology Readiness Level (TRL) of 6 was targeted for completion through the technology demonstrator program for noted critical technologies. The basic definition for TRL 6 is "System/subsystem model or prototype demonstration in a relevant environment (ground or space)." As described in Section 3.3.1, more detailed definitions of the elements needed to reach TRL 6 indicate that a demonstrator aircraft will be needed to reach this level of technical maturity. As the BWB configuration is a central focus of the technology development, flight test on a BWB demonstrator aircraft is the event that causes many technology areas to reach TRL 6.

The Subscale Test-bed Vehicle (STV) is a scaled demonstrator of the PSC that provides the means for performing the TRL 6 demonstrations. The STV is integral to technology maturation to the point of being the focus of all the near-term technology development activities. At the start of the plan, numerous activities will be performed on other BWB configurations because of existing models and data, but the knowledge generated by these activities will influence the design of the STV. As the work progresses, activities will shift to testing the actual STV configuration.

The STV will have a representative shape to test and validate aerodynamic and acoustic features of the PSC (such as drag and acoustic shielding resulting from the upper-surface engine installation). It will be large enough to validate BWB-unique structural concepts (such as the flat-sided pressure vessel). This size will also facilitate maturation of Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) composite structure technology (which will bring weight and cost benefits to the production PSC). Similar to the PSC, the STV will have large secondary power requirements (stemming from the demands of controlling a flying-wing configuration) that will drive flight control and actuation system development. The STV will accommodate geared turbofan engines, providing a means to test propulsion technology and address concerns with propulsion-airframe integration (including engine operability in the upper-surface location). After numerous technical concerns with the basic BWB configuration are addressed through flight test, the STV will provide a platform for validating additional enhancing technologies, such as laminar flow.

The technologies applied to the PSC are introduced in Section 3.2. The technologies are described briefly and the benefits of selected technologies are quantified. A number of technologies are enabling for the BWB, and they collectively generate the benefits shown for the BWB configuration. The incremental benefits of enhancing technologies are identified. Some of the enhancing technologies have technology maturation plans in this document. Some enhancing technologies do not have maturation plans because their maturation is expected to occur outside the ERA program (riblet technology for example).

Technology maturation plans are presented in Section 3.4. This section begins with an overview that describes how the maturation plans are organized (Section 3.4.1.1). Key performance parameters and technical performance measures that appear in the maturation plans are summarized in Section 3.4.1.2. The plans describe the risks that will be reduced with technology development. Risk assessments are shown along with the expected progression of risk with technical maturity. The definitions used in assessing risk are described in Section 3.3.2. The criteria for assessing technical maturity are described in Section 3.3.1.

Maturation plans are presented in Section 3.4 for the technology areas listed below.

- **BWB Structures** – This work will validate BWB-unique structural features while helping to mature PRSEUS composite structures technology. This work will address a risk for increased weight that will affect the ability to reach ERA goals (the fuel burn goal is particularly affected by weight). This risk results partially from BWB-unique structural features (such as the flat-sided pressure vessel and load paths around landing gear). It also results partially from the need to learn how to do many things with PRSEUS (such has handling cut-outs, splices, and wing-to-body joints). Development of the STV will address BWB-unique features and advance the knowledge of PRSEUS to reduce the uncertainty in weight. As work with PRSEUS on the STV establishes its suitability for use on a production vehicle, the risk of missing the cost benefits of PRSEUS will also be reduced. While reducing cost is not an ERA goal, potential cost benefits of PRSEUS will help reduce economic barriers to deploying ERA technology in a fleet of production aircraft. The BWB Structures maturation plan uses a building-block approach that addresses progressively larger pieces of structure (from components to subassemblies, to assemblies, to the complete airframe). This methodical approach limits cost and schedule risk on the STV program by seeking to find manufacturing and design problems early, when they are most easily corrected.
- **BWB Aerodynamics –** While seeking to achieve the low drag estimated for the BWB, this work will also support risk mitigation in the propulsion and flight control actuation system areas. Engine operability is the main propulsion concern for the STV. The aerodynamics work should help determine whether there is a risk of engine operation being adversely affected by the flow field around the engine. The aerodynamics work would seek changes to the BWB aerodynamic design to address that risk. Managing the power demands of the flight control system has been identified as an issue for the BWB. The aerodynamic design of the control surfaces may be part of the solution, including the use of tab surfaces and other means to reduce hinge moment.
- **BWB Propulsion** – This work will initially focus on engine operability because it could have a significant effect on the design of the STV. While the BWB Aerodynamics work will focus on the STV design, the work under BWB Propulsion would look at opportunities to address the engine operability concern with existing BWB configurations and wind-tunnel models. Later in the plan, BWB Propulsion work will address concerns affecting the PSC that are not required for the STV, including thrust reversing and protection from engine fratricide.
- **BWB Stability & Control, Flight Controls, and Flying Qualities (S&C, FC, & FQ)** – BWB Stability & Control, Flight Controls, and Flying Qualities (S&C, FC, & FQ) work will develop simulations to determine actuation system requirements and assess high-speed flying qualities. The large power requirements currently estimated for the actuation system could potentially be reduced with piloted simulations targeted at getting better requirements. Hinge moment reducing devices, such as tab controls, would need to be accommodated in the control laws, if used. Although no issues are anticipated, control of BWB configurations at high speed needs to be addressed.
- **BWB Actuation System –** This work will explore different options for actuating flight controls while minimizing power demand of the actuation system. Options include hydraulic, electric, and hybrid hydraulic-electric systems.

- **Acoustics** – This work will explore options for increasing acoustic shielding and for reducing airframe noise. This exploration will provide information to guide the design of the PSC and STV toward a better demonstration of reduced noise levels.
- **Advanced PRSEUS** – While the STV will be built using current PRSEUS technology to enable an earlier flight test, additional development will be needed to make PRSEUS suitable for use on a production aircraft. Advanced PRSEUS covers the additional development. Concerns with micro-cracking will be addressed with a toughened resin system. Concerns with smoke-and-burn properties will be addressed with low-flame foam materials (or by removing the need for foam). These concerns do not need to be addressed for a demonstrator, but they would for a production aircraft. While making changes to these basic materials, there is an opportunity to investigate new fiber materials for improved performance. Work on Advanced PRSEUS will prepare PRSEUS for production use on the PSC.
- **Laminar Flow** – The PSC will use laminar flow for drag reduction. The STV will be designed for laminar flow, but it will initially lack equipment for laminar flow control. This equipment will be developed, retrofitted to the STV wing leading edges, and flight tested. While wind tunnel testing will be used to develop the scheme for achieving laminar flow on the STV, issues with wind tunnel flow quality and limitations on the ability to scale details of the flow control system limit the information that can be collected on laminar flow in the wind tunnel. Flight testing will be needed to truly determine the achievable extent and drag reduction of laminar flow.
- **Geared Turbofan** – The PSC will use geared turbofan engines for improvements in fuel burn, noise, and emissions. To complement existing efforts on combustor and low spool technologies, work under ERA would focus on technologies for a high overall pressure ratio engine core.
- **Open Rotor** – Though not selected for the PSC, open rotor engines are an alternative for geared turbofans that may provide similar benefits. Development would address technology for open rotors as well as high overall pressure ratio engine cores.

An integrated schedule for technology development is presented in Section 3.4.10. A rolled-up schedule summary is given as well as detailed schedules for each technology area. First flight of the STV ends up in May 2018 while technology readiness for the PSC is needed by December 2018 to reach Entry into Service (EIS) or Initial Operational Capability (IOC) in 2025.

Costs for technology development were generated. These costs are presented in Volume 4.

The work to develop technology maturation plans has identified technology benefits and risks. It has identified and described tasks needed to mature the technologies and reduce risks. The tasks fit a schedule that could support fielding aircraft employing the technology in 2025.

3.2 Critical Technologies for Preferred System Concept

This section describes technologies that enable the BWB configuration and technologies that enhance BWB performance to help meet ERA goals. The technologies are described in subsections for BWB enabling and enhancing technologies. The technologies are applied to 2025 conventional and BWB configurations as indicated in Table 50.

Table 50: Configuration Technologies

	1998	**2025 Conventional**	**2025 BWB**
High Speed Aerodynamics	• Supercritical Airfoils	• Hybrid Laminar Flow • Riblets • High Aspect Ratio	• Hybrid Laminar Flow • Riblets • High Aspect Ratio
Low Speed Aerodynamics	• Slotted Flap • Slat	• Slotted Flap • Low Noise Krueger Flap	• Plain Flap • Low Noise Krueger Flap
Propulsion	• High-Bypass Turbofan	• Geared Turbofan • Open Rotor	• Geared Turbofan • Open Rotor
Fuselage Structure	• Aluminum	• Composite (PRSEUS)	• Composite (PRSEUS)
Wing Structure	• Aluminum	• Composite	• Composite
Empennage Structure	• Composite	• Composite	• Composite
Systems		• (Electric Controls) • Advanced APU	• (Electric Controls) • Advanced APU
Acoustics		• Leading Edge Acoustic Treatment • Landing Gear Acoustic Treatment • Engine Acoustic Treatment	• Shielding • Leading Edge Acoustic Treatment • Landing Gear Acoustic Treatment • Engine Acoustic Treatment

3.2.1 Blended Wing Body Enabling Technologies

The following technologies are enabling components of the overall BWB system. These technologies may show little benefit individually, but they collectively enable the larger benefits associated with the BWB.

Table 51 lists BWB enabling technologies and key technology benefits or issues. Subsequent sections describe the technologies in more detail.

Table 51: BWB Enabling Technologies

Technology	Key Development
BWB Structures	• Flat-sided pressure vessel
BWB Aerodynamics	• Reduced fuel burn from aerodynamic efficiency • Propulsion airframe integration
BWB Stability & Control, Flight Controls, and Flying Qualities	• S&C requirements for BWB configuration • High-speed control law assessment • Actuation system requirements • Ride quality requirements for BWB
BWB Propulsion	• Engine operability • Thrust reverser • Armored nacelle
BWB Actuation System	• Large secondary power requirement

3.2.2 Blended Wing Body Enhancing Technologies

The following technologies enhance the ability of the BWB to meet the ERA fuel burn and noise goals. These technologies show significant benefits to earn their way onto the PSC.

Table 52 lists BWB enhancing technologies and key technology benefits or issues. Laminar flow, PRSEUS, and acoustics are included in the technology maturation plan. Open rotor and geared turbofan propulsion technologies are covered in separate reports by the engine manufacturers.

The remaining technologies in grey are not covered in the technology plan for various reasons. Lightning protection was incorporated in the plans for BWB structures and PRSEUS composites. The advanced APU could reduce fuel burn and emissions in practical real-world operations, but since the CAEP 6 LTO NOx emissions goal does not consider APU emissions, there was little benefit to using advanced APU technology in this study. Riblets are on the PSC, but this technology is already at or beyond the maturity level targeted by the technology maturation plan. Variable camber trailing edge technology was not incorporated on the PSC, but some of its benefits might be captured with small deflections of the many trailing-edge control surfaces on the BWB.

Table 52: BWB Enhancing Technologies

Technology	Key Development
Laminar Flow	• Drag and fuel burn reduction • Configuration accommodation for laminar flow • Flow control system • Bug strike degradation
PRSEUS	• Lower airframe weight and cost
Acoustics	• Acoustic shielding • Low noise leading edge • Landing gear acoustic treatment
Open Rotor	• Reduced fuel burn • Vehicle integration • Noise
Geared Turbofan	• Reduced fuel burn • Vehicle integration • Noise
Lightning Protection	• Advanced protection
Advanced Auxiliary Power Unit	• Reduced ground emissions
Riblets	• Drag and fuel burn reduction • Application and maintenance
Variable Camber Trailing Edge	• Improved aerodynamic efficiency from shape change • Shape change mechanism

3.2.3 Technology Benefits

To identify the contribution of selected technologies, the PSC was evaluated and sized with a few different technology combinations.

To show the benefit of the BWB configuration plus composites, the PSC was evaluated with a 1998 engine and without laminar flow or riblet technology. As the BWB needs composites for competitive flat-sided pressure vessel weights, there was no attempt to isolate the benefits of the BWB configuration and composites. The BWB configuration with composite structure provided a 32% reduction in fuel burn relative to the 1998 baseline configuration (Figure 108).

Adding the geared turbofan engine, laminar flow and riblets creates a 30% reduction in fuel burn relative to the BWB with just composites. When this reduction is properly combined with the 32% reduction for the BWB with composites, as indicated in the box in Figure 108, the combined benefit is 52% fuel burn reduction relative to the 1998 baseline.

Figure 108 labels the percentage fuel burn reduction between the start and end cases for each bar (the percentage reduction between the top and bottom of each bar). This approach depicts the relative importance of each technology more accurately than the percentage reduction relative to the 1998 baseline, which reduces the indicated benefit of the later technologies. For example, the 2025 BWB technologies (geared turbofan, laminar flow and riblets) create a 30% reduction relative to the BWB with composites but only 20% relative to the 1998 baseline. The 32% reduction from the BWB with composites reduces all subsequent increments when taking percentages relative to the 1998 baseline. The indicated relative fuel burn percentages should not be sensitive to the order in which they are applied, and they give the fairest assessment of the relative importance between the technologies.

The benefit of advanced propulsion was evaluated by substituting a 1998 engine for the geared turbofan in the BWB with 2025 technologies. The geared turbofan provided a 23% fuel burn reduction.

Laminar flow and riblets were removed from the BWB with 2025 technologies to evaluate their benefit, a 9% fuel burn reduction.

The 23% fuel burn reduction for geared turbofan combines with the 9% reduction for laminar flow and riblets to create the 30% reduction evaluated for 2025 technologies on the BWB. The box in Figure 108 shows how the component benefits combine to generate the total benefit.

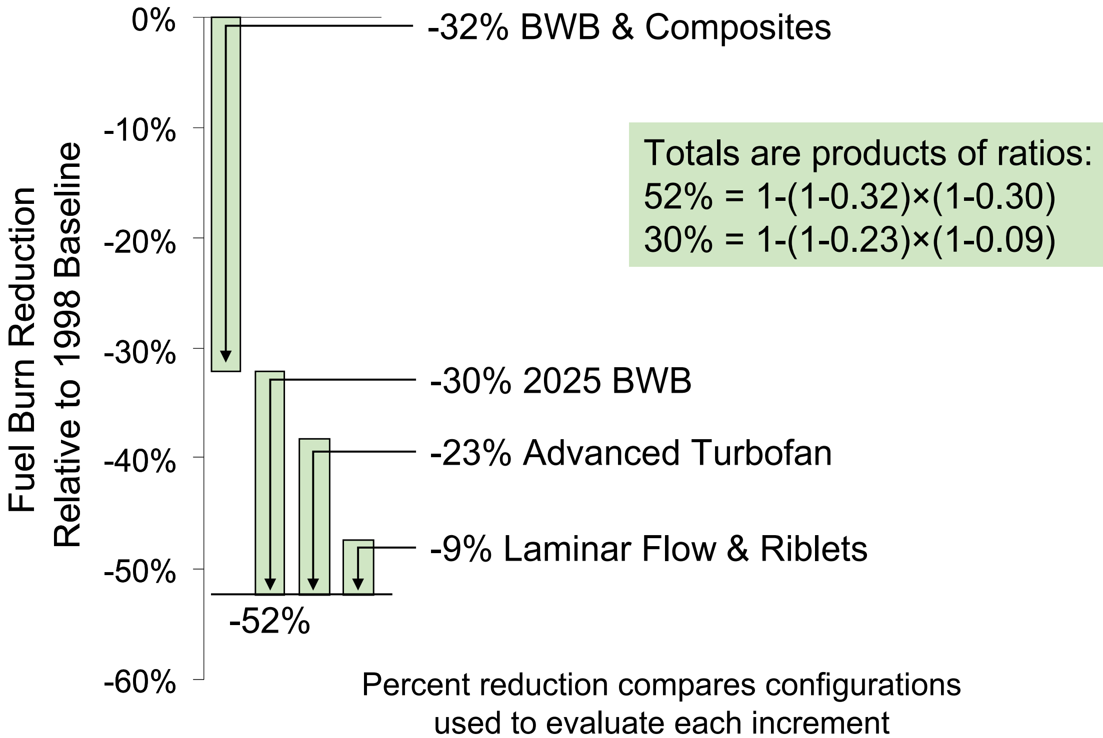


Figure 108: Technology Fuel Burn Reduction Benefits

Noise reduction benefits of technology are indicated in Figure 109. The 1998 baseline aircraft was not evaluated, but existing aircraft from that time (such as the 777) are known to have cumulative Effective Perceived Noise Level (EPNL) 11 dB below Federal Aviation Regulations (FAR) Part 36 Stage 4. The 2025 conventional aircraft with geared turbofan engines gets an 18 dB reduction relative to the 1998 aircraft for cumulative EPNL nearly 29 dB below Stage 4. This improvement is attributed primarily to the geared turbofan engine. The basic PSC aircraft adds acoustic shielding with the BWB configuration to achieve an additional 5 dB reduction for cumulative EPNL 34 dB below Stage 4.

Additional acoustic treatments will be applied to the PSC configuration to reach the goal of 42 dB cumulative EPNL below Stage 4. Details of the technology need to be worked out, but existing data suggest that landing gear noise may be reduced by 5 dB (with fairings) and leading-edge device noise may be reduced by 3 dB (by filling slat coves).

Since the decibel measurement is logarithmic, the acoustic benefits measured in dB can be added to obtain the total benefit.

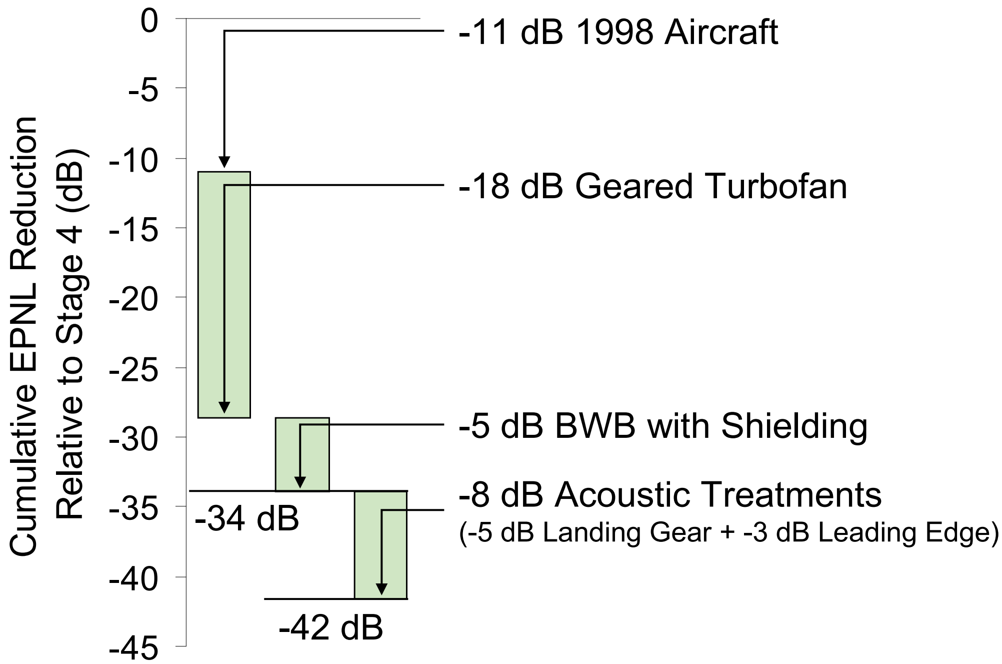


Figure 109: Technology Noise Reduction Benefits

3.3 Technical Maturity and Risk Definitions

3.3.1 Technology Readiness and System Readiness Levels

Technology readiness levels have recently been linked to Department of Defense (DOD) acquisition milestones. In particular, a TRL of 6 must be achieved prior to Milestone B, which authorizes the start of Engineering and Manufacturing Development (EMD). The relationship of TRL to the acquisition milestones is indicated in Figure 110. Boeing employs a similar assessment of technical maturity to determine whether a technology is ready to be applied on a production aircraft.

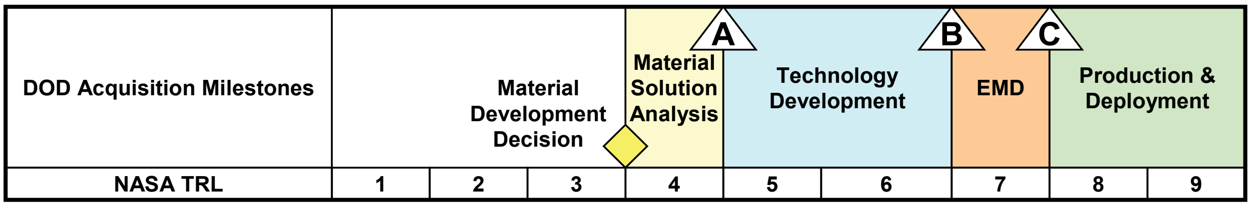


Figure 110: Mapping of NASA Technical Maturity Levels to DOD Acquisition Milestones

Air Force Research Laboratory (AFRL) has published a transition readiness level calculator for assessing maturity of a technology (Reference 12). The calculator goes beyond technology readiness and evaluates manufacturing and program readiness. The sum of technology, manufacturing, and program readiness levels forms what the calculator calls transition readiness level. Milestone B is actually linked to achieving a transition readiness level of 6, not just technology readiness level 6. Since transition readiness provides a more complete picture than technology readiness, transition readiness level was adopted as the definition for system readiness level (SRL) for this project.

The AFRL transition readiness level calculator lists many criteria that need to be met to achieve a given readiness level. The criteria provide a more rigorous and less subjective means to assess the maturity of technologies than the standard definitions of technology readiness levels. The criteria can be used to resolve ambiguities that arise from different interpretations of the standard definitions.

The criteria cover many aspects that would be addressed in the usual progression of technology development. These criteria have been used to guide definition of the tasks needed to achieve given TRL and SRL.

Figure 111 clarifies how TRL is assessed in this project based on the maturity of the testing that has been completed.

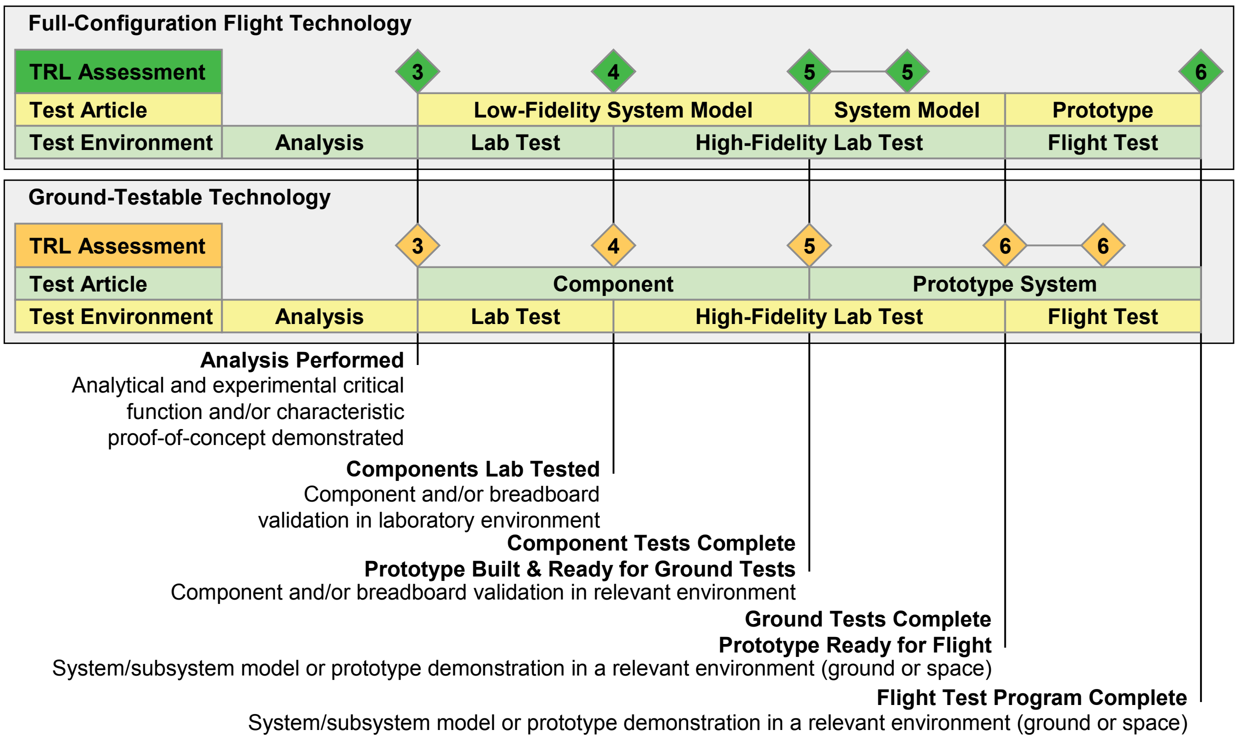


Figure 111: Relationship between TRL and Maturity of Testing

3.3.2 Risk Assessment

Within the description of the technology maturation plan in Section 3.4, each broad technology area has a section that describes the technical risks and how the maturation plan is expected to reduce those risks. Risk assessments are presented on a risk grid. Interpretation of the risk grid is described in Figure 112.

The risk grid rates risks as low (green), medium (yellow), or high (red) based on assessment of the likelihood and consequence of the risk.

The likelihood of the risk is rated on the vertical axis according to the definitions listed beside the numeric ratings in Figure 112. The consequence of the risk is rated on the horizontal axis according to the definitions listed just below the numeric ratings.

For more consistent assessments of consequence, percentage penalty levels were suggested as a way to guide the assessment for this study. The penalty levels would be applied to a key performance parameter, such as fuel burn or cumulative EPNL, not to lower level performance measures that might have to change substantially to affect performance parameters of interest. The percentage penalty thresholds were adopted from the definitions used to evaluate cost risk, but the levels appeared to give good guidance for technical risk, particularly for risks affecting fuel burn performance.

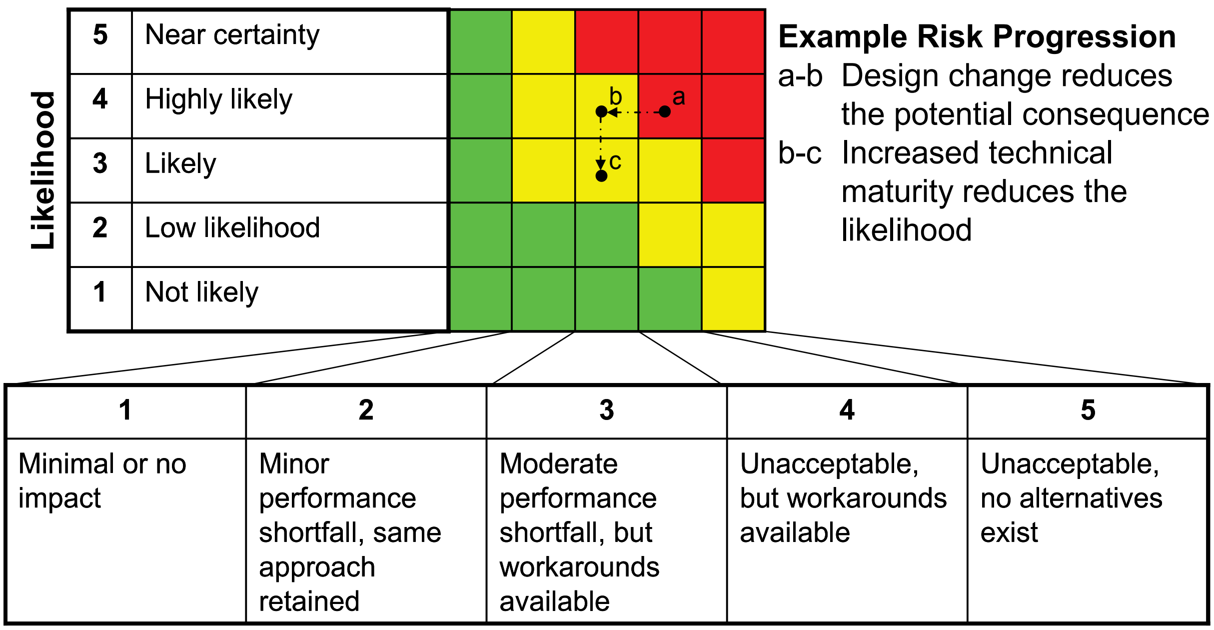


Figure 112: Risk Grid Interpretation

In the discussion on risk for each technology area, the progression of risk with technical maturity milestones is described. The current assessment of risk is shown on the risk grid, and predicted assessments are shown for selected milestones for completing the work necessary to raise TRL. The predicted assessments indicate the risk assuming all the technology development goes as expected.

Example risk progressions are given in Figure 112 to indicate typical reasoning behind the progressions shown in the technology maturation plan. The first progression in the figure, from point a to point b, is a typical result from a design change reducing the potential consequence. The current design may have an unacceptable penalty relative to the target performance, but design work leading to point b is expected to reduce the penalty to moderate. The second progression, from point b to point c, is a typical result of increased technical maturity reducing the likelihood of the risk. The design at point b may be analyzed to be on the target performance with a high likelihood of the analysis being inaccurate such that a moderate penalty could result. Testing performed between points b and c is expected to reduce the likelihood of a moderate penalty occurring on the final product, but there may still be the potential for a moderate penalty. The technology maturation plans frequently combine design work with the work to increase technical maturity. Such combinations can create diagonal movement, which might be visualized as a jump from point a to point c in Figure 112.

3.4 Technology Maturation Plan

3.4.1 Overview

3.4.1.1 Organization of the Technology Maturation Plan Descriptions

This document describes the technology maturation plan for the following technology areas.

- BWB Structures
- BWB Aerodynamics
- BWB Propulsion
- BWB Stability & Control, Flight Controls, and Flying Qualities
- BWB Actuation System
- Acoustics
- Advanced PRSEUS
- Laminar Flow
- Geared Turbofan
- Open Rotor

Each technology area is presented in its own section containing the following subsections.

- Description – a general description of the technology.
- Benefits – a description of the benefits provided by the technology.
- Risks – a description of the technical risks associated with the technology and how those risks are mitigated in the technology maturation plan.
- Expected Outcomes and No-Go Points – a description of the expected outcomes of the work leading to TRL increments and the no-go triggers that could lead to significant redirection of the technology development.
- Development Tasks – a summary of the top-level development tasks leading to advances in TRL.

Following the Development Tasks subsection, additional subsections will present the top-level development tasks. Multiple tasks combine to form these top-level tasks. All tasks are described in a summary table for each top-level task. Critical near-term tasks are given their own subsection for more detailed task descriptions.

3.4.1.2 Key Metrics for Technology Maturation

The risk descriptions for each technology area indicate what key performance parameters (KPP) and technical performance measures (TPM) are affected by each risk. KPPs represent required or desired capabilities. TPMs represent measurable quantities that affect the KPPs. During technology development, TPMs will be regularly monitored for the earliest indication of performance problems; KPPs may be evaluated less frequently because of the need to roll up a significant amount of information for those evaluations.

The KPPs and TPMs that appear in the risk descriptions are shown together in Table 53. The NASA ERA goals set three KPPs, for fuel burn, noise, and emissions. An additional KPP for affordability was introduced to track the potentially large cost benefit of PRSEUS composite technology. This affordability KPP is recommended for study; however, it is not required for successful completion of technology demonstration goals and objectives.

Table 53: Key Metrics for Technology Maturation

Key Performance Parameters (KPP)	Fuel Burn	Noise	Emissions	Affordability
Goal	-50% Block Fuel	-42 dB Cumulative EPNL	-75% LTO NOx	
Technical Performance Measures (TPM)	• Structural Weight Fraction • System Weight Fraction • Lift to Drag Ratio • Specific Fuel Consumption • Actuation System Power • Control Surface Hinge Moment • Inlet Distortion • CG Range	• Cutback Noise • Sideline Noise • Approach Noise • Maximum Lift Coefficient	• CAEP/6 LTO NOx	• Life Cycle Cost • Recurring Production Cost • Touch Labor • Scrap Rate • Fastener Count

The fuel burn KPP has a few TPMs that are directly related, including weight, drag, and specific fuel consumption. The control surface hinge moment and center-of-gravity (CG) range TPMs affect the actuation system power TPM that affects the specific fuel consumption TPM via power draw off the engine. The inlet distortion TPM affects how much the engine must be designed for robustness at the expense of efficiency, and it thereby affects specific fuel consumption.

The noise KPP has TPMs for the three noise measuring points. The maximum lift coefficient TPM affects aircraft speed, which then affects airframe noise. As the strategy for achieving the noise KPP goal solidifies, TPMs for specific noise sources (such as landing gear and leading-edge devices) are likely to be added to the list.

The emissions KPP is determined entirely by engine characteristics. The airframe manufacturer can monitor engine companies' evaluation of CAEP/6 LTO NOx (Committee on Aviation Environmental Protection/6 landing-takeoff nitrogen oxide) emissions as a TPM. The engine companies are likely to have additional TPMs visible at their level.

The affordability KPP and TPMs are directed at validating assumptions about reducing the cost of composite construction to lower a potential barrier to entry for the BWB as a military solution. Although the 787 provides an example where the business case closes for using existing composite technology for fuel savings, it is not clear whether the same will be true for a military transport that will see lower utilization, which reduces the importance of fuel cost and increases the importance of acquisition cost. TPMs such as touch labor hours required per pound of built structure should be tracked during fabrication of the many structural articles needed for technology development. These data should then be incorporated in the cost estimates that will affect the decision to launch EMD of the PSC.

3.4.2 BWB Structures

3.4.2.1 Description

The BWB fuselage structure has a pressurized centerbody, outboard wing, aft body, tails, and nose (Figure 113). This plan will focus on the centerbody and outboard wing, the two most challenging elements of the airframe.

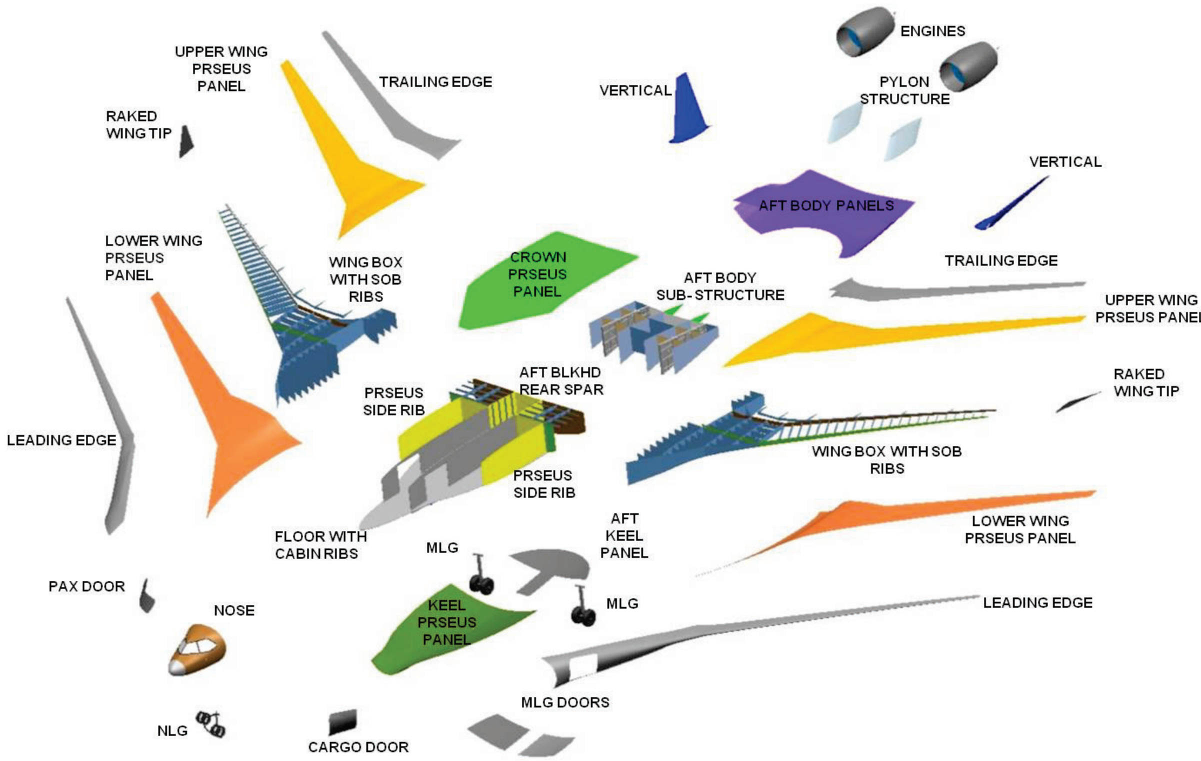


Figure 113: BWB Structures Breakdown

A unique characteristic of the BWB airframe is the bi-axial loading pattern in the shell (Figure 114). The load magnitudes are more nearly equal in each direction (Nx and Ny) than what is normally found in conventional tube-and-wing fuselage architectures. To address this condition, the Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) fuselage panel is bi-directionally stiffened, in which the wing bending loads are carried by the frame members and the fuselage bending loads are carried by the stringers. Features of this design include loads paths that are continuous in both directions, skin and flange laminates that are highly tailored to operate in the post-buckled design regime, and stitched interfaces to arrest damage propagation. The resulting panel design effectively eliminates the weight penalty associated with the non-circular BWB pressure cabin.

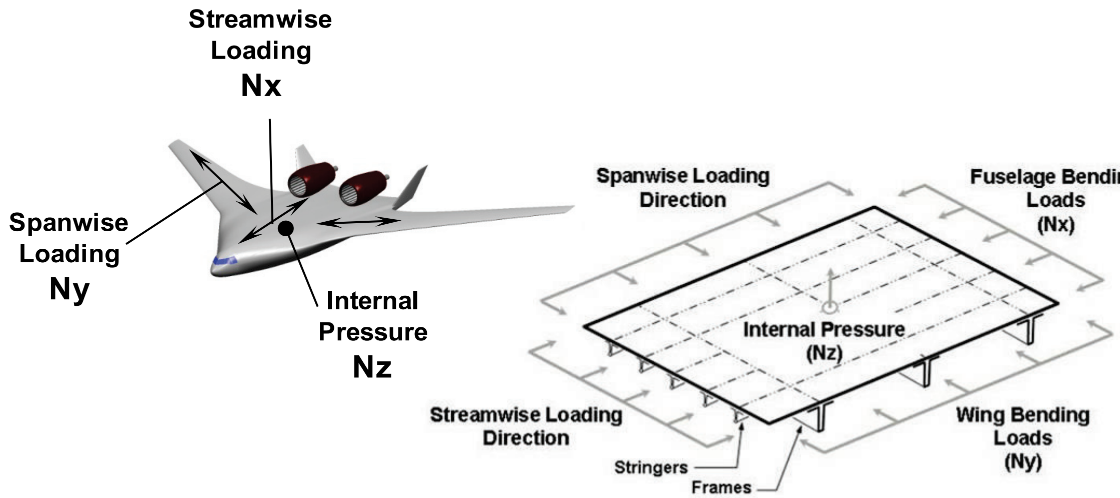


Figure 114: Pressure Cabin Internal Running Loads

Another essential feature of the BWB structures approach is the capability to economically produce large-scale, integrated, compound-curvature panels. The variable loft geometry makes the cost of tooling individual structural elements (skins, stringers, frames, bulkhead caps, etc.) prohibitively expensive. As such, this condition precludes the use of conventional composite fabrication techniques that require numerous detail and subassembly tools to lay-up individual parts and then subsequently bond or bolt them together into completed panel assemblies. Structures solutions with less tooling are clearly appealing, and indeed this single aspect formed the basis on which the PRSEUS structural concept was developed.

This section describes the development of BWB structures and PRSEUS technology related to the STV. Advanced PRSEUS continues the development of PRSEUS for production use on the PSC as described in Section 3.4.8.

3.4.2.2 Benefits

Benefits of the BWB structures configuration include the following.

- Vehicle mass distributed closer to lift profile lowers bending moments.
- Deeper wing section results in a stiffer wing that mitigates dynamics issues associated with controls, winglets, flutter, etc.
- Deeper wing reduces skin gauges.
- Deeper wing increases internal volume for fuel.
- Multifunctional body structure that carries both body bending and wing carry-through loads reduces overall weight.

Benefits of PRSEUS technology include the following.

- PRSEUS stitching increases the capability to react to out-of-plane loads created by cabin pressure, pull-off and point loads, post-buckling, and ply drop-offs. This out-of-plane capability is achieved without creating an "open hole" for a fastener. The stitching also arrests damage much as a metal structural design would. Equipment and tooling are an important part of the total cost.
- PRSEUS uses an out-of-autoclave resin curing process that eliminates the need to limit the maximum dimensions of structural components based on the size of available autoclaves. The number of manufacturing breaks can be minimized to reduce cost and weight. The out-of-autoclave process particularly accommodates fabrication of the BWB center-body in large panels (avoiding splitting those panels into strips to fit within cylindrical autoclaves).

- PRSEUS cost advantages include self-supporting features that minimize expensive inner mold line (IML) cure tooling, and the use of dry ply-knit carbon reinforcement that enables faster lay-down rates with minimal out-time concerns.
- Perhaps the biggest cost advantage is unitization and the reduction of subsequent assembly by means of bonding or bolting. With conventional composites, required through-thickness strength is typically achieved by using expensive titanium bolts instead of robotically installed aluminum rivets as with metal aircraft. The use of stitching fibers enables the widespread elimination of metallic fasteners.

3.4.2.3 Risks

Novel features in the BWB structural configuration present a risk of weight increasing as more is understood about these features. They also present an opportunity for weight to decrease with improved design knowledge. The landing gear cutout on the lower surface of the wing and body, with its complex load paths, is an example where further study might show the need for more structure. This type of risk will be addressed as the structural design of the STV is developed and tested.

In addition to the development work on PRSEUS to date, there is a considerable amount of work that needs to be accomplished to reduce risk for STV development. This work is needed to establish the characteristics of PRSEUS components to reduce the risk that inadequate structural design will require expensive and time-consuming rework. This work is also needed to develop PRSEUS manufacturing processes to reduce the risk of manufacturing problems creating schedule delays and cost increases in the STV program.

Reflecting these concerns, two primary risks are defined below – “BWB Structures and PRSEUS Performance,” and “PRSEUS Cost.” Each risk is mitigated via the defined technology development plan.

3.4.2.3.1 BWB Structures and PRSEUS Performance

Benefit (KPP)

BWB structures and PRSEUS materials and design technology contribute to the goal of 50% fuel burn reduction on the PSC.

TPM

The risk mitigation will be quantitatively tracked via structural weight fraction.

Risk Statement

If the performance of PRSEUS materials and design is not achieved, then ERA fuel burn objectives will not be met.

Risk Mitigation Plan

Figure 115 shows the mitigation of the risk over the course of the technology development effort. The figure shows how risk mitigation (in terms of likelihood and consequence) is associated with TRL (technology readiness level) advancement. The current state of the art (TRL 3) is associated with a high risk level (point a). Completion of the first portion of the technology development improves TRL without making a large enough improvement in risk to change the assessed risk level (point b). The successful completion of STV-related large-scale structures testing with current PRSEUS will reduce the risk to moderate and improve TRL to 5 (point c). Subsequent to that testing, assembly and test of the STV airframe will increase TRL to 6 (point d). Further technology development of Advanced PRSEUS through subassembly testing will reduce risk to low (point e).

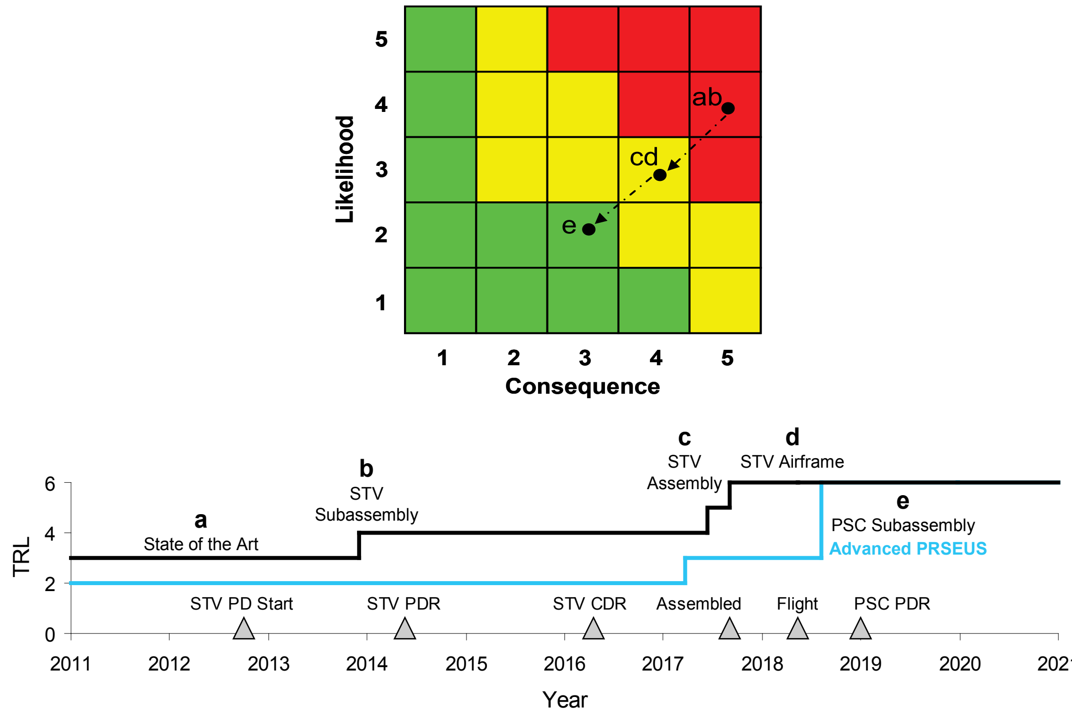


Figure 115: Structures Risk – BWB Structures and PRSEUS Performance

3.4.2.3.2 Cost of PRSEUS Materials and Design

Benefit (KPP)

The PRSEUS materials and design technology will enable a substantially lower recurring production cost.

TPM

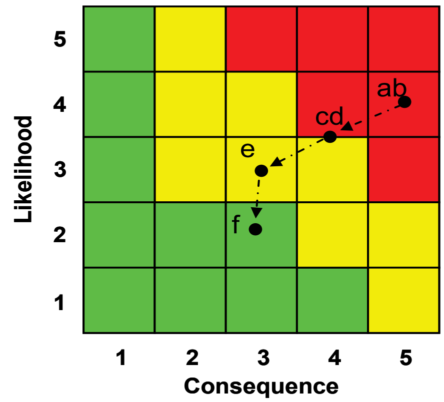
The risk mitigation will be quantitatively tracked via (1) estimate of recurring production cost, (2) touch labor per unit weight, (3) scrap rate, and (4) fastener count.

Risk

If the recurring production cost of large-scale, unitized PRSEUS structures increases over that predicted, then PSC cost targets (and operational business case) will not be met.

Risk Mitigation Plan

Figure 116 shows the mitigation of the risk over the course of the technology development effort. The figure shows how risk mitigation (in terms of likelihood and consequence) is associated with TRL advancement. The current state of the art (TRL 3) is associated with a high risk level (point a). Completion of the first portion of the technology development improves TRL without making a large enough improvement in risk to change the assessed risk level (point b). The successful completion of STV-related large-scale structures testing with current PRSEUS will reduce the risk between high and moderate (point c). Subsequent to that testing, assembly and test of the STV airframe will increase TRL to 6 (point d). Further technology development of Advanced PRSEUS through subassembly testing will further reduce risk to moderate (point e). The cost risk will be reduced to a low level after low rate initial production (point f).



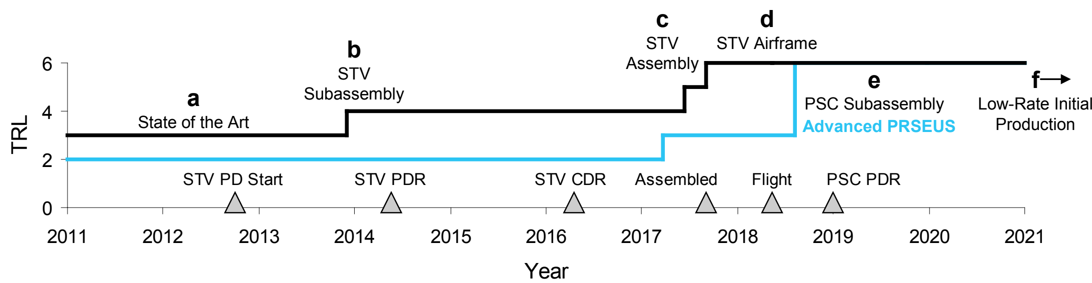


Figure 116: Structures Risk – PRSEUS Cost

3.4.2.4 Expected Outcomes and No-Go Points

Table 54 describes the expected outcome of technology development at TRL jump milestones indicated in Figure 115 and Figure 116.

Table 54: BWB Structures Expected Outcomes

Milestone	TRL	Expected Outcome
STV Subassembly	4	Approaches to handling critical subassembly areas understood with weight and cost consistent with current projections.
STV Assembly	5	Large assemblies (including fuselage and wing) designed and fabricated with weight and cost consistent with current projections.
STV Airframe	6	STV airframe assembled and ground tested with tests validating predictions.
PSC Subassembly	6	Advanced PRSEUS meets requirements for production aircraft as demonstrated through subassembly tests.

Table 55 describes no-go points that could require significant change or abandonment of the technology. Some conditions that could occur during the development of the technology would trigger consideration of alternative approaches. It is expected that these conditions would be caught during the work performed to reach the range of milestones indicated in the table.

Table 55: BWB Structures No-Go Points

Milestone Range	Trigger	Alternative
STV Subassembly – STV Airframe	Structural weight of BWB configuration increases to significantly reduce fuel burn advantages.	Drop BWB configuration if not competitive with conventional.
STV Subassembly – PSC Subassembly	PRSEUS cannot meet requirements for production aircraft.	Switch to different composite material system. Accept higher cost.

3.4.2.5 Development Tasks

A series of building-block experiments will develop and verify that the structural configuration concept behaves as anticipated and meets BWB design requirements (Table 56). The Component Tests milestone (building block) will support the preliminary design of the STV.

Additional tasks for preparing PRSEUS for production use on the PSC are contained in the description of Advanced PRSEUS in Section 3.4.8.

Table 56: BWB Structures Development Milestones

Milestone	TRL	Description
Component Tests (current)	3	PRSEUS component level manufacture and performance demonstrated
STV Structures Subassembly Ground Tests	4	Subassembly-level performance demonstrated by tests – includes COLTS combined loads test Key manufacturing processes demonstrated in laboratory
STV Structures Assembly Ground Tests	5	STV-scale vehicle structures (body, wing) fabricated and tested on the ground to failure
STV Airframe Ground Test	6	All PRSEUS building block tests complete Airframe structure integrated with all systems Demonstrator vehicle ground tested

3.4.3 BWB Aerodynamics

3.4.3.1 Description

Aerodynamics affects all elements of the flight profile. At cruise, the aerodynamic technology produces a configuration with high lift-to-drag ratios that are a first-order term in the fuel savings benefit. At low speed, the vehicle must produce enough lift at a reasonable flight speeds for takeoff and landing and do so in an acoustically quiet and low drag manner. Additionally, the flying characteristics of the configuration in terms of stability and control must be within limits for acceptable flying qualities.

The ERA configuration introduces vertical tails and changes in propulsion system installation. The vertical tails provide acoustic shielding. Extending the aft body beyond the engine nozzles also provides acoustic shielding. Larger diameter turbofans or open rotor engines reduce fuel burn. All these feature changes create a need to again develop the BWB aerodynamic design and validate with wind-tunnel testing. Technology readiness level would further increase with validation of BWB aerodynamic performance in flight test of a demonstrator aircraft.

Of particular note is the integration of the propulsion system with the airframe. The engines are located above the aft body, forward of the trailing edge and between the vertical tails for noise suppression. This location presents integration issues due to the higher than free-stream flow produced by the lifting body.

The propulsion system must work in an efficient and acceptable manner in the presence of the aerodynamic flow field produced by the external lines in the presence of the propulsion system. Two types of propulsion concepts are being considered: (1) a geared fan and (2) open rotor. Each has its own design challenges.

(1) Geared Fan – the nacelle will be large relative to current technology and creates issues with the integration with the airframe. The large nacelle and higher than free-stream velocity will require careful CFD (computational fluid dynamics) tailoring and surface contouring for efficient operation.

(2) Open Rotor – the presence of the open rotor will make it susceptible to variations in onset flow produced by the surrounding airframe. Non-uniform onset flows and distortions at the rotor will decrease propulsion efficiency and increase the noise.

3.4.3.2 Benefits

The efficient aerodynamic design will have a first-order and direct impact on the program objectives of noise and fuel burned. A key benefit of the BWB is improved aerodynamic performance resulting from increased span and reduced wetted area relative to a conventional configuration. Increased span is enabled by the structural efficiency created by deep sections at the wing root and through the body. Reduced wetted area results from the blending of wing and body surfaces and also the reduction of tail surfaces. Aerodynamic advantages have been validated in wind-tunnel tests on prior BWB configurations, the BWB 450-1L in particular.

These attributes are obtained by designing the external lines of the configuration in such a way that all fight regions mentioned above are met by controlling the airflow. Interactions with other elements include:

- Propulsion system – efficient, quiet and acceptable operation
- Structures – a compromise with the structural weight and aerodynamic flow quality
- Flight controls – control surface design and location
- Acoustics – low drag for reduced engine jet noise and low noise of aerodynamic surfaces
- Interior arrangement – external lines must contain the payload and be aero efficient

3.4.3.3 Risks

3.4.3.3.1 Propulsion-Airframe Integration & Drag

Benefit (KPP)

Low drag associated with the BWB configuration contributes to the goal of 50% fuel burn reduction relative to 1998 technology aircraft.

TPM

Cruise lift-to-drag ratio (L/D) provides a quantitative measure for tracking the aerodynamic contribution to the fuel burn goal.

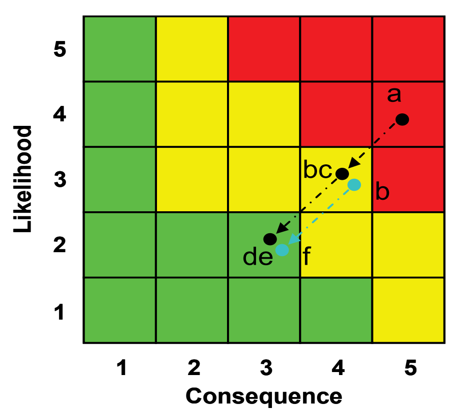
Risk Statement

If the integrated wing-body-nacelle is not near maximum aero efficiency for the configuration then the fuel burn goal will not be met. If laminar flow benefits are not achieved, then the fuel burn goal will not be achieved.

Risk Mitigation Plan

Figure 117 shows the mitigation of the risk over the course of the technology development effort. While there has been considerable work on the BWB 450-1L configuration to reduce risk and improve technical maturity for that configuration, the PSC currently carries more risk because propulsion-airframe integration (PAI) has not been developed and analyzed (point a). In its current state, the PSC configuration is likely to carry a large amount of PAI drag that will be reduced with further development. Developing and analyzing the design in CFD improves TRL to 3 and it is expected to reduce the drag as well as the likelihood that it will be a problem for the PSC (point b). Performing wind-tunnel tests on the configuration will improve TRL to 4 (point c). Further refinement of the design to the final STV configuration and subsequent wind-tunnel test will improve TRL to 5 and is expected to reduce the risk to a low likelihood that a moderate penalty could arise for the PSC (point d). Flight test of the STV will improve TRL to 6 (point e).

As a technology that is not required to enable the BWB, laminar flow is expected to be added to the STV in a spiral development. The risk for laminar flow is not currently considered as high as for PAI. Following the initial design of the STV (point b), laminar flow will mature later than PAI because of the expected spiral development. Unlike PAI, where significant progress can be demonstrated in the wind tunnel, laminar flow is very difficult to demonstrate in the wind tunnel because of sensitivity to wind-tunnel flow quality and difficulties associated with scaling laminar flow control systems. While technical maturity of the laminar flow system will improve, significant risk reduction is unlikely to be shown until laminar flow flight test (point f).



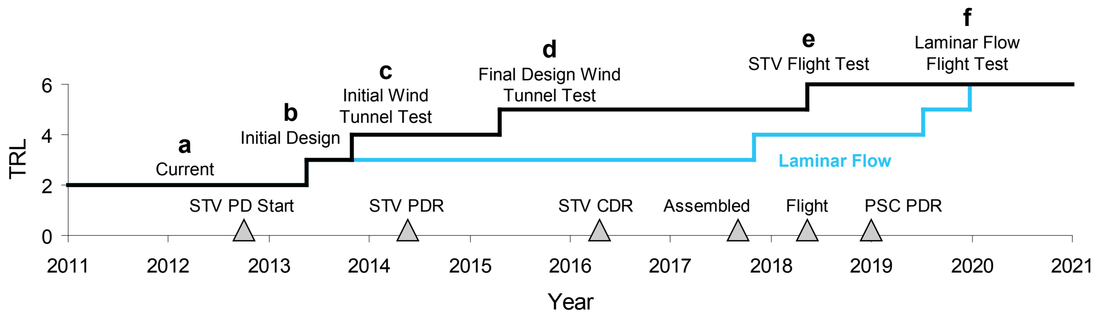


Figure 117: Aerodynamics Risk – Propulsion-Airframe Integration & Drag

3.4.3.3.2 High-Lift and Control Aerodynamics

Benefit (KPP)

Low-speed performance with low-noise high-lift systems contributes to achieving the goal of 42 dB cumulative EPNL below FAR Part 36 Stage 4. Reduced control surface hinge moments can contribute to lower actuation system power and associated reduced fuel burn to contribute to the goal of 50% reduced fuel burn relative to 1998 technology aircraft.

TPM

Maximum lift coefficient provides a quantitative measure for tracking aerodynamic contribution to reduced takeoff and approach speeds.

Actuation system power requirements provide a measure for tracking the benefit of reduced control surface hinge moments.

Risk Statement

If the low-noise high-lift devices significantly reduce maximum lift, then the fuel burn or acoustic goals will not be met. If control surface hinge moments are not reduced, actuation system power requirements will increase fuel burn.

Risk Mitigation Plan

Figure 118 shows the mitigation of the risk over the course of the technology development effort. The PSC currently requires large amounts of actuation system power, which affects fuel burn, and it has a relatively high approach speed, which impacts noise. The risk for high-lift and control aerodynamics is currently rated high (point a). Initial design work on the STV configuration is expected to improve low-speed performance and reduce hinge moments to reduce risk while performing the analysis required to improve technical maturity to TRL 3 (point b). Performing wind-tunnel tests on the configuration will improve TRL to 4 (point c). Further refinement of the design to the final STV configuration and subsequent wind-tunnel test will improve TRL to 5 and is expected to reduce the risk to a low likelihood that a moderate penalty could arise for the PSC (point d). Flight test of the STV will improve TRL to 6 (point e).

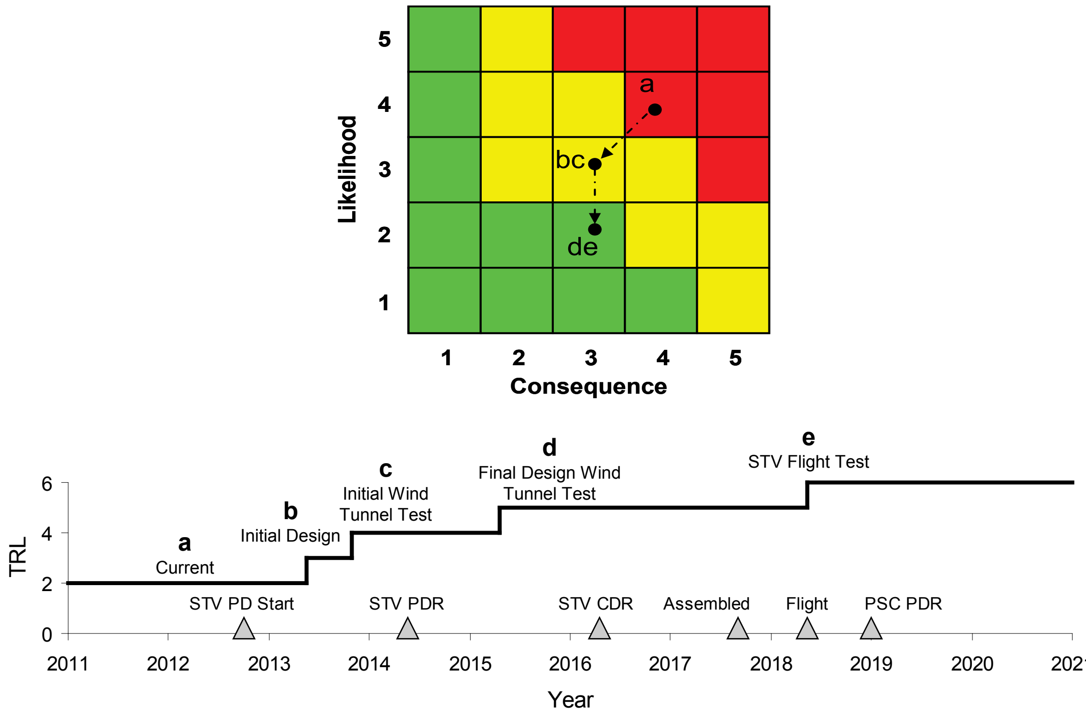


Figure 118: Aerodynamics Risk – High-Lift and Control Aerodynamics

3.4.3.4 Expected Outcomes and No-Go Points

Table 59 describes the expected outcome of technology development at TRL jump milestones indicated in Figure 117 and Figure 118.

Table 57: BWB Aerodynamics Expected Outcomes

Milestone	TRL	Expected Outcome
Initial Design	3	Design and high-fidelity analysis shows drag and maximum lift consistent with current projections. Control surface hinge moments are reduced sufficiently to allow actuation system power levels within achievable limits.
Initial Wind Tunnel Test	4	Wind tunnel tests show aerodynamic characteristics consistent with predictions for initial design. Areas for improvement are identified.
Final Design Wind Tunnel Test	5	Aerodynamic characteristics for final design are improved from initial design and validated in the wind tunnel.
STV Flight Test	6	Aerodynamic characteristics validated in flight test.
Laminar Flow Flight Test	6	Laminar flow benefits validated in flight test.

Table 58 describes no-go points that could require significant change or abandonment of the technology. Some conditions that could occur during the development of the technology would trigger consideration of alternative approaches. It is expected that these conditions would be caught during the work performed to reach the range of milestones indicated in the table.

Table 58: BWB Aerodynamics No-Go Points

Milestone Range	Trigger	Alternative

Initial Design – Final Design Wind Tunnel Test	Propulsion-airframe integration cannot be designed to projected drag levels.	Switch to alternate engine installation (further aft or under wing) with reduced acoustic shielding.
Initial Design – Final Design Wind Tunnel Test	Low-noise leading edge device cannot provide adequate maximum lift increment.	Revert to slotted device (accept increased noise) or add wing area (accept increased fuel burn).
Laminar Flow Flight Test	Laminar flow benefits cannot be achieved with practical operations.	Drop laminar flow from PSC and accept increased fuel burn.

3.4.3.5 Development Tasks

The PSC reference configuration was developed during this ERA N+2 Advanced Vehicle Concepts Study (AVCS). The PSC resulted from a number of trade studies that used inputs from all disciplines to arrive at the best design meeting requirements, as illustrated in Figure 119.

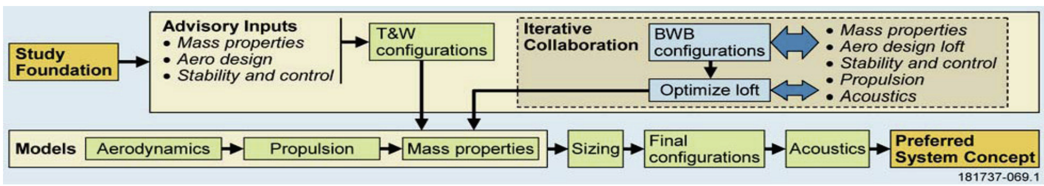


Figure 119: Process for Defining Reference Configuration

Starting with the Preferred System Concept the development tasks for aerodynamics are illustrated in Figure 120.

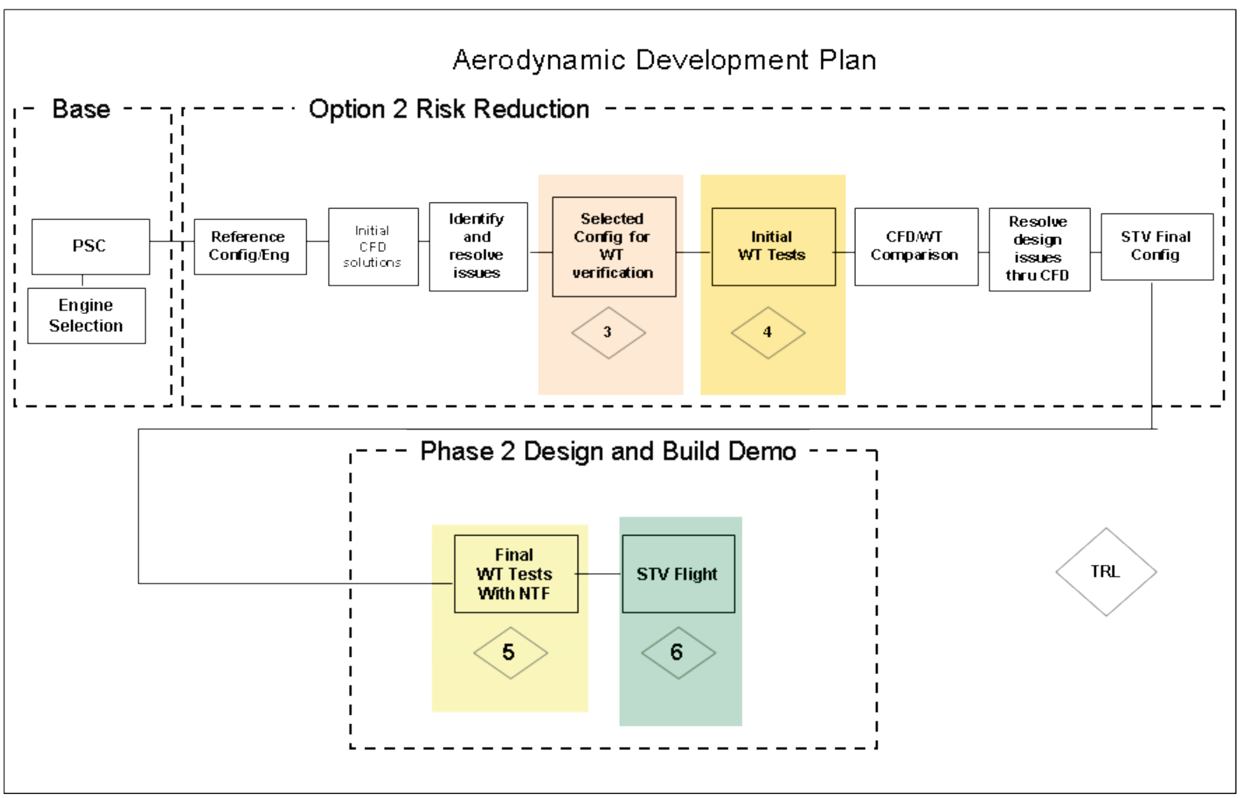


Figure 120: BWB Aerodynamics Development Plan

The progression of TRL through the aerodynamics development is indicated in Table 59.

Table 59: BWB Aerodynamics Development Tasks

Milestone	TRL	Description
Current	4	Extensive analysis and wind-tunnel tests conducted X-48B flight tests
Wind-Tunnel tests	4	Propulsion-airframe integration design and analysis Wind-tunnel tests indicate basic functionality
Demonstrator Wind-Tunnel tests	5	Wind-tunnel tests of demonstrator support readiness for flight High-fidelity tests (powered nacelles, high Reynolds number)
Flight Demo	6	Full flight envelope coverage Aero performance benefits validated

3.4.4 BWB Propulsion

3.4.4.1 Description

Reducing engine SFC (specific fuel consumption) and emissions are required to meet the combined N+2 goals. Improving propulsive efficiency with UHBPR (ultra high bypass ratio) engines in combination with improving the thermodynamic efficiency with increased OAPR (overall pressure ratio) is needed while concurrently reducing emissions. The open rotor and geared turbofans with 2025 gas generator technologies are avenues for meeting the goals, but they present airframe integration challenges largely due to larger rotor diameters combined with upper-body placement for noise shielding. The location of engines on the aft upper surface of the BWB body is a unique feature that provides propulsion noise shielding, enabling very low flyover noise.

It is expected that maintaining equivalent levels of safety will require aircraft deceleration on slippery runways comparable to that provided by thrust reversers. The engine location on the BWB creates a potential issue with nose wheel liftoff from pitch-up when current types of thrust reversers are used. Pitch-up is caused by the reverse flow being directed upwards aft of the aircraft center-of-gravity. The technical challenge is to devise a system that produces effective thrust reversal with manageable pitch-up characteristic.

Compared to conventional transports, the BWB has engines that are located with the spanwise spacing of aft-engine twinjets but without a fuselage between them. This arrangement increases the likelihood of an uncontained rotor burst on one engine causing damage to another. Wing-mounted conventional transports that do not have complete fuselage line-of-sight blockage between engines are either quads or have larger spacing between engines. While an assessment based on the FAA Advisory Circular 20-128A showed an acceptable hazard risk from large rotor segments, the advisory circular is based on conventional wing mounted engines. A review of uncontained rotor failure data show such failures also release multiple small fragments, raising the potential need for lightweight armor built into the engine nacelles to provide a barrier equivalent to the fuselage to protect against multiple small fragments in the event of a rotor burst.

3.4.4.1.1 Engine Operability

Studies on a BWB have primarily focused on the efficiency and noise improvement potential for a BWB configuration. This has addressed the normal take-off, climb, cruise, descent and landing performance. Building a flight worthy STV will require suitable operation throughout the flight operating envelope. An important consideration is engine operability at off-design conditions.

Inlet Distortion

The BWB with the nacelles located above the afterbody presents differences compared to installations on tube & wing configurations that must be accounted for. While the body acts as a flow straightener in the longitudinal plane, avoiding upwash, there are other considerations to examine.

A BWB at cruise flies at a relatively low angle-of-attack with leading-edge devices retracted. NASA-funded BWB studies (Reference 13) conducted CFD analysis on the inlet of a BWB that showed negligible fan face distortion during Mach 0.85 cruise with the inlet located above the boundary layer.

The BWB will encounter more challenging conditions, including a roll maneuver in cross wind at low speed, with leading-edge devices extended and high angle-of-attack. Current configuration development studies show leading-edge devices may be needed to achieve a satisfactory low-speed lift coefficient. At the side edge of a leading-edge device, such as a Krueger or slat, the pressure differential will create a vortex. This vortex normally trails over the top of the lifting surface. On a BWB, there is potential for the vortex to enter an inlet, particularly with cross-wind and roll conditions. In addition, as the BWB approaches maximum lift, flow separation may occur on the wing and body ahead of the engine, causing the separated flow to be ingested. Interaction between the vortex off the leading edge and the separated flow may also create a vortex burst. Ingestion of a vortex, vortex burst, or separated flow can create distortion levels that will affect engine operability. Distortion levels that could cause engine compressor surge or stall need to be avoided.

Configuration development of the STV requires a design capability for avoiding adverse distortion. In order to develop an early design capability, it is proposed that CFD analyses be conducted to establish preliminary design methods that are substantiated by wind-tunnel tests.

Exhaust Nozzle Flow Matching

Another consideration for the geared turbofan is exhaust nozzle exit area matching with low fan pressure ratio. Since the exhaust flow during take-off and initial climb-out is subsonic, the engine exhaust flow matching can be affected by changes in back pressure. A change in the static pressure at the nozzle exit changes the nozzle pressure ratio, which then changes the thrust because the nozzle flow coefficient and fan operating line will change. This effect is particularly pronounced with a low pressure ratio fan at low speeds.

A knowledge base is needed to either minimize the sensitivity or account for this effect in the power management system. In order to develop this knowledge base, it is proposed to again conduct CFD analyses and then conduct method validation wind tunnel tests.

3.4.4.2 Risk

3.4.4.2.1 Engine Operability

Benefit (KPP)

Placement of engines on the wing upper surface provides acoustic shielding, which contributes to achieving the goal of 42 dB cumulative EPNL below FAR Part 36 Stage 4. It also allows more efficient larger diameter fans than might be accommodated under the wing, which contributes to the goal of 50% fuel burn reduction relative to 1998 technology aircraft.

TPM

Inlet distortion provides a measure for the quality of the flow going into the engine.

Specific fuel consumption provides a quantitative measure for tracking changes to engine efficiency needed to tolerate the flow conditions affecting engine operability.

Risk Statement

If inlet distortion or exhaust back pressure requires engine features to avoid engine stall or fan blade failures, then specific fuel consumption will increase and the fuel burn goal will not be met. If engine operability considerations require configuration changes (such as increased wing area or an under-wing engine installation) that result in significant drag or noise penalties, the fuel burn or noise goals will not be met.

Risk Mitigation Plan

Figure 121 shows the mitigation of the risk over the course of the technology development effort. Recent work with the N2A-EXTE configuration shows unacceptable flow characteristics for engine operability (point a). Design and analysis of the STV configuration is expected to reduce risk by improving the flow conditions affecting engine operability (point b). This work is also expected to improve TRL to 3 by completing a more thorough analysis of engine operability than performed previously. Wind-tunnel tests of engine operability on the STV configuration will improve TRL to 4 and reduce the likelihood of further changes affecting fuel burn (point c). Ground test of the engine installation will improve TRL to 5 (point d). Flight test of the STV will improve TRL to 6 and allow a more thorough evaluation of engine operability that is expected to allow reducing the estimate of risk on the PSC to a low likelihood of a moderate penalty in fuel burn performance (point e).

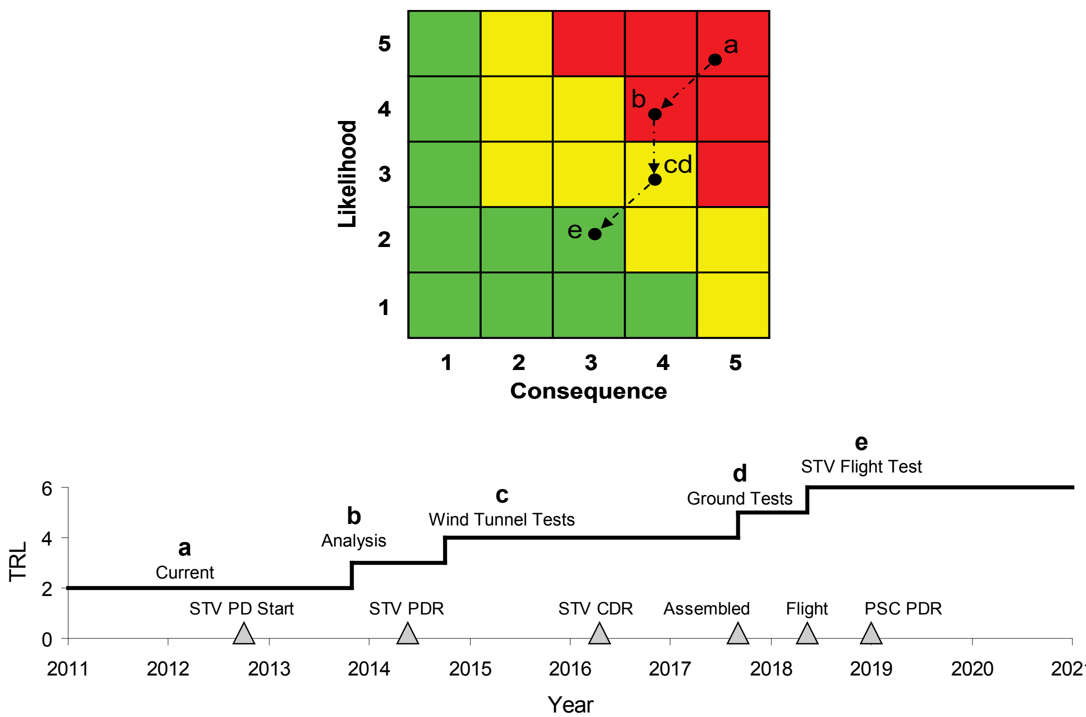


Figure 121: Propulsion Risk – Engine Operability

3.4.4.2.2 Equivalent Safety

Benefit (KPP)

Placement of engines on the wing upper surface allows more efficient larger diameter fans than might be accommodated under the wing to contribute to the goal of 50% fuel burn reduction relative to 1998 technology aircraft. Upper surface engine placement also enables acoustic shielding, which contributes to achieving the goal of 42 dB cumulative EPNL below FAR Part 36 Stage 4.

TPM

The upper surface engine placement introduces difficulty with implementing thrust reversing. Landing field length on slippery runways with thrust reversing provides a measure for tracking progress toward developing a thrust reversing system with equivalent safety to conventional configurations.

The relatively close spacing of the engines combined with the lack of other structure between the engines introduces the possibility that armor will need to be applied to the nacelles for equivalent safety. The weight of armor and more complex thrust reversing systems will be tracked using systems weight fraction (systems weight divided by maximum takeoff weight).

Risk Statement

If the upper-wing engine placement requires significantly heavier provisions for thrust reversing or protection from engine fratricide, then the fuel burn goal will not be met or the engines will need to move to an under-wing location and the noise goal will not be met.

Risk Mitigation Plan

Figure 122 shows the mitigation of the risk over the course of the technology development effort. The work associated with attaining equivalent safety is necessary for the PSC but not essential to the STV, so the development activities are scheduled as a spiral development on the STV, occurring later than the critical engine operability tasks. It is currently recognized that work is needed to address equivalent safety and that solutions could impose moderately high penalties in fuel burn or noise (point a). Analysis will improve TRL to 3 and is expected to reduce the likelihood of carrying penalties on the PSC (point b). Developing and laboratory testing of solutions will improve TRL to 4 and is expected to reduce the likelihood and consequence of the risk (point c). Ground test of systems applied to the STV is expected to further reduce the likelihood of risk (point d).

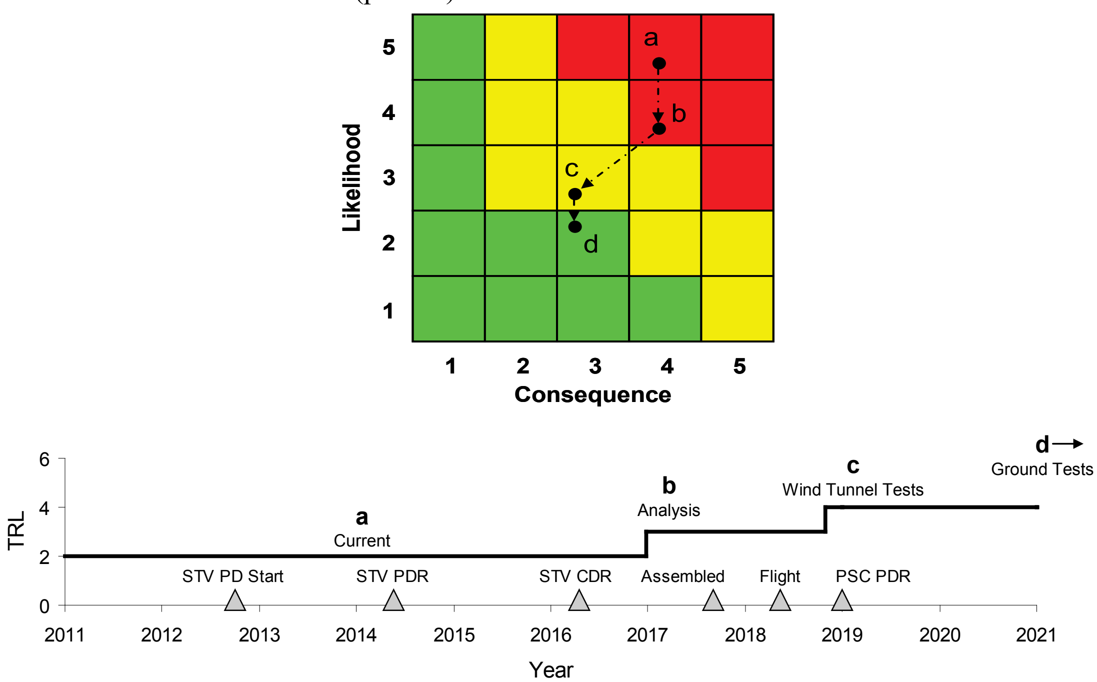


Figure 122: Propulsion Risk – Equivalent Safety

3.4.4.3 Expected Outcomes and No-Go Points

Table 60 describes the expected outcome of technology development at TRL jump milestones indicated in Figure 121 and Figure 122.

Table 60: BWB Propulsion Expected Outcomes

Milestone	TRL	Expected Outcome
Analysis	3	Design and high-fidelity analysis address concerns for engine operability.
Wind Tunnel Tests	4	Wind tunnel tests confirm characteristics needed for engine operability.
Ground Test	5	Ground tests indicate readiness for flight.
STV Flight Test	6	Engine operability validated in flight test.

Table 61 describes no-go points that could require significant change or abandonment of the technology. Some conditions that could occur during the development of the technology would trigger consideration of alternative approaches. It is expected that these conditions would be caught during the work performed to reach the range of milestones indicated in the table.

Table 61: BWB Propulsion No-Go Points

Milestone Range	Trigger	Alternative
Analysis - STV Flight Test	Aerodynamic flow characteristics cannot support engine operability over a reasonable envelope.	Switch to alternate engine installation (under wing) with reduced acoustic shielding and possibly higher fuel burn (reduced fan diameter).
Analysis - Ground Test	Provisions for thrust reversing become significantly heavier than projected.	Switch to alternate engine installation (under wing) with reduced acoustic shielding and possibly higher fuel burn (reduced fan diameter).
Analysis - Ground Test	Nacelle armor for equivalent safety becomes significantly heavier than anticipated.	Switch to alternate engine installation (under wing) with reduced acoustic shielding and possibly higher fuel burn (reduced fan diameter).

3.4.4.4 Development Tasks

Development tasks for BWB propulsion are indicated in Table 62.

Table 62: BWB Propulsion Development Tasks

Milestone	TRL	Description
Current	2	Limited analysis of engine operability No analysis of thrust reverser concept No analysis of armor required for equivalent safety against engine fratricide
Analysis	3	Design and analyze configuration for engine operability Develop and analyze thrust reverser design Develop and analyze armored nacelle structure
Test	4	Wind-tunnel test to demonstrate flow characteristics compatible with engine operability Wind-tunnel test to demonstrate basic functionality of thrust reverser Nacelle structural test
Prototype	5	Demonstrator wind tunnel tests show flow characteristics compatible with engine operability Demonstrator hardware integrated and ready for test Thrust reverser demonstrated in taxi test Demonstrator nacelle structure tested
Flight Demo	6	Engine operability demonstrated in flight Thrust reverser demonstrated on landing

3.4.5 BWB Stability & Control, Flight Controls, and Flying Qualities

3.4.5.1 Description

To gain maximum performance from its flying wing configuration, the BWB requires a full authority augmented flight control system to keep within a safe operating envelope and to provide good handling qualities to the edges of that envelope. In order to develop the necessary control laws, the BWB stability and control characteristics need to be well understood and actuation system requirements need to be defined.

A series of wind-tunnel tests (low speed, high speed and aero loads) need to be conducted in order to develop the aero database. The aero database is needed to develop the aero model and associated simulation, from which the bare airframe stability and control characteristics can be assessed.

Based on the bare airframe stability and control characteristics, full flight envelope control laws will be developed to meet the flying qualities requirements, and preliminary actuation system and failure requirements.

Once the flight control system has been designed, a series of piloted simulation tests need to be conducted to develop the formal actuation and failure requirements as well as verifying that the control system functionality and handling qualities are acceptable. A final simulation test will need to be conducted to verify and validate a realizable actuation system to ensure it meets the requirements.

3.4.5.2 Benefits

The benefits of using the planned BWB control law design are (1) the ability to directly specify key augmentation levels and damping in the control law structure and (2) the ability to permit quick and easy control law updates for changes in the vehicle aerodynamics. It essentially permits control law rapid prototyping, as well as making it easier to meet the specified flying qualities requirements.

Given the uniqueness for the BWB configuration and associated control system actuation power requirement issues, performing piloted simulation tests to develop the formal actuation and failure requirements as well as verifying that the control system functionality and handling qualities requirements are met will significantly reduce the risk of unexpected flight controls issues regarding the flight vehicle.

3.4.5.3 Risks

3.4.5.3.1 STV Stability & Control

Benefit (KPP)

Acceptable stability and control (S&C) characteristics are needed to enable the BWB configuration and thereby contribute to the goal of 50% reduced fuel burn relative to 1998 technology aircraft.

TPM

The impact of S&C changes to the aerodynamic configuration will be tracked in lift-to-drag ratio.

The effect of S&C on the actuation system will be tracked by actuation system power requirements and system weight fraction (weight of aircraft systems divided by maximum takeoff weight).

Center-of-gravity (CG) range provides a measure for tracking the ability of the flight control system to provide control, given the S&C characteristics of the aircraft.

Risk Statement

If a large uncertainty in the STV S&C power requirement remains, then there will be a significant margin on the flight control surface areas, actuator rates, and bandwidth requirements to ensure safe and controllable aircraft, which in turn will drive up the actuation system weight and power requirements, as well as increase drag and limit CG travel.

Risk Mitigation Plan

Figure 123 shows the mitigation of the risk over the course of the technology development effort. Since there is a lack of data to define better rate and bandwidth requirements, current assessments of the PSC and STV use conservative assumptions that result in very high actuation system power requirements (point a). Simulations with the BWB 450-1L configuration are expected to show reduced requirements that reduce the likelihood of a problem with the PSC configuration (point b). These simulations will improve TRL to 4, particularly by including the first evaluations of high-speed control. Design of the STV control and validation of its control system with high-fidelity piloted simulation is expected to reduce the potential consequence (by demonstrating lower actuation system requirements) and likelihood (through higher-fidelity modeling) (point c). Completion of simulations for the STV will improve TRL to 5. Validation of the control system in flight test will improve TRL to 6 while reducing the likelihood of risk for the PSC (point d). Flight test may or may not show further reduced actuation system requirements that could further reduce the risk consequence for the PSC.

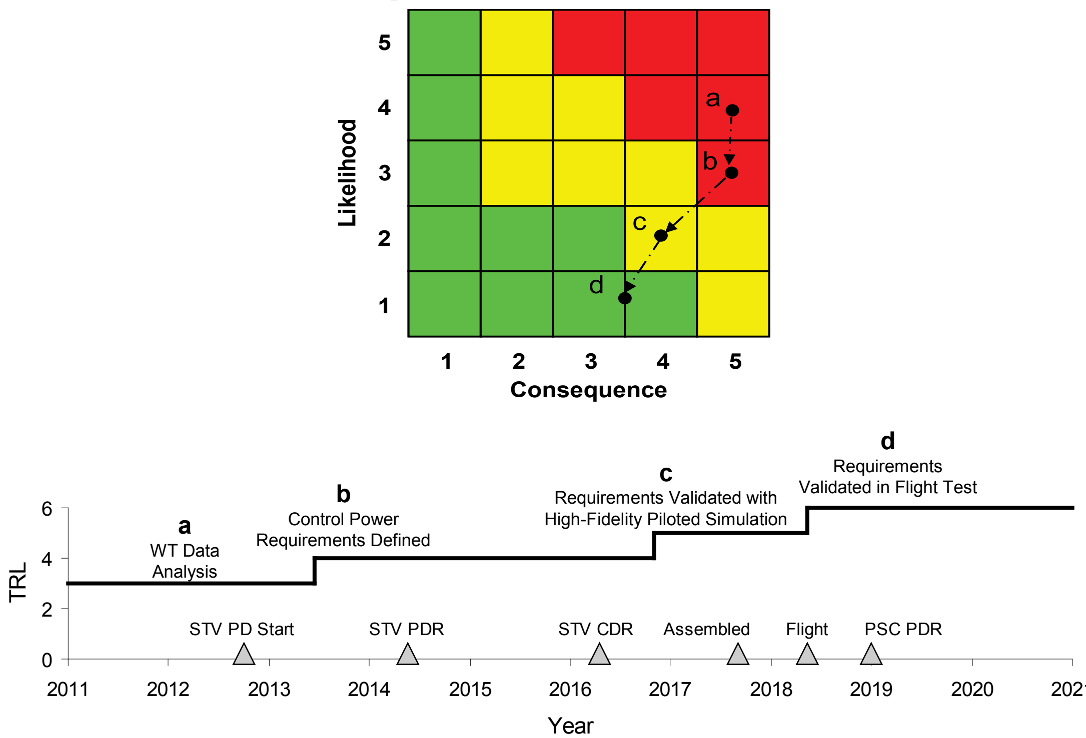


Figure 123: Flight Controls Risk – STV Stability & Control

3.4.5.3.2 STV Flight Controls

Benefit (KPP)

The BWB flight control system helps enable the aerodynamically efficient shape that contributes to reaching the goal of 50% reduced fuel burn relative to 1998 technology aircraft.

TPM

Risk mitigation on the flight control system will be tracked by evaluation of actuation system power requirements and system weight fraction (weight of aircraft systems divided by maximum takeoff weight).

Risk Statement

If high power (hydraulic and/or electrical) is needed by the flight control actuators to meet stability and flight control (gain/phase margin) requirements, then high flight control system weight fraction and large power extraction from propulsion system and/or separate secondary power system will reduce efficiency gain by the BWB configuration.

Risk Mitigation Plan

Figure 123 shows the mitigation of the risk over the course of the technology development effort. Current assessments of the PSC and STV indicate actuation system power requirements are unacceptable (point a). Simulations with the BWB 450-1L configuration are expected to show reduced requirements that reduce the likelihood of a problem with the PSC configuration (point b). These simulations will improve TRL to 4, particularly by including the first evaluations of high-speed control. Design of the STV control and validation of its control system with high-fidelity piloted simulation is expected to reduce the potential consequence (by demonstrating lower actuation system requirements) and likelihood (through higher-fidelity modeling) (point c). Completion of simulations for the STV will improve TRL to 5. Validation of the control system in flight test will improve TRL to 6 while reducing the likelihood of risk for the PSC (point d).

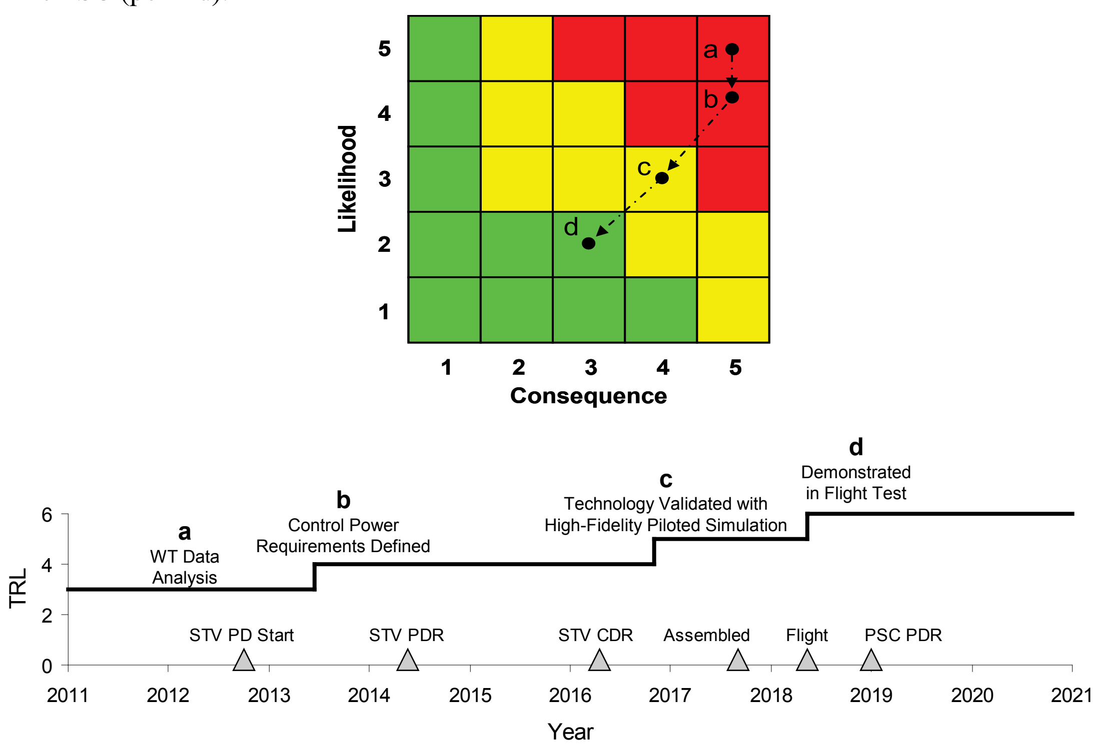


Figure 124: Flight Controls Risk – STV Flight Controls

3.4.5.4 Expected Outcomes and No-Go Points

Table 63 describes the expected outcome of technology development at TRL jump milestones indicated in Figure 123 and Figure 124.

Table 63: BWB Flight Controls Expected Outcomes

Milestone	TRL	Expected Outcome
Control Power Requirements Defined	4	Piloted simulation with similar configurations shows requirements for actuation system can be relaxed. Simulation shows no issues with high-speed flight.
Technology Validated with High-Fidelity Piloted Simulation	5	Piloted simulation of STV configuration shows STV flight control system is adequately sized. Reasonable actuation system power projected for PSC.

Demonstrated in Flight Test	6	Flight control system for BWB validated in flight test.

Table 64 describes no-go points that could require significant change or abandonment of the technology. Some conditions that could occur during the development of the technology would trigger consideration of alternative approaches. It is expected that these conditions would be caught during the work performed to reach the range of milestones indicated in the table.

Table 64: BWB Flight Controls No-Go Points

Milestone Range	Trigger	Alternative
Control Power Requirements Defined – Demonstrated in Flight Test	Configuration cannot provide reasonable control characteristics.	Change configuration to provide reasonable control characteristics. Accept penalties in fuel burn and acoustics. Drop BWB configuration if resulting performance is non-competitive.
Control Power Requirements Defined – Demonstrated in Flight Test	Configuration cannot be controlled with reasonable actuation system power requirements.	Change configuration to require reasonable actuation system power levels. Accept penalties in fuel burn and acoustics. Drop BWB configuration if resulting performance is non-competitive.

3.4.5.5 Development Tasks

The control laws for the BWB configuration are well understood, primarily from the X-48B low-speed flights. Although X-48B flights were at low-speeds, we do not expect any surprises at high speeds. However, high-speed control laws need validation. Since the current configuration is much different from the initial BWB configuration, 450-1L, that was extensively tested in the low- and high-speed wind tunnels, the basic stability and control characteristics for the new configuration must be determined. The power requirements for the control system actuation could be a challenge; hence, a greater focus is required to mature the actuation technologies. The following tasks are proposed to mature the overall Stability & Control, Flight Controls, and Flying Qualities technologies:

1. **Wind-tunnel tests:** At least three wind-tunnel tests of the new configuration will be required: One for low-speed data, one for high-speed data, and one for the overall aero loads data. These data are needed to develop the aero database for the control law design and to reduce the aerodynamic uncertainties, as well as used in structural design.
2. **Aero model and simulation development:** From the wind-tunnel tests results, an aero and associated simulation model will be developed. The aero model and simulation will be used to assess the stability and control characteristics and in developing the control laws.
3. **Control law (Flight Control System) development:** The control laws will be developed to meet the flying qualities requirements based on the bare airframe stability and control characteristics and initially-defined actuation system requirements.
4. **Motion-based piloted simulation tests:** At least three simulation tests will be required: One to understand and develop the actuation requirements, one to understand and develop the failure requirements, and one to verify and validate a realizable actuation system to ensure it meets the requirements.

A description of the roadmap for development of BWB Stability & Control, Flight Controls, and Flying Qualities technologies is provided in Table 65.

Table 65: BWB Stability & Control, Flight Controls, and Flying Qualities Development Tasks

Milestone	TRL	Description

Current	2-4	X-48B flight tests sets low-speed control to TRL 4 No evaluation of high-speed S&C and flight characteristics
Motion-Based Simulation	4	Wind-tunnel tests for high-speed S&C characteristics Piloted simulation to test flying qualities and ride qualities Assess and develop actuation system requirements
Validation Using Motion-Based Simulation	5	Based on actuation requirements, demonstrate high-fidelity actuator model in motion-based piloted simulation Simulation validates actuation requirements Piloted simulation supports readiness for flight
Flight Demo	6	Full flight envelope testing of control laws to confirm resolution of the issues

3.4.6 BWB Actuation System

The BWB actuation system is responsible for positioning the control surfaces in response to the flight control system. The BWB configuration creates a technical challenge because it has many relatively large control surfaces that need to be actuated at high rate. The power consumed by the actuation system goes with the hinge moments and rates of the control surfaces. The predicted hinge moments and rates for the control surfaces are higher than the typical aircraft. These higher hinge moments will require an actuation system that incorporates multiple actuators on each control surface in order to meet the rates against the higher loads. This multiple actuator architecture will require high flow rates if a hydraulic actuation system is used and large power systems if electric actuation system is used.

Prior studies indicate the BWB actuation system could use a large amount of power. This power consumption could cut into fuel efficiency in regular operation. Work is needed to show how actuation will be provided in emergency situations, including operation with all engines out and no fuel.

Studies are needed to determine the architecture of the BWB actuation system. It is not clear whether hydraulic, electric, or a mix of systems will meet flight control requirements with the lowest power. These studies will also need to determine how emergency power will be generated, whether by ram air turbine or some form of auxiliary power unit with an independent fuel supply. These studies should also consider the use of mechanisms such as control surface tabs to reduce the hinge moments that affect the power consumed by the actuation system.

3.4.6.1 Benefits

Studies will determine the best actuation architecture to be used on the BWB program by comparing the different options. The different options will be evaluated on several criteria, efficiency, cost, readiness level and availability.

3.4.6.2 Risk

3.4.6.2.1 Flight Control Actuation

Benefit (KPP)

Limiting the power requirements of the BWB flight control actuation system will contribute toward reaching the goal of 50% reduced fuel burn relative to 1998 technology aircraft.

TPM

The effect of actuation system changes on fuel burn will be tracked by evaluating actuation system power requirements.

These power requirements affect specific fuel consumption, which is more directly used in the evaluation of fuel burn.

Actuation system power requirements are affected by control surface hinge moments, which will be tracked in the aerodynamic design of the control surfaces.

Risk Statement

If actuation system power requirements are not reduced, then additional power will be extracted from the engines, adversely affecting specific fuel consumption and fuel burn.

Risk Mitigation Plan

Figure 125 shows the mitigation of the risk over the course of the technology development effort. Current assessments of the PSC and STV indicate actuation system power requirements that could impose large penalties in fuel burn (point a). Evaluating approaches to reduce actuation system power is expected to reduce the potential penalties and their likelihood (point b). This evaluation will also improve actuation system TRL to 3. Testing in the laboratory will improve TRL to 4 and reduce the likelihood of risk (point c). Ground testing of the STV actuation system will improve TRL to 5 and is expected to reduce the likelihood and potential penalties on the PSC (point d). Flight test of the actuation system on the STV will improve TRL to 6 (point e).

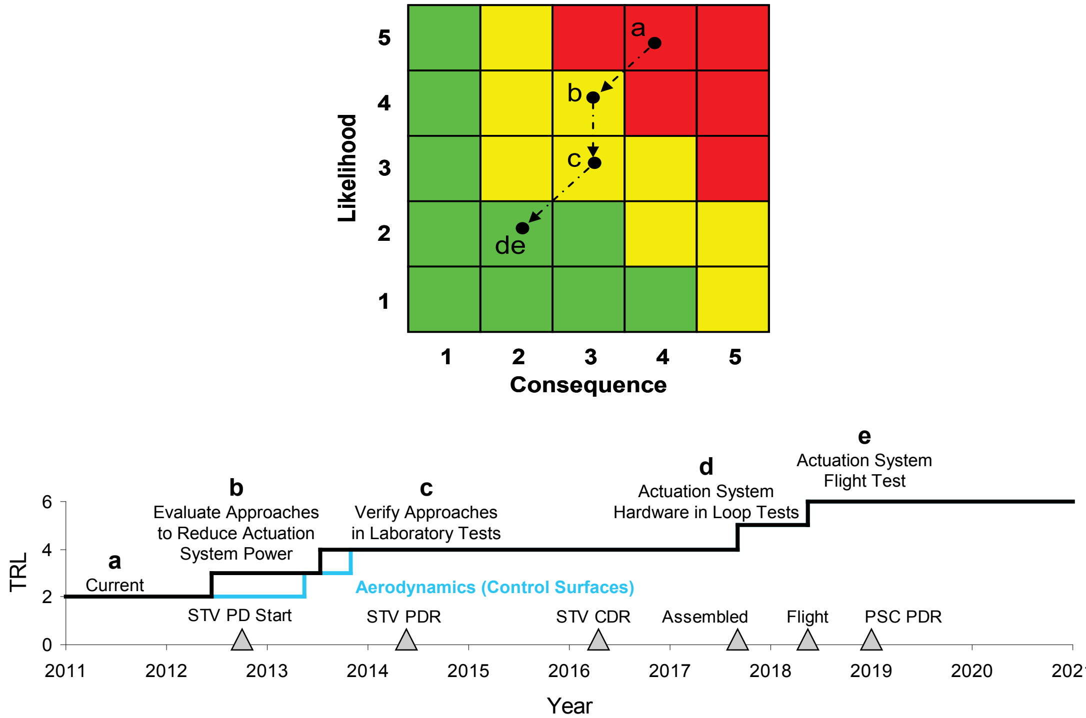


Figure 125: Actuation Risk – Flight Control Actuation

3.4.6.3 Expected Outcomes and No-Go Points

Table 66 describes the expected outcome of technology development at TRL jump milestones indicated in Figure 125.

Table 66: BWB Actuation System Expected Outcomes

Milestone	TRL	Expected Outcome
Evaluate Approaches to Reduce Actuation System Power	3	Design and analysis of the actuation system generates a system with reasonable actuation system power requirements.
Verify Approaches in Laboratory Test	4	Testing of actuation system components shows they will meet actuation system requirements.
Actuation System Hardware in Loop Tests	5	Tests of the STV actuation system verifies it will work. Reasonable actuation system power projected for PSC.
Actuation System Flight Test	6	Actuation system for BWB validated in flight test.

Table 67 describes no-go points that could require significant change or abandonment of the technology. Some conditions that could occur during the development of the technology would trigger consideration of alternative approaches. It is expected that these conditions would be caught during the work performed to reach the range of milestones indicated in the table.

Table 67: BWB Actuation System No-Go Points

Milestone Range	Trigger	Alternative

Evaluate Approaches to Reduce Actuation System Power – Actuation System Hardware in Loop Tests	Actuation system power requirements cannot be reduced to a reasonable level.	Change configuration to provide reasonable actuation system power levels. Accept penalties in fuel burn and acoustics. Drop BWB configuration if resulting performance is non-competitive.

3.4.6.4 Development Tasks

With the higher hinge moments, the actuation system and power system will need to be increased in size to a point that the systems will most likely be bigger than what is currently being produced for other programs. This high power actuation system will need to be developed and tested to prove the functionality. Thermal effects due to the higher power requirements will also need to be addressed. If actuator size and power system capability is above currently available hardware, then the TRL would be considered to be TRL 4 for the actuation system. A new larger actuation system would need to be tested to verify the actuators, power system and thermal affects against the high hinge moments.

Due to the high loads, multiple actuators will be required on each of the control surfaces, which will require some type of force fighting control between the actuators to prevent the actuators from working against each other. With multiple actuators on a surface, the actuators must be capable of being back driven in the event the actuator or power system fails. When being back driven, the actuator must not provide any significant load on the other actuators on the surface. This multiple actuator configuration with dis-engageable actuators is currently being studied with the plan to verify by laboratory testing in the 3rd quarter of 2011. After completion of this testing, the hardware would be considered to be at a TRL 5.

Tasks to mature BWB actuation system technology are indicated in Table 68.

Table 68: BWB Actuation System Development Tasks

Milestone	**TRL**	**Description**
Current	3	Studies for actuation system Studies for emergency power system
System Studies	3	Define requirements from X-48B and piloted simulation Design and analyze actuation system for preferred configuration Include design of emergency power system
Component Testing	4	Test actuation and emergency power system components
Prototype Flight Control System	5	Actuation and emergency power system integrated and ready for test
Flight Demo	6	Actuation and emergency power system tested in flight

3.4.7 Acoustics

BWB acoustic technology can have drastically different features from conventional aircraft configurations. Engine noise shielding is an obvious example. Also, the unique airframe of the BWB design may also lead to unique noise characteristics. Thus, this task aims to cover various aspects of the BWB acoustics, including technology development to ensure the achievement of the NASA N+2 noise goal and the development of noise assessment tools that are needed not only for the current BWB studies, but also for future advanced configurations.

3.4.7.1 Description

3.4.7.1.1 Acoustic Shielding

Acoustic shielding technologies for BWB aircraft include the following.

- **Engine location optimization:** Engine location is the most important parameter that impacts the noise shielding efficiency of BWB aircraft, and thus, should be optimized with respective constraints in aerodynamic performance, propulsion efficiency, etc.
- **Low-noise pylon design:** Pylon shape, location, and local surface treatment can be configured to both dissipate noise and alter engine wake flow to reduce source strengths.
- **Surface treatment:** Acoustic liner may be a potential noise reduction technique in the local regions of the engine location.
- **Vertical tails:** For noise shielding at sideline locations, vertical tails may be efficient, especially for tones that have directivity mostly in the forward and overhead locations. The locations, sizes and surface properties can be optimized for minimum noise with respective constraints in aerodynamic performance, propulsion efficiency, etc.

The NASA N+2 noise goal is 42 dB cumulative below FAR Part 36 Stage 4. An objective for the STV is to demonstrate technologies that will allow the PSC to meet this goal. The absolute noise goal itself cannot be demonstrated on the STV because FAR 36 noise is a function of takeoff weight, and the STV will have a lower weight than the PSC.

The delta noise required to enable meeting the N+2 goal can potentially be demonstrated. The basic propulsion noise is measured in a ground static test stand and this data is projected into flight using current methods. The noise is then measured with STV flight tests at the FAR 36 points. Some separation of noise sources can be done using transient flight conditions such as flying in a clean configuration with gear up at low gross weight and high power to make propulsion noise dominant. The noise shielding level is thus determined from the flyby noise compared to the ground to flight projections by using an accelerating flyby with high power at low gross weight since the lift coefficient will be lower without the slats extended.

Noise evaluations have not yet been conducted, and it has not yet been determined whether jet noise reduction is needed for the PW1524 engine selected for the STV. If jet noise is a dominant source, it may require reduction to in order to demonstrate a cumulative -42 dB for the STV at its maximum takeoff weight. NASA reported LSAF (Low Speed Aeroacoustic Facility) test results[14] that show the potential to reach the goal with a GE90 type engine. Since the PW1500G has a higher bypass ratio, the jet noise will be lower, though not as low as in the PSC, which has a lower FPR (fan pressure ratio). Thus, with effective jet noise compression, the STV with the PW1500G could have the potential to meet FAR 36 Stage 4 minus 42 dB cumulative for the STV maximum takeoff weight. This demonstration will require development of a suitable jet noise device for the PW1500G on the STV and be considered for a Phase II spiral up on the STV.

3.4.7.1.2 Airframe Noise

The technologies to reduce airframe noise include

Local fairing: For landing gear parts identified as the most important noise sources, local fairing (either rigid and/or porous) can be applied to reduce the velocity of the local flow impinging on the components, and hence, reduce the strengths of the noise sources.

Component relocation: By relocating the gear components, if feasible, inter-component interactions can be reduced and high velocity flows can be avoided, both of which reduce the radiated noise.

Grouping: Small parts, such as cables, can be grouped together and enclosed in aerodynamically streamlined containers, which can reduce high frequency noise.

Shaping: For components that cannot be relocated and grouped, the shapes of the components may be modified to minimize noise radiation.

Local liner: Acoustic liner may be able to reduce noise in strategically identified locations by both dissipating the noise and altering the local flow to reduce source strength.

For BWB aircraft configurations that use leading edge slats, the noise reduction technologies include the following.

Cove filler: By shaping the lower surface of the slat following the flow, this technique can reduce the cove region flow separation, and hence reduce noise. The shaping can be implemented by an extension surface either from the slat or from the main wing.

Reduced and sealed gap: Within the constraints of maximum lift requirements, reducing or sealing the gap between the slat trailing edge and the main wing can reduce slat-related noise.

Drooped leading edge: The noise reduction potential of the cove filler and the sealed gap can be achieved by drooped leading edge.

Low-noise slat bracket: Redesigning the shape of the bracket and/or local surface treatment may further reduce noise.

It is expected that the initial STV configuration will focus on establishing flying qualities and efficiency and that lowering noise will be a spiral development.

3.4.7.2 Benefits

Acoustic shielding provides the largest noise reduction on BWB compared with conventional aircraft.

With acoustic shielding, airframe noise becomes a larger component of to total noise. Reductions to landing gear and leading edge device noise would address the most important airframe noise components, which may set the noise floor for total aircraft noise.

3.4.7.3 Risk

3.4.7.3.1 Acoustics

Benefit (KPP)

Acoustic shielding and approaches to reduce airframe noise are expected to enable achieving the goal of 42 dB cumulative EPNL below FAR Part 36 Stage 4.

TPM

The cumulative EPNL is the sum of noise measured in three conditions: cutback, sideline, and approach. These three noise measures will be used to track acoustic performance.

Risk Statement

If the STV design has less than ideal acoustic characteristics, then the STV will not demonstrate noise levels consistent with PSC goals.

Risk Mitigation Plan

Figure 126 shows the mitigation of the risk over the course of the technology development effort. As currently analyzed, the PSC very likely misses the noise goal by a moderately large amount (point a). When additional acoustic treatments are developed and analyzed, the gap in acoustic performance is expected to be reduced as well as the likelihood of missing the goal (point b). Completing the planned analysis will improve TRL to 3. Acoustic tests on configurations similar to the PSC will raise the TRL to 4 (point c). Lessons learned from these similar configurations will be applied to the design of the STV. When the final STV design is tested in the wind tunnel, TRL will increase to 5 and it is expected that the likelihood of missing the noise goal on the PSC will be reduced (point d). Acoustic flight tests on the STV will improve TRL to 6 (point e).

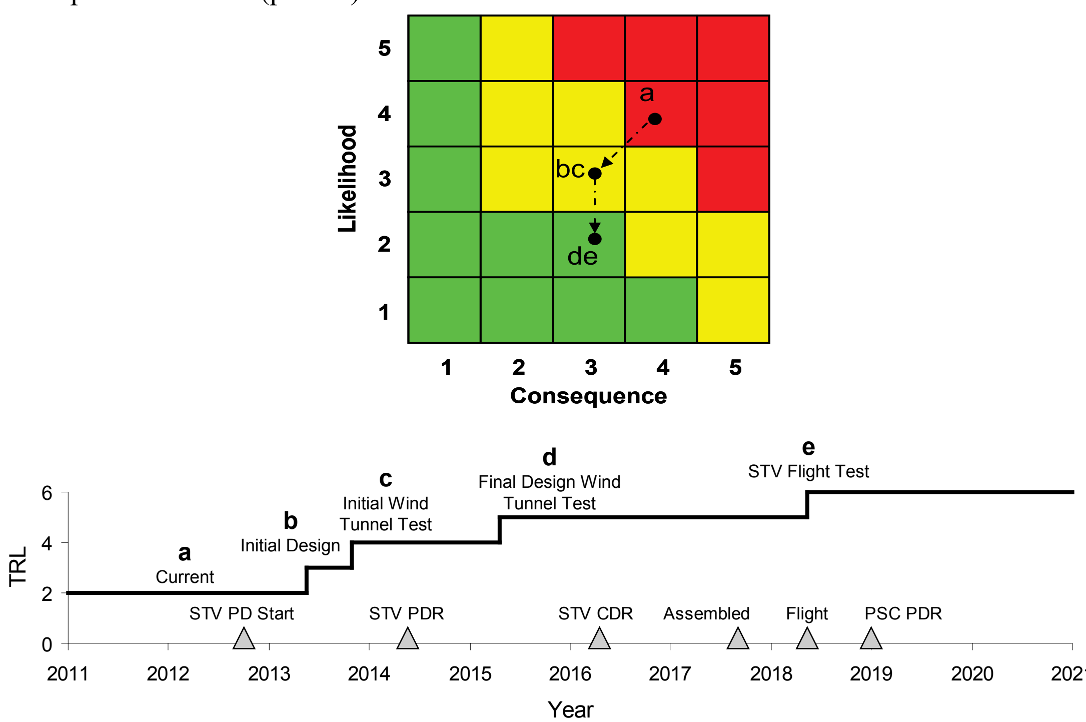


Figure 126: Acoustics Risk

3.4.7.4 Expected Outcomes and No-Go Points

Table 69 describes the expected outcome of technology development at TRL jump milestones indicated in Figure 126.

Table 69: Acoustics Expected Outcomes

Milestone	TRL	Expected Outcome
Analysis	3	Design and analysis show options for reducing noise.
Similar Configuration Noise Tests	4	Noise tests on similar configurations provide information to aid efforts to reduce noise.
STV Noise Test	5	Noise tests on STV configuration confirm predictions.
STV Flight Test	6	STV flight tests demonstrate predicted noise levels.

Table 73 describes no-go points that could require significant change or abandonment of the technology. Some conditions that could occur during the development of the technology would trigger consideration of alternative approaches. It is expected that these conditions would be caught during the work performed to reach the range of milestones indicated in the table.

Table 70: Acoustics No-Go Points

Milestone Range	Trigger	Alternative
Analysis – STV Flight Test	Features to reduce noise fail to show noise reduction benefits in testing.	Remove affected noise-reducing features from PSC with loss in noise benefits.

3.4.7.5 Development Tasks

Acoustic Shielding

A key need for acoustic shielding is to develop noise prediction and design tools that can optimize noise shielding. Development of these tools is included in the plan sketched in Table 71.

Table 71: Acoustic Shielding Development Tasks

Milestone	TRL	Description
Current	3	Extensive analytical work LSAF tests
Fundamental Testing	3	Testing to develop and validate acoustic prediction methods for shielding
Testing	4	Acoustic testing of preferred configuration to demonstrate acoustic benefits
Prototype	5	Prototype hardware integrated and ready for test
Flight Demo	6	Acoustic testing with demonstrator vehicle

Airframe Noise

In the task proposed here, an iterative, hybrid design approach will be developed and demonstrated, which consists of high-fidelity acoustic prediction, gear flow computation, and wind-tunnel testing, all three combined into an integrated iterative process for low noise gear design. The design starts with local mean flow computations for the initial geometry that contains the gear parts suspected to generate the most noise. The geometry is also tested in a quick turn-around wind tunnel. The computations provide the mean flow quantities needed for high-fidelity noise prediction, as well as parameters that can be used as indicators of strong noise sources. The wind-tunnel test, on the other hand, provides noise measurements, either in conventional noise metrics by microphones or in relative amplitudes by phased microphone arrays, for total noise calibration. These are fed into the acoustic prediction that not only provides noise levels to see if the gear design meets the noise goals, but also supplies the component noise levels, so that the noisiest parts are identified. Low-noise design proceeds from here to the identified parts by a combination of local fairings, component reshaping, relocation, grouping and local liner treatment. The new design goes back to the flow computation and wind-tunnel testing, restarting the iterative process. The process may iterate a few times, because a new design has the possibility of introducing new noise sources, until the noise goals are met. The process is illustrated in Figure 20.

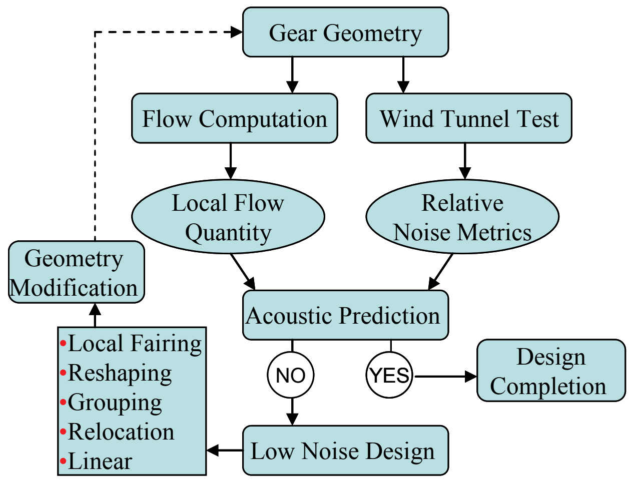


Figure 127: Landing Gear Acoustic Design Approach

Tasks to develop low-noise landing gear are indicated in Table 72. A similar approach would be used in the development of low-noise leading-edge devices, also indicated in Table 72.

Table 72: Airframe Noise Reduction Development Milestones

Milestone	TRL	Description
Current	2	Concepts for landing gear noise reduction generated Concepts for low noise leading edge devices generated
Fundamental Testing	3	Testing or analysis to show basic noise reduction Analysis to show effect of low noise leading edge devices on maximum lift
Testing	4	Acoustic testing of preferred configuration to demonstrate acoustic benefits
Prototype	5	Prototype hardware integrated and ready for test
Flight Demo	6	Acoustic testing with demonstrator vehicle

3.4.8 Advanced PRSEUS

3.4.8.1 Description

PRSEUS in its current form is suitable for application to the STV demonstrator. Such an application will help accelerate the development of PRSEUS. However, some development that does not fit the desired timeline for the STV is needed to prepare PRSEUS for use on a production PSC aircraft. This additional work to mature PRSEUS for production use on primary aircraft structure is referred to as Advanced PRSEUS in this technology maturation plan. While PRSEUS development for the STV will focus on the essential effort needed to design the STV structure, Advanced PRSEUS will have a larger scope as needed to support the design of a production aircraft.

Advanced PRSEUS development will examine toughened resins to address micro-cracking. It will examine using low-flame and low-smoke foam materials to address smoke-and-burn. It should also examine approaches for eliminating foam altogether. In the process of examining different resins, there will also be opportunity to examine advanced fibers.

With changes to the fundamental materials, Advanced PRSEUS will require reevaluation of many features of PRSEUS that may be addressed under BWB structures technology development targeted at the STV. These features include fuel containment, electro-magnetic protection, and lightning protection.

If some tasks for Advanced PRSEUS were performed up front and the development of the STV was delayed so that the STV was developed using the Advanced PRSEUS material system, a significant amount of effort could be eliminated by avoiding repeated work necessitated by differences between current PRSEUS and Advanced PRSEUS. PRSEUS development was split to allow earlier development of the STV, but the cost of overall technology development for the PSC would be reduced if portions of Advanced PRSEUS were developed ahead of the STV.

The plan for Advanced PRSEUS includes development and test of PSC wing and fuselage structure. This activity may or may not be required for technology development, depending on differences between current PRSEUS and Advanced PRSEUS as well as differences between the STV and PSC structural arrangement. If the STV wing and fuselage are tested to failure, most critical technical aspects of large-scale BWB structures will be addressed. These aspects may need to be reevaluated for various reasons. If the manufacturing process changes significantly (potentially because of the new resin), fabrication of large-scale wing and body components may need to be demonstrated again. If significant changes in material properties are identified in component and subassembly testing or if the PSC structural arrangement changes significantly from the STV, there may be reason for additional structural testing. If differences in manufacturing process, material properties, and structural arrangement are small enough, development and test of PSC wing and fuselage structure should not be required in technology development.

3.4.8.2 Benefits

Advanced PRSEUS will address issues that may become barriers to applying PRSEUS to primary structure for production aircraft. Advanced PRSEUS will be an enabler for achieving the benefits claimed for PRSEUS, including weight and cost savings.

3.4.8.3 Risks

The discussion on risk for Advanced PRSEUS is included in the discussion on risk for BWB structures in Section 3.4.2.3.

3.4.8.4 Development Tasks

The milestones coinciding with increments in TRL are described in Table 73.

Table 73: Advanced PRSEUS Development Milestones

Milestone	TRL	Description
Constituent Tests (Current)	2	Advanced PRSEUS panels manufactured and coupons tested
Component Tests	3	Advanced PRSEUS component-level manufacture and performance demonstrated
PSC Structures Subassembly Tests	4	Advanced PRSEUS subassembly-level performance demonstrated by tests Key manufacturing processes demonstrated in laboratory
PSC Structures Assembly Ground Test	5	PSC-scale vehicle structure (body, wing, etc) fabricated and tested on the ground to failure
PSC Airframe Ground Test	6	All Advanced PRSEUS building block tests complete Airframe structure integrated with all systems PSC flight test vehicle ground tested

3.4.9 Laminar Flow

3.4.9.1 Description

Laminar flow technology seeks to reduce drag by maintaining laminar flow over a significant portion of aerodynamic surfaces, including wings, tails, and nacelles. Laminar flow creates significantly less skin friction than turbulent flow, but current typical transport aircraft aerodynamic designs do not provide the conditions required for laminar flow, including smooth surfaces, favorable pressure distributions, and low sweep or active laminar flow control.

Very small disturbances can trip the boundary layer from laminar to turbulent. The step at the trailing edge of a slat stowed on a wing will trip the boundary layer, so Krueger flaps, which stow on the lower surface of the wing, would be used to enable laminar flow on the wing upper surface. These Krueger flaps may be used to shield the wing leading edge from insect strikes and other debris to maintain the necessary smoothness for laminar flow. The joint between the wing leading edge and wing box needs to be carefully designed and manufactured to avoid tripping the boundary layer at that junction.

Favorable pressure distributions promote laminar flow, with higher pressures upstream pushing the boundary layer flow toward lower pressures downstream, stabilizing the naturally occurring instabilities in the boundary layer. Adverse pressure gradients, with higher downstream pressures pushing backward on the boundary layer flow, tend to trip boundary layers to turbulent flow. The basic aerodynamic design of the wing needs to provide favorable or neutral pressure distributions. This requirement is not very different from the flat rooftop pressure distributions used for limiting shock strength and associated compressibility drag in modern supercritical airfoils. While the plan is to investigate laminar flow as a spiral development on the STV, the basic wing design for the STV is expected to provide a favorable pressure distribution for laminar flow.

The final requirement is for low sweep or laminar flow control to prevent cross-flow instability from tripping the boundary layer. It would be difficult to get a low-sweep wing to have the desired compressibility drag performance for 0.85 Mach cruise. Instead, a laminar flow control system will remove the lower energy boundary layer flow that would be most affected by cross-flow instability caused by 3-D effects at the leading edge. The envisioned laminar flow control system includes a perforated leading edge connected via a pressure channel to a low pressure suction device.

Testing the laminar flow control system will be difficult to impossible to do without the large size STV. Laminar flow is sensitive to the size of the perforations and the manufacturing process is limited in how small the perforations can be. The boundary layer flow and stability of the laminar flow is also a function of Reynolds number. These considerations favor a large model. The size of available wind tunnels limits model size, particularly when blockage at 0.85 Mach is considered. The competing requirements on size make a stub wing test the best way to demonstrate the basic functionality of a laminar flow control system in a wind tunnel. By testing a small span-wise segment of the wing, a stub wing test will have difficulty matching the 3-D flow conditions of the actual wing. In addition, the flow quality inside a wind tunnel is not as smooth as in flight, so it is not possible to demonstrate the full extent of laminar flow. Therefore, validation of the extent and benefit of laminar flow will need to wait for flight test.

3.4.9.2 Benefits

Laminar flow provides a skin friction drag reduction.

3.4.9.3 Risks

The discussion on risk for laminar flow is included in the discussion on risk for BWB aerodynamics in Section 3.4.3.3.

3.4.9.4 Development Tasks

The milestones coinciding with increments in TRL are described in Table 74.

Table 74: Laminar Flow Development Milestones

Milestone	TRL	Description
Current	2	Conceptual analysis shows benefit for laminar flow
Design	3	Laminar flow extent and drag benefit evaluated with high-fidelity aerodynamic analysis Laminar flow control system performance estimated
Wind Tunnel Test	4	Pressure distributions compatible with laminar flow demonstrated in wind tunnel test Basic functionality of laminar flow control system demonstrated in stub wing test
System Construction	5	Laminar flow control system for STV constructed and ground tested
Flight Test	6	Laminar flow extent and fuel burn benefits measured in flight test

3.4.10 Geared Turbofan

3.4.10.1 Description

Next-generation ultra high bypass (UHB) propulsion systems, and specifically the Pratt & Whitney geared turbofan (GTF), will feature a comprehensive suite of technology to deliver unsurpassed fuel burn efficiency and reduced emissions while simultaneously reducing the noise signature of the engine.

Ongoing efforts with NASA and the Federal Aviation Administration (FAA) Continuous Lower Energy, Emissions, and Noise (CLEEN) project are advancing combustor and low spool technology for improved emissions and noise. These advancements will be directly applicable to the ERA N+2 configuration. Critical technologies that are envisioned to be the focus of immediate investment for ERA are centered on the core technologies enabling high overall pressure ratio.

High overall pressure ratio (OPR) core technologies are of critical need to achieving aggressive fuel burn reduction in cooperation with advanced low spool technology development already underway. Fundamental advanced aero work is underway for the high pressure turbine (HPT). The aero geometries produced will need to be combined with advances in high pressure compressor (HPC) aero to form an altogether new advanced core concept. High temperature capability provided by advanced materials development and aggressive cooling reduction will further enhance fuel burn reduction potential.

3.4.10.2 Benefits

The geared turbofan contributes to meeting all three ERA goals. Next generation combustor technology will reduce LTO NOx emissions. The low pressure ratio fan combined with low noise features will reduce noise. Numerous technologies targeting development of a high OPR core, along with the inherently more efficient GTF low spool, will collectively improve fuel burn performance.

3.4.10.3 Risks

If the high OPR core technologies do not achieve the performance estimated for the PSC, the ERA goal for fuel burn reduction may be missed. If next generation combustor technologies do not achieve the estimated performance, the ERA goal for reducing LTO NOx emissions will not be met. If low spool technologies do not achieve predicted noise reduction, the ERA noise reduction goal will not be met.

3.4.10.4 Development Tasks

Early development must begin now to attain needed progress towards TRL 6 in 2020. With some work being accomplished on low spool technologies in existing programs, special focus should be paid to the enabling core technologies to achieve higher OPR as a driver towards enhanced fuel burn metrics. This near term focus is driven by higher risk in these components (HPC, combustor, HPT) as the parts get significantly hotter and smaller in the advanced architectures needed to enable true UHB propulsion system potential. Continued cooperation between NASA, Pratt & Whitney, and Boeing will enable technology insertion into a spiral technology flight of the STV that can demonstrate all three NASA ERA goals.

The milestones coinciding with increments in TRL are described in Table 75.

Table 75: Geared Turbofan Development Milestones

Milestone	TRL	Description
Current	2	Concepts have been generated but analysis or basic testing is not complete for some technologies
Analysis	3	Design and analysis performed on key components Basic testing performed for some technologies
Component Test	4	Basic tests completed on representative components
Engine Test	5	Key components tested in representative conditions Engine tested on the ground
Flight Test	6	Integrated system tested in flight

3.4.11 Open Rotor

3.4.11.1 Description

The open rotor (OR) architecture proposed by Rolls-Royce LibertyWorks incorporates a unique suite of technology features and is believed to offer unsurpassed fuel burn efficiency and reduced emissions. The combination of an open rotor integrated with the BWB platform may simultaneously meet the aggressive noise target established in the ERA goals. Critical technologies such as Variable-Pitch OR Blades, Super-Hydrophobic Anti-Ice Coating and Tapered Roller Blade Support are considered key enablers for meeting NASA ERA goals.

Applicable Versatile Affordable Advanced Turbine Engines (VAATE) and Highly Efficient Embedded Turbine Engine (HEETE) technologies for enabling a high overall pressure ratio (OPR) core are needed to achieve fuel burn reduction, combined with contra-rotating open rotor technology development already underway. Advanced cycle technologies focus on core system improvements to reduce specific fuel consumption (SFC), through higher pressures and temperatures with lower cooling and fan/low pressure system improvements. Noise is improved with higher bypass ratio while fan system weight is reduced.

Ongoing efforts with NASA and the Federal Aviation Administration (FAA) Continuous Lower Energy, Emissions, and Noise (CLEEN) project are advancing combustor and low spool technology for improved emissions and noise. These advancements will be directly applicable to the ERA N+2 configuration. Critical technologies that are envisioned to be the focus of immediate investment for ERA are centered on the core technologies enabling high overall pressure ratio.

3.4.11.2 Benefits

The critical open rotor technologies contribute to meeting all three ERA goals. The reduced tip-speed, contoured rotor design and noise shielding installation on the BWB platform feature will reduce overall noise. Advanced core technologies enable a higher OPR and T41 (takeoff turbine rotor inlet temperature), which also result in a higher bypass ratio and reduced cruise SFC. Advanced combustor technology will reduce LTO NOx emissions.

3.4.11.3 Risks

If the rotor and high OPR core technologies do not achieve the performance estimated for the PSC, the ERA goal for fuel burn reduction may be missed. If the advanced combustor technologies do not achieve the estimated performance, the ERA goal for reducing LTO NOx emissions will not be met. If the rotor (LP spool) technologies do not achieve predicted noise reduction, the ERA noise reduction goal will not be met.

3.4.11.4 Development Tasks

Concurrent development is needed to progress towards TRL 6 in 2020. Some initial open rotor technologies are currently under study on existing programs, along with enabling core technologies to achieve higher OPR, as a driver towards enhanced fuel burn metrics. Near term focus is driven by higher risk in these components: OR, HPC, combustor, and HPT. While the OR component needs development because it is relatively new, development of the engine core components is also needed as the parts operate significantly hotter and are physically smaller for the advanced architectures needed to enable true open rotor propulsion system potential. Continued cooperation between NASA, Rolls-Royce LibertyWorks, and Boeing could enable technology insertion into a spiral technology flight of the STV that can demonstrate all three NASA ERA goals with.

The milestones coinciding with increments in TRL are described in Table 76.

Table 76: Open Rotor Development Milestones

Milestone	TRL	Description
Current	2	Concepts have been generated but analysis or basic testing is not complete for some technologies
Analysis	3	Design and analysis performed on key components Basic testing performed for some technologies
Component Test	4	Basic tests completed on representative components
Engine Test	5	Key components tested in representative conditions Engine tested on the ground
Flight Test	6	Integrated system tested in flight

3.5 Schedule

A schedule for technology maturation was developed and is presented in this section. The entire schedule to reach technology readiness of the PSC is shown; however, the tasks pertaining to Option 2 occur from January 2012 through May 2014.

January 2012 is assumed to be the start for initial time-critical tasks. The period from January 2012 through September 2012 is referred to as the feasibility study. Preliminary design is assumed to start in October 2012. The layout of tasks in the schedule supports a preliminary design review (PDR) in May 2014, which closes the preliminary design phase.

A conceptual roadmap for the early portion of the technology plan is illustrated in Figure 128.

Four phases are indicated in the background: feasibility study, preliminary design, detailed design, and post detailed design.

Top-level tasks are indicated in boxes. The placement of the boxes over the phases is significant in terms of indicating whether some portion of the task will be performed in that phase. All the tasks that start in the feasibility study will carry on into preliminary design. The Structures Subassembly task will run from the feasibility study through part of detailed design. The Initial STV Simulation and STV Propulsion Validation tasks carry over from preliminary design into detailed design. The STV Simulation task carries over from detailed design into post detailed design.

The color of the task boxes indicates whether the task will be working with generic BWB configurations (yellow), the initial STV configuration (green), or the final STV configuration (blue). Most of the initial work will be with generic BWB configurations. The Initial Aero Design task will develop the initial STV configuration, which will then be used in downstream tasks. The Final Aero Design task will develop the final STV configuration, which will be used in the remainder of the program.

The borders around the task boxes indicate whether the task is strictly demonstrator development (green), technology development that is outside the usual development for a demonstrator (blue), or demonstrator development that addresses technology development (dashed blue).

The conceptual roadmap clearly shows that the Initial Aero Design task needs to start promptly because many tasks are dependent on it. The Structures Subassembly task needs to start promptly because of its long duration will eventually make it schedule-critical. The importance of the other three feasibility study tasks is not as clear in the figure, but the knowledge gained from these tasks is expected to influence the initial design of the STV. The BWB 450-1L Simulation task will affect sizing, placement, and design of the control surfaces. The Propulsion Analysis task is likely to affect the aerodynamic shape of the configuration ahead of the engines. The Acoustic Analysis task is likely to affect design of the leading-edge device, arrangement of the engines and tails, and shaping of the underbody (for landing gear noise). The transfer of this information is not shown explicitly in the figure, but it is a key reason for including these tasks in the feasibility study.

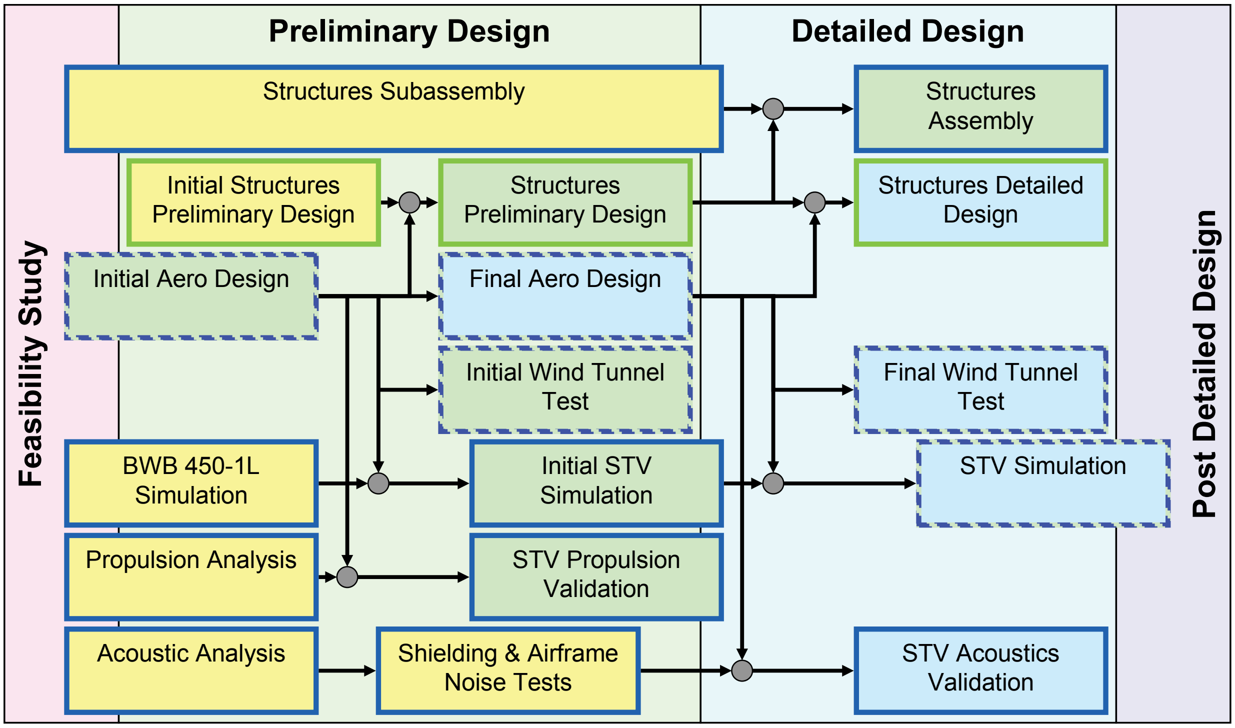


Figure 128: Conceptual Technology Roadmap

Figure 129 gives a summary of the overall technology maturation plan. The program milestones line shows the critical program milestones as envisioned at the start of this study. The projected milestones line shows the critical program milestones after development of the technology maturation plan.

The feasibility study is expected to start at the Risk Reduction Start milestone at the beginning of 2012. Preliminary design of the STV would start in October 2012. The STV Preliminary Design Review (PDR) would occur in May 2014, after wind tunnel testing of the initial STV design (Initial WTT under BWB Aerodynamics) and generation of the final STV aerodynamic design (Final Design under BWB Aerodynamics).

Between the STV PDR and the STV Critical Design Review (CDR), several key evaluations will be completed to show the STV is mature enough to be built. Engine operability of the initial STV configuration will be validated in wind tunnel testing (STV Validation under BWB Propulsion). Piloted simulation of the initial STV configuration will establish technical readiness of the STV flight controls (Initial STV Simulation under BWB SC, FC, & FQ). Wind tunnel testing of the final STV configuration will be complete (Final WTT under BWB Aerodynamics). Subassembly testing to establish technical readiness of PRSEUS and provide data for detailed design will complete mid-way through detailed design (STV Subassembly for CDR under BWB Structures). Following completion of the subassembly testing, there will be about a year of dedicated structural detailed design (STV Detailed Design under BWB Structures) that will pace the STV Critical Design Review. Acoustic wind tunnel testing of the final STV configuration will complete just before the STV CDR (STV Test under Acoustics).

Piloted simulation of the final STV configuration will complete after the STV CDR. Structural test articles for at least initial versions of the STV fuselage and wing will be built and ground tested to failure (STV Assembly under BWB Structures). While testing to failure is not necessary to fly the STV, it is considered necessary to prove technical aspects of BWB structures. Construction of the complete STV airframe is expected shortly after the structural ground tests (STV Airframe under BWB Structures and STV Assembled under Projected Milestones).

Following assembly of the STV, it is expected that a significant time will be spent in ground testing to prepare for STV first flight.

The PSC PDR and PSC CDR milestones under Projected Milestones represent the latest dates that would reasonably support a 2025 Entry into Service (EIS) or Initial Operational Capability (IOC). With STV First Flight less than a year before the PSC PDR, it appears that it is possible to demonstrate technical readiness in time to make an EMD decision that will support having the technology in service in 2025. The schedule leaves little room for delays, so it is likely that the PSC and its technologies will enter service somewhat later than 2025.

Laminar flow and Advanced PRSEUS technologies were arbitrarily scheduled to start after the STV CDR. These technologies are not critical for the STV, and the chosen start date merely reflected the notion that there would be available engineering resources following the completion of detailed design. The end dates for these technology development activities fall after the PSC PDR, meaning they do not achieve technology readiness by that PDR on this schedule; however, these technology activities could be started earlier to meet the desired technology readiness date. The shift in start times has not been made because the technology plan cost was developed to the schedule presented here. The desired adjustments should be made in future updates to the technology maturation plan.

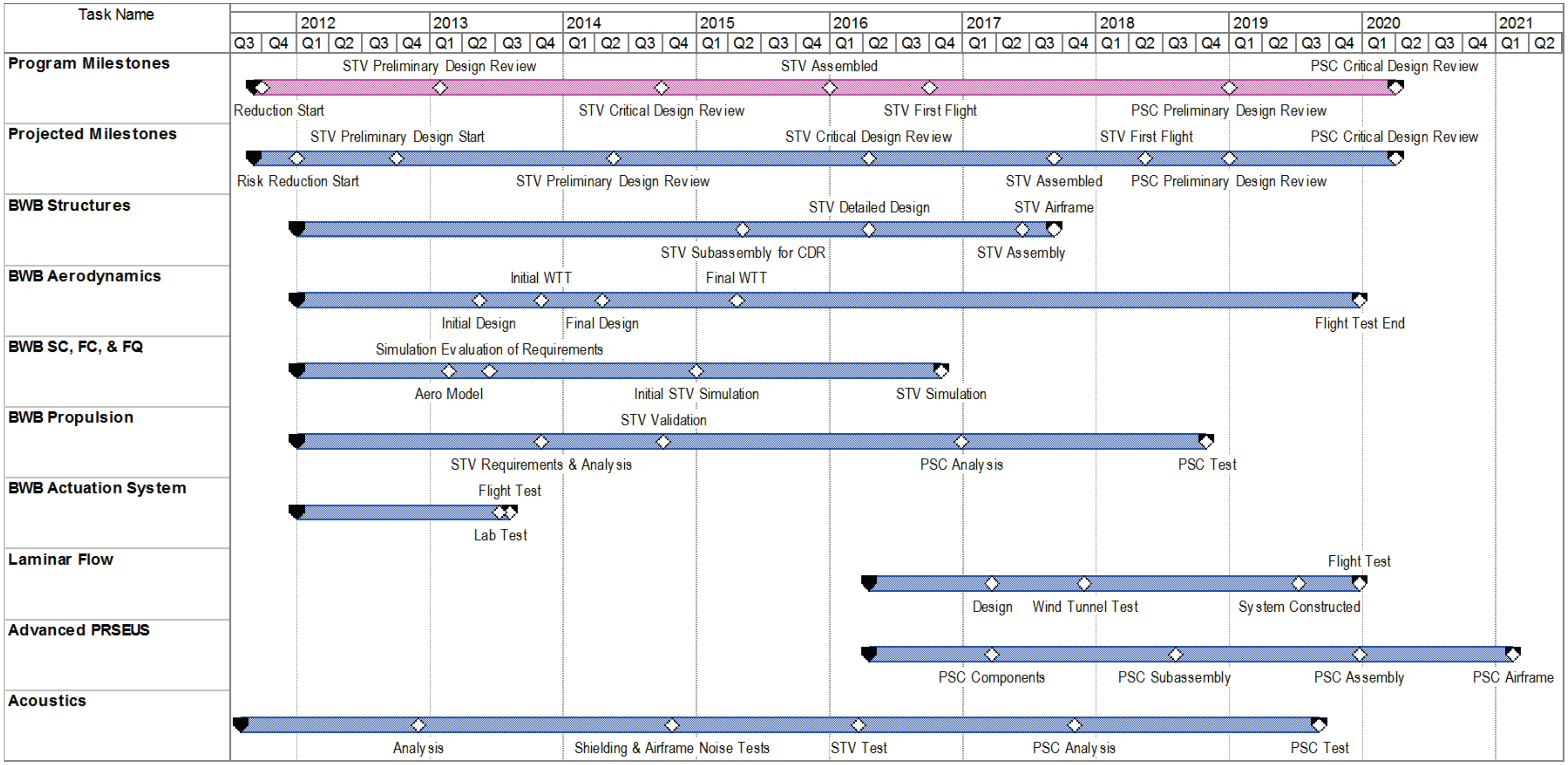


Figure 129: Technology Roadmap

3.6 Conclusions

The PSC relies on a significant amount of technology development to achieve the ERA goals. Much of this development is associated with maturing the BWB configuration, which itself is a new technology. Development of the BWB configuration is divided into five enabling technology areas: structures, aerodynamics, propulsion, flight controls (including stability & control and flying qualities), and actuation system. Beyond the BWB-enabling work, PSC performance will be enhanced by work in three additional airframe-related technology areas: acoustics, PRSEUS composites, and laminar flow. Engine technology is also needed to reach the ERA goals.

Technology maturation plans were developed for the identified airframe-related technology areas. These plans were built to achieve technology readiness sufficient to authorize EMD or the equivalent commercial aircraft development process for a program to produce the PSC. The decision to start EMD requires critical technologies to be matured to TRL 6, which will require flight test of a demonstrator aircraft for most of the technology areas. The STV provides the means for maturing technologies to TRL 6. The STV will also become the focus for near-term technology development as its design is heavily integrated with technology activities.

In each technology area, a series of tasks was defined to reach TRL 6 as well as intermediate TRL milestones (TRL 3 through 5). The AFRL transition readiness level calculator was used as a guide to determine the tasks that need to be completed for achieving TRL milestones. Descriptions of these tasks were developed and are presented in this document (with near-term tasks described in greater detail than far-term tasks).

Benefits of the PSC were evaluated assuming successful development of all the identified technology areas. That assumption introduces the risk of missing PSC performance estimates or ERA goals if technology development does not yield the expected performance.

With each technology area, risks were identified and a risk assessment was performed. The assessment included the current level of risk as well as the expected progression of risk as TRL milestones are achieved. The technology areas typically have risks that start high and end low following successful test on the STV. The notable exception is for structures, where development of Advanced PRSEUS composites continues past the STV. Risks for structures reduce to moderate on the STV and reach low on the PSC.

With estimates for task durations, an integrated schedule was developed. The schedule assumes some technology development activity starting in January 2012 with a full kickoff of technology development in October 2012, corresponding with the start of STV preliminary design. The technology development supports an STV PDR in May 2014, an STV CDR in April 2016, and STV first flight in May 2018. In order to achieve entry into service for a commercial aircraft or initial operational capability for a military aircraft in 2025, technology readiness is needed by December 2018. With STV first flight coming before the needed technology readiness date, it is possible that these ERA technologies could be fielded by the desired 2025 date. With little room in the schedule for delays, it is more likely that the PSC and its technologies will enter service somewhat later than 2025.

PRSEUS development was split into two parts to allow the STV to be built with current PRSEUS technology while necessary improvements are made on Advanced PRSEUS for the production PSC. This division allows technology readiness to be achieved by the desired date, but it results in additional effort and cost as some of the work needed to mature current PRSEUS will have to be repeated for Advanced PRSEUS. A lower-cost approach would defer entry into service for the PSC in order to develop Advanced PRSEUS on the STV.

The benefits of selected technologies were quantified by evaluating and sizing the PSC with a few different technology combinations. The BWB-enabling technologies were evaluated as a group, with their collective benefit described as the benefit of the BWB configuration.

The BWB configuration and advanced composite structure provide a 32% reduction in fuel burn. The geared turbofan provides 23%. Laminar flow and riblets provide 9%. When combined, these three components cause the PSC to provide a 52% fuel burn reduction relative to the 1998 baseline. Although there is some margin over the 50% fuel burn reduction goal, there is not enough margin to back off on technology development. Removing any of the three components will cause the fuel burn goal to be missed.

For noise reduction, 1998-technology aircraft already provide 11 dB cumulative EPNL below Stage 4. The geared turbofan provides an additional 18 dB reduction. The BWB configuration with acoustic shielding provides an additional 5 dB reduction. Potential acoustic treatments for BWB airframe noise could provide an additional 8 dB reduction (nominally 5 dB from landing gear noise and 3 dB from leading-edge device noise). These components can combine to reach the ERA goal of 42 dB cumulative EPNL below Stage 4.

The PSC achieves the ERA goals, but it requires successful development in all its supporting technology areas. Very little technology can be left out without affecting the ability to reach these goals.

The plan for maturing technologies for the PSC is large in scope, maturing a new vehicle configuration (the BWB), a new material system (PRSEUS), and multiple supporting technologies. The plan also supports technology development to the high level of readiness needed to support a decision to go forward with a commercial or military product. Executing the plan has the potential to enable a production PSC that can realize the benefits of the ERA goals.

4 Subscale Testbed Vehicle

4.1 Introduction

This section presents the development of the Subscale Testbed Vehicle (STV), shown below as an artist's concept at NASA Dryden (Figure 130). It describes the requirements, design mission profiles, and ConOps; and shows how the STV design meets them. Later subsections discuss the plans for the next development phase of the STV – preliminary design and the associated ground testing to address identified potential risks.

Figure 130 Artist Concept of Boeing's STV

4.2 Systems Engineering

4.2.1 Requirements

The driving requirements for the STV and Boeing's design to meet them are:

- *Demonstrate at a subscale level the integrated key enabling technologies to simultaneously meet the N+2 goals and EIS of 2025. Provide quantitative evidence that the N+2 goals can be met by the PSC.*

  The STV design incorporates all key PSC technologies: scaled PSC BWB configuration with fuselage verticals and engine location for maximum noise shielding, advanced turbofan engines, advanced PRSEUS fuselage structure, incorporates HLFC and riblets.

- *Sufficient scale to demonstrate aerodynamic efficiency and support current noise reduction methodology (minimum 50%).*

65% scale of PSC with minimum OML mod to accommodate crew. Analysis shows this scale is large enough to match cruise aero and airport noise flight conditions

- *Flight envelope and cruise Mach number matches that of the PSC*

  PSC cruise Mach is 0.85. The STV matches PSC flight envelope (altitude, Mach, load factor, maneuvers)

- *Vehicle design allows for insertion of developing technology and avionics that will enable routine operation of UAS in the NAS (capable of operation in piloted, remotely piloted, and fully autonomous modes).*

  Digital flight control and mission manager provides functional flexibility. Ample internal volume provided by the BWB configuration

- *2 pilots, pressurized cargo area*

  Business jet-like cockpit. PRSEUS provides weight-efficient pressurized structure

- *Provide a flexible test bed for future flight test campaigns.*

  Modular structural concept for wings, tails, and unpressurized aft fuselage

- *digital research flight control system capability for assessing advanced flight control laws*

  Triplex basic digital flight control system with partitioned research control laws provides flight investigations with automatic or manual return to primary control. Hardware based on Boeing research FCCs provide flexibility to make software changes rapidly.

- *Capable of traveling between all city pairs in lower 48 with design payload, using 100 busiest airports in US. Minimum 3 hour endurance.*

  STV has sufficient field performance and fuel to carry a representative payload between any city pair. Payload weight is scaled from the PSC and loaded in standard LD3 containers.

- *Capable of performing extended simulated airline or cargo service (all weather operations)*

  Requires all weather capability, durable structure, cargo capability, and reliable subsystems. These are provided by advanced PRSEUS with lightning protection, container handling doors and floor, off-the-shelf airliner components, redundant systems, anti-icing.

- *20-year and 10,000-hour projected useful life.*

Provided by durable advanced PRSEUS, selection of commonly available and supported components

A DRAFT STV requirements document has been released. It represents a flow down of NASA's top level requirements and objectives for the STV as provided initially in Appendix D "Integrated Systems Research Program" of the NASA Research Announcement, Reference 15, and modified during the advanced vehicle concept study (Reference 16). The starting point top level requirements are listed in Appendix D of this report below.

The requirements document defines functional and performance requirements for the ERA/UAS subscale testbed vehicle system and verification methods (inspection, test, demonstration, analysis) for each requirement.

4.2.2 Design Reference Mission

The details of the STV design reference mission are described in a preliminary version of the STV Design Reference Flight Mission (Task 5b). This document defines the reference flight missions and envelopes that the ERA/UAS subscale testbed vehicle has been designed for. It describes the test article (the STV), the vehicle flight envelope, and the flight test objectives.

Three types of missions are envisioned: a manned (piloted) mission, a remotely controlled (remotely piloted) mission, and an autonomous mission. The piloted mission consists of two sub-missions: a flight test mission to verify STV technical and functional performance, and demonstration mission to demonstrate the capabilities of STV and compatibility with National Airspace System (NAS) Air Traffic Control system.

The remotely piloted and autonomous missions are to verify the technologies and systems associated with operating an Unmanned Aircraft System (UAS) and it will follow the same incremental capability buildup approached as piloted mission.

4.2.3 Concept of Operations

The concept of operations for the STV is described in a preliminary version of the STV Concept of Operations (Task 5c). This document defines the operational concept for the ERA/UAS Subscale Testbed Vehicle (STV) throughout the lifecycle of the system. The purpose of this document is to define the operational concept that the ERA/UAS subscale testbed vehicle will be operated under throughout its lifetime. It describes the Concept of Operation (ConOps) from the start of manufacture, ground test, flight test operation, and modification to incorporate advanced technologies.

The ConOps document describes manned, remotely piloted or autonomous operations, including operations for UAS integration into the NAS operations including the option to operate with an on-board safety pilot. It also describes the proposed assembly location vs. first flight location and transportation between those sites; vehicle modularity for future technology spirals; level of software and hardware V&V required; and operational contingencies for off nominal vehicle behavior, etc.

ConOps flight operation of the STV is divided into piloted, remote piloted, and autonomous ops. The majority of flights will be with a pilot on board, including flights to demonstrate remote and autonomous operation of the STV.

The initial flights will be piloted. These will complete flight test blocks in a build-up fashion:

- High speed taxi and first flight
- Airworthiness & functional checkout
- Envelope clearance (Mach, altitude, maneuver, load factor, dynamic pressure, flutter)
- N+2 technology development and validation
- Demonstration flights of extended simulated cargo service
- UAS in the NAS
- Technology spirals

The objective of the N+2 technology development and validation flight testing is to validate the analysis methods used to predict the performance of the PSC. It is important to conduct the tests of the STV at flight conditions that are as representative of the PSC. Appendix A discusses the selection of the geometric scale of the STV in relation to its ability to match the PSC for different performance metrics of interest.

Cruise performance testing

The STV is designed to validate cruise performance predictions for the PSC by matching cruise CL and Mach. This is first accomplished by selection of a configuration that closely matches the PSC OML. The STV has only modest changes to the forebody to accommodate non-scalable crew, and nacelles to accommodate available engines. Next is selection of a scale that allows approximation of the aerodynamics of the PSC at cruise. This is accomplished by the 65% scale STV with heavy-weight flights, using ballast, possibly with increased altitude or small load factor. With the aerodynamics approximating the PSC, calibrated engines will allow measurement of the airframe drag from flight data.

High speed flying qualities testing

The dynamic Mach scaling relations discussed in Appendix A show that the 65% STV with its design weight range, can match the full scale PSC handling qualities conditions by conducting the tests at a modest load factor.

Low speed flying qualities and acoustics testing

Appendix A discusses the ability of the STV to match characteristic conditions of the full scale PSC. The 65% scaled STV thrust requirements for both the acoustics and the terminal area handling qualities experiments fall within the maximum thrust capability of the SGTF1775 engine. The Scaled OEW for acoustics testing is within the STV weight range, so acoustics experiments can be conducted at conditions representing the entire PSC weight range. The scaled OEW for the terminal area handling qualities experiment is outside the allowable weight range for the STV, but this is not a major issue. Tests can be conducted at higher weights, and the results correlated to simulator experiments. The simulator can be used to assess handling qualities at lighter weights.

Acoustic performance testing

Mach number and flow velocity are primary driving parameters in acoustic measurements. Also, a relatively large scale is needed for Strouhal scaling with atmospheric attenuation for acoustics. The 65% scale STV operated at high weight will allow matching of the aircraft velocity and thrust velocities to those of the PSC.

The STV provides the best opportunity to demonstrate all elements of the PSC acoustic design that would enable it to achieve the lowest certification noise levels of any aircraft of its class.

Noise certification of all production aircraft includes static engine calibration noise testing followed by a comprehensive acoustic flight test program for the production aircraft with the calibrated engines installed. Derivative aircraft in the same "family" of aircraft and engine may be certified for noise by analysis. Static-to-flight correction adjustments derived from the parent aircraft / engine data are applied to the static engine test data of the derivative engine. All of these testing techniques can be applied to the STV as well; however, an additional scaling factor may be required to infer what the PSC noise certification levels would be.

Typically static engine noise testing is carried out on an engine test stand located in the center of a 150' polar arc with a microphone mounted on 4' poles and another flush-mounted on a ground board in 10 degree increments from 0 to 180 degrees. Flight testing includes similar certification ground and pole microphones located at the approach, sideline, and takeoff locations on the ground directly under and to the side of the flight path. Recent flight tests have also included a phased array system of microphones. Such a system involves hundreds if not thousands of low cost microphones typically located under the flight path where the aircraft is 200' above the ground. This data is useful for determining the specific location of dominant noise sources at the various flight conditions.

As aircraft noise research has driven the certification noise levels down, noise at conditions other than certification have become increasingly important. As an example, approach noise further from the airport and the impact of quiet procedures such as continuous descent delayed deceleration, and flap and landing gear deployment have required additional noise testing. Enroute noise is also a concern, but more so for open rotor engine designs.

Another noise testing technique has been developed where microphone arrays are hung from construction cranes. The test aircraft is flown between the cranes and the noise measurements are used to analyze shielding and atmospheric effects at various aircraft speeds and power settings with clean wing and other flap deflection configurations, with and without landing gear and speed brakes deployed.

The STV aircraft can also serve as test bed platform to evaluate or validate noise reduction technologies such as low noise landing gears, advanced slat systems, or even different propulsion systems such as the open rotor.

Such a comprehensive noise database of the STV would enable very accurate predictions of PSC noise levels with minimal risk.

Demonstration flights of extended simulated cargo service

Objective is to demonstrate robustness of the technologies under operational conditions and schedules. These flights will expose operation of the STV to the effects of weather, long range flight, and time constraints. This phase is a stress test of the design implementation of the PSC technologies.

UAS Ops in the NAS

An important second objective is that the STV serve as a testbed and demonstrator of capabilities and technologies to enable routine UAS operations in the NAS. The capability of operation in piloted, remotely piloted, and fully autonomous modes is important because with a safety pilot on board the STV can perform a rapid build-up of autonomous operations. The pilot can establish conditions and turn over operations to the autonomous function. He then serves as a safety pilot should the aircraft need to abort the test point and return to piloted operations. This reflects the basic flight test philosophy of safely expanding the flight envelope by always having the ability to quickly return to a previously cleared condition – in this case, piloted control of the aircraft.

4.3 System Integration

The STV is a blended wing body configuration powered by two advanced turbofan engines designed to validate the technologies and design methods for the N+2 PSC. Figure 131 shows the dimensions of the STV and component geometry.

The STV represents a subscale version of Boeing's N+2 Preferred System Concept (PSC) Vehicle designed to meet the requirements of NASA Environmentally Responsible Aviation Program. Figure 132 and Figure 133 is a size comparison between PSC, STV, and 737-800.

The secondary objective for the STV is to demonstrate technologies required to operate as an UAS in the National Airspace System (NAS). The STV will have the ability to operate in piloted, remotely piloted, or autonomous modes but for safety, a pilot will be onboard when STV is operating in the UAS mode.

A third objective is to provide a flexible testbed for future technology development. The STV modular design will facilitate replacement/incorporation of structural components and subsystems to support these spiral experiments.

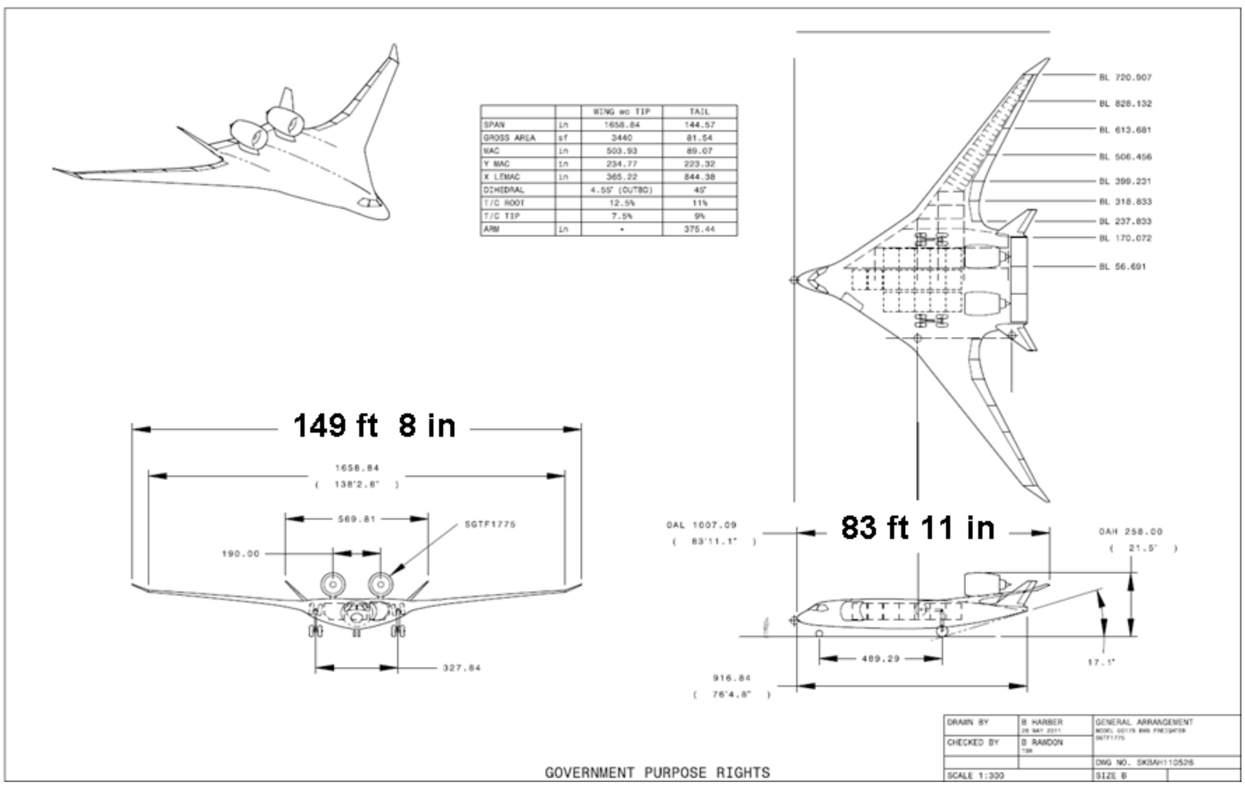


Figure 131 STV 3-View

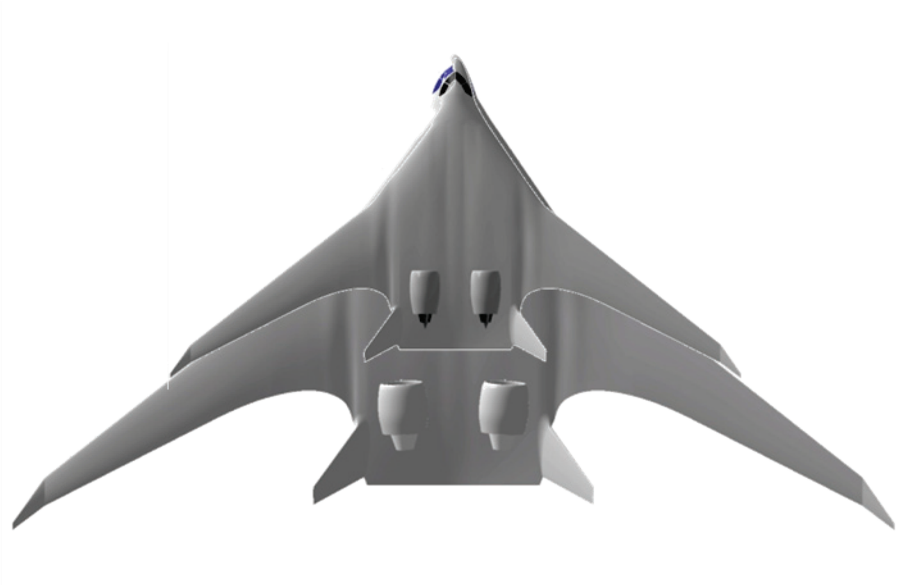


Figure 132 External Comparison, STV and PSC

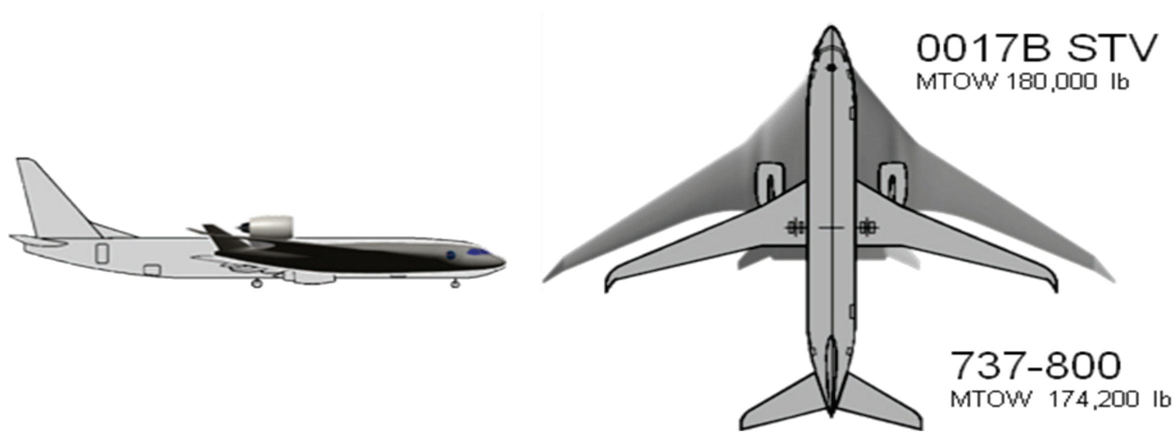


Figure 133 STV Comparison to Existing Aircraft

4.3.1 Configuration

4.3.1.1 Payload Volume

The design payload volume was determined by the vehicle fuselage outer mold line (OML), a 65% scale of the Preferred System Concept OML, internal structure, and the use of standard cargo containers.

4.3.1.2 Payload Weight

The design payload weight of 27,500 lbs was computed from the design payload of the PSC cargo aircraft (100,000lbs), ratio by the cube of the scale (65%). The 27,500 payload carried in 13 LD3 containers with a density of 12.5 lbs/cu-ft.

4.3.1.3 Similarity Ratios and Scaling

Large vehicle scale is essential to properly verify technology readiness of the BWB concept. The square/cube law implies that the structure must be near full-scale to be representative. For aerodynamic and flight mechanic research, achievement of Mach scaling and dynamic scaling with the same airplane requires near full-scale. Large scale is needed for Strouhal scaling with atmospheric attenuation for acoustics. Finally, the design, fabrication and flight test of a large scale manned demonstrator will identify and resolve the many “unknown unknowns” of the BWB concept. This will enable the industry to proceed with confidence to a production program of a BWB subsonic transport.

Choosing the vehicle scale factor is the most important of the conceptual design trade studies. The only way that a test-bed vehicle can match all relevant experiment parameters is if it were built full scale. This is probably cost prohibitive, so subscale vehicle testing is used. Unfortunately, this requires compromising some of the relevant experiment parameters. The goal is to strike the correct balance between cost and creating a relevant flight environment for the experiments.

Scale selection was based on considerations of

- Static Mach Scaling
- Dynamic Mach Scaling
- Conventional Dynamic Scaling
- Available off-the-shelf-engines

Using considerations anchored to available off-the-shelf-engines, Boeing has selected a 65% scale for the STV.

4.3.2 Aerodynamics

4.3.2.1 Aerodynamic Design

The STV is derived from a simple linear scaling of the preferred system concept (PSC). As such the following section outlines the aerodynamic design process used to develop the PSC. Details of the PSC design can be found in the PSC section of this report. While the final loft is not of “wind tunnel” quality, it is sufficient to provide the performance basis for the purposes of this study. The envisioned process is to refine the configuration during the preliminary design phase.

The aerodynamic design process consists of adjusting the airfoils, sweep and chord distribution of a preliminary concept provided by the configuration designer while respecting the payload envelope, including structural margin. Key objectives of this process are to maximize the cruise lift-to-drag ratio (L/D); maintain the center-of-pressure at the center-of-gravity; strive for a small wing area; delay cruise pitch-up (i.e. buffet onset) to beyond the operational lift coefficient (provide a minimum of 1.30 g's to buffet onset), and maintain sufficient clean wing, low speed C_{Lmax} to assure adequate take-off, climb and landing performance with the addition of a leading edge flap. L/D is the primary measure of merit for the designer – this has a direct impact on fuel consumption. A small wing area directly reduces airplane weight and drag force. This provides additional savings in propulsion and fuel weight. During cruise, as the angle of attack and lift coefficient are increased, flow starts to separate in localized areas of the airplane. This typically tends to result in a progressive, destabilizing pitch up. The design is adjusted to make sure that this occurs at lift coefficients well above those of operational interest.

The primary computational fluid dynamics (CFD) tool used for much of the previous BWB analysis is CFL3D. This is a Reynolds-averaged, thin-layer, Navier-Stokes flow solver for structured grids. Analysis and design work is done only on the wing-body. Wing tip treatments, such as raked tips, engine nacelles and pylons are not included in the analysis. Based on prior detailed experience, it is assumed that integration of these components can be made without significant disruption to the overall configuration of the airplane by localized surface modifications. An in-house optimization method is also used to arrive at a trimmed optimum design using on the order of 20 design variables including wing sweep, twist and camber. The resulting lines and pressure distributions are then "cleaned-up" using the NASA inverse design tool CDISC coupled to CFL3D.

The overall design of the PSC with respect to the driving aerodynamic considerations mentioned above is documented in the PSC section of this report. The CFD analysis of that configuration is the foundation of the following STV performance estimates of a 65% scaled PSC.

4.3.2.2 Performance Aerodynamics

STV aerodynamics was derived from the full scale PSC. Scaled effects to obtain the 65% configuration were used in the aerodynamic data for aircraft performance. High speed and low speed data were estimated for the STV configuration.

High speed aerodynamics characteristics for the total airplane drag and representative buffet boundary were estimated for the STV.

Technology improvements from the PSC are made available for the STV aerodynamic performance. HLFC was applied to the wing, tails, and nacelles. Riblets are assumed on non-HLFC surfaces..

4.3.3 Mass Properties

The STV is a 65% linear scale OML of the BWB PSC. Current planning requires the STV to approximate the PSC wing loading during performance flight test, therefore the Operating Weight Empty was sized for Maximum Takeoff Gross Weight (MTOGW). The STV fuel volume and a maximum payload weight were used to size the STV airframe.

A preliminary OEW center of gravity will be calculated using systems-level detail when the data is available. A preliminary loading envelope will be constructed using the calculated OEW CG.

- **Sizing Max TOGW scaled from BWB-0009A**
  - Vehicle sized by MTOGW
  - STV need to meet PSC wing loading for some test missions

- **maximum fuel capacity**
  - Based on internal arrangement
  - Additional ballast capability in fwd/aft body ballast tanks

- **27,500 lbs design mission payload**

– Payload volume determined by 65% scale of the Preferred System Concept OML - Cube of the scale (65%) applied to the design payload of the PSC cargo aircraft (100,000lbs),
– Payload carried in LD3 containers
– Container tare included in mission payload weight

- **maximum payload**
  – Max payload based on MTOGW and fuel

- **737-800 landing gear**

- **P&W PW1X24G Engine**

- **Slotted Krueger LE , no HLFC**

4.3.4 Propulsion

The propulsion modeling used for the STV is for the Pratt & Whitney PW1X24G. Pratt and Whitney provided a data matrix for thrust and fuel flow, and scaled dimensioned engine drawing and the propulsion system weight. All data were generated accounting for horsepower extraction off the high-spool and no compressor bleed extraction. Fuel flow levels represent 50 hour, new engine with typical conceptual engine study 50% confidence level component performance for technology levels consistent with entry into service of ~2014. Pratt & Whitney used an inlet recovery of 0.998 that is typical for wing mounted engines and consistent with the NASA funded cruise CFD studies on a BWB. The installation factors will be refined in the PD phase. This will be done consistent with the secondary power system architecture that is now currently planned to use pneumatics in order to use off the shelf systems.

4.3.5 Stability & Control

The BWB airplane design represents a departure from the configuration of conventional tube and wing transport aircraft. For traditional designs, the parts of the airplane that provide stability and control are largely segregated into the tails, which primarily provide stability, and the control surfaces, which primarily provide control. They perform these respective functions, but there is some coupling and crossover. Vertical tails on modern transports are primarily designed to provide enough rudder control authority to handle engine out control and crosswind landing. Providing Dutch roll stability is of secondary importance and augmented by the yaw damper system. All stability and control constraints must be evaluated and the tail sized large enough to meet both the minimum un-augmented stability requirements (for when the yaw damper fails) and to provide a large enough surface to hang a rudder of adequate control authority.

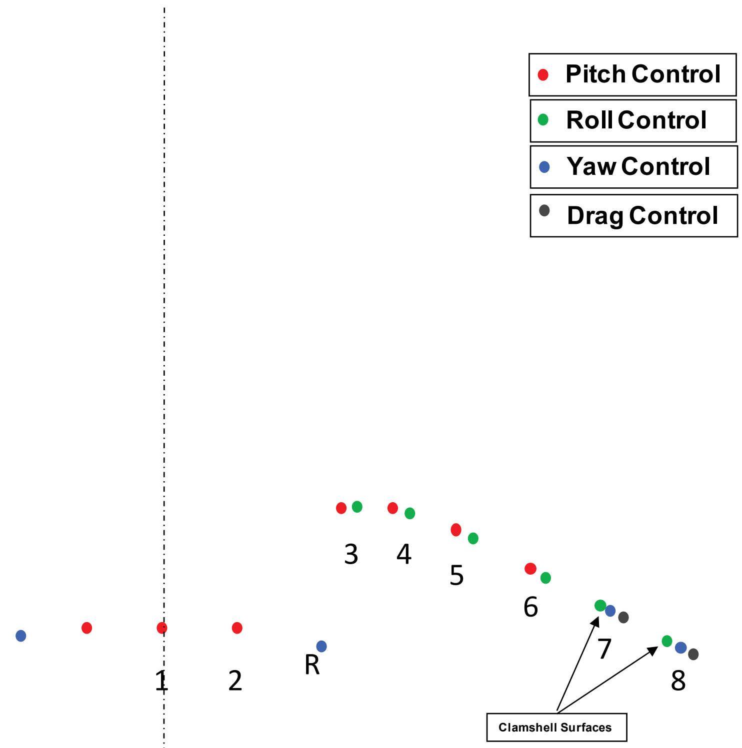


Figure 134 STV Aerodynamic Control Surfaces Allocation

The BWB is different in that all control surfaces (Figure 134) provide both stability and control in conjunction with the flight control system. The two issues can no longer be largely segregated. This makes the BWB a control configured vehicle. Complete evaluation of the stability of the airplane can only be accomplished after a flight control system is designed, simulated, and checked against control law robustness requirements. So, in the initial design phase, before all of this other engineering is accomplished, the stability and control engineer can only focus on control authority.

Adequate control authority is a necessary requirement for stabilizing a reduced stability or unstable system. Other items that are absolutely required in order to stabilize an unstable system are identifiability of the motion to be stabilized using appropriate sensors, well designed control algorithms to compute the corrections required, processing bandwidth to make the computations within an adequately short delay, and actuators to move the controls quickly enough to affect a response on the system.

Only the control authority of the BWB can be meaningfully evaluated during the initial design process. An implicit assumption is made that the rest of the flight control system can cope with any instability in the airplane without requiring too much additional control authority that would limit the ability of the airplane to perform critical maneuvers. In order to have adequate control authority to both perform critical maneuvers and to insure enough remains for stabilization, conservative assumptions and criteria are applied in evaluating the control authority.

Control authority analysis is broken down into longitudinal and lateral-directional. Each has its own set of requirements and is evaluated separately. Because BWB control surfaces are multi-axis, meaning they affect multiple vehicle axes when used, simplifying assumptions must be made about which surfaces are used for various tasks. For the STV control authority analysis, elevons 1 and 2 are used exclusively for pitch control. Elevons 3 through 6 are used for both pitch and roll control. These elevons are only used for pitch control for the critical nose wheel liftoff maneuver on takeoff. In flight, elevons 3 through 6 are only used for roll control. Elevons 7 and 8 are clamshell surfaces that have independent control of the upper and lower halves of each surface. This allows the upper and lower halves to be deflected together as conventional elevons or the upper and lower halves can be deflected in opposite directions to open up as clamshell drag rudders or speed brakes. So, elevons 7 and 8 are used for roll control, yaw control, drag control (speed brakes), and can be scheduled for pitch trim. The STV control authority analysis did not use elevons 7 and 8 for pitch control or trim. The rudders on the vertical tails are assumed to only be used for yaw control. There is a possibility that they can also be used for pitch control and trim at certain flight conditions, but for the critical pitch flight conditions that set the CG limits of the airplane these surfaces need to be reserved to handle simultaneous engine out or crosswind yaw control. So, the Rudders are not assumed to be available to help with critical pitch maneuvers. When the control allocator in the flight control laws is designed, it must provide at least the control authority in each axis that was assumed when the S&C control authority analysis was performed. In this area, the S&C engineers must work closely with the Flight Control engineers to make sure the above assumptions are not violated.

In the longitudinal axis, control is evaluated using a series of maneuvers to determine what center of gravity (CG) locations are allowable with the available control authority. Some of the maneuvers relate only to forward CG and the others only relate to aft CG. Below are summarized the longitudinal forward CG and aft CG requirements evaluated:

4.3.5.1 Forward CG

Takeoff nose wheel liftoff at 3.0 deg/s^2 pitch acceleration (nose-up longitudinal control authority)

Trim at Landing Reference Speed (V_{REF}) and maneuver to stall ($V_S = V_{REF}/1.23$) (nose-up longitudinal control authority)

Trim at Landing Reference Speed (V_{REF}) and go-around at 6.0 deg/s^2 pitch acceleration (nose-up longitudinal control authority)

Landing nose wheel hold-off down to stall speed (nose-up longitudinal control authority)

4.3.5.2 Aft CG

Takeoff nose wheel steering with >4.0% weight on nose gear (main landing gear placement)

Stall recovery at -4.0 deg/s^2 pitch acceleration (nose-down longitudinal control authority)

Experience with full scale BWB airplane simulations and actual flight testing of the X-48B has shown that this set of critical maneuvers defines a CG envelope in which a BWB can safely operate. Once all maneuvers are evaluated, the most restrictive set is used to define the allowable flight CG range. The airplane must be loaded within this CG envelope or it will not be able to perform all required maneuvers. If the fore/aft position of the main landing gear was adjusted to meet the aft CG nose wheel steering requirement, then this must be reported back to the Configuration group so that they can adjust the airplane drawings.

If the CG envelope becomes too restrictive for the desired payload and fuel loading ranges, then either the simplified control allocation assumed for the analysis needs to be adjusted, the takeoff and landing reference speeds need to be increased, or the pitch control surfaces need to be enlarged. The problem with adjusting the control allocation is that it may impact the ability to meet the lateral-directional control requirements. Increasing takeoff and landing reference speeds will increase takeoff and landing field lengths. Increasing control surface areas will increase weight, drag, and secondary power requirements. If the longitudinal S&C requirements are not met, then the project must choose the lesser of the above evils to fix the problem.

Longitudinal CG analysis was not specifically carried out for the STV. The PSC was analyzed for longitudinal CG limits and the STV will use the same CG limits as the PSC. The reason for this is to keep scaling similarity between the STV and the PSC so that STV results can be projected back to the PSC. If the STV mass properties do not line up within the PSC/STV CG limits, then ballast must be used to get the STV CG within the CG limits. This is the same approach that was successfully used on the X-48 flight test program.

The lateral-directional control requirements are evaluated at the most critical CG locations (usually aft CG), and therefore, cannot be evaluated until the longitudinal CG envelope is established. Below are summarized the lateral-directional control requirements:

4.3.5.3 Engine-Out Minimum Control Speed

Balance engine-out on ground with no sideslip and no nose wheel steering (yaw control authority at V_{MCG})

Balance engine-out in air with no sideslip and less than 5 degrees bank angle (yaw control authority at V_{MCA})

4.3.5.4 Crosswind Landing Trim

Trim in 35 knot crosswind with no crab angle at slowest approach speed (lightest weight)

4.3.5.5 Crosswind Landing Maneuver

A 6 degree heading (sideslip) change in 2 seconds at maximum wing fuel landing weight (yaw control authority). This requirement equates to TBD deg/s^2 yaw acceleration and TBD deg/s steady state yaw rate. The above TBD's will be determined during the 6 Degree-Of -Freedom (6 DOF) simulation to be performed in Option 2.

4.3.5.6 Landing Roll Maneuver

A 30 degree bank angle change in 2.5 seconds at maximum wing fuel landing weight (roll control power). This requirement equates to 20 deg/s^2 roll acceleration and 20 deg/s steady state roll rate.

Experience with full scale BWB airplane simulations and actual flight testing of the X-48B has shown that the engine out and crosswind landing trim requirements by themselves are only marginal for determining if a BWB can operate safely. These requirements do not provide enough control authority to simultaneously stabilize the yaw axis and provide enough control for these maneuvers. Experience has shown that the yaw axis of the BWB requires the most augmentation to provide desired stability. Because the control demands to provide this stabilization cannot be specified in the early design process, the crosswind landing maneuver requirement has been added. This maneuver endeavors to define enough control authority in yaw to make a quick heading change similar to what is required when the flight control system must correct for an upset in yaw. In addition, the engine-out in air requirement needs to be extended down to below the required V_{MCA} speed. It is known that the B-2 was designed for engine out capability down to the stall speed. This should be considered a target for design of the yaw control surfaces.

During critical multi-axis maneuvers such as engine out or crosswind landing, the inboard control surfaces will be busy handling pitch demands and the most outboard wing surfaces (split drag rudders) will be handling yaw demands. This only leaves the remaining mid-wing surfaces for use in roll. For normal flight with no crosswind or engine-out, the outboard wing surfaces can also be used for roll. But, the mid-wing surfaces need to provide the minimum roll maneuver requirement without the help of the outboard surfaces for the most critical maneuvers.

4.3.5.7 Vertical Tail Sizing

Explicit vertical tail sizing was not performed on the PSC or STV airplanes. The tails were sized to provide the same vertical tail volume as the X-48C - a BWB configuration -vertical tail. Explicit vertical tail sizing was performed on the X-48C (Figure 135) to provide somewhat more crosswind and engine out control margin than the X-48B. This is based on pilot comments that X-48B was somewhat deficient in yaw control authority, as described above. More detailed vertical tail sizing analysis will be performed on the STV when the project moves forward into the next design phase.

Figure 135 X-48B with Wing Tip Verticals and X-48C with Fuselage Verticals

4.3.5.8 Control Surface Hinge Moments

The BWB uses multiple surfaces on the wing and fuselage for maneuver and trim. The control utilization is very different from conventional tube and wing configurations, tending to require higher rates and deflections with more surfaces moving simultaneously.

In order to more accurately size the hydraulic system and the required power, a short analysis of hinge moments and control utilization was performed. Control surface hinge moments were estimated for the STV and provided to the hydraulic systems engineers for use in sizing the actuation system. These were then used to calculate the control system power required.

The resulting high power requirements confirmed that control system power management is an enabling technology for the BWB configuration. The STV will address this with a combination of control surface allocation and hinge moment reduction technologies such as tab assist and hydraulic spring. These will be investigated in the Option 2 preliminary design simulation and test program.

4.3.6 Acoustics

Assessment of system noise for unconventional aircraft, such as the BWB design, has to date, largely relied on empirical predictions of sub-component noise. This approach has been widely accepted for conventional T&W configurations. However, application of this methodology to unconventional aircraft has never been validated and demonstrated. As such, it is very important to have flight test demonstrations to validate the system noise prediction process, and hence, to demonstrate the feasibility and potential of achieving the NASA N+2 noise goal. The flight tests can be at reduced scales, but need to have all the essential acoustic features, such as realistic engines and high lift systems. The STV therefore provides this opportunity, serving as a reduced-scale testbed for validating the noise benefits and technology of the PSC.

The STV, like the PSC, will have high bypass ratio engines. The STV engines will be similar in design to the PSC engines. Also, the STV engines will be placed in relatively the same location as the PSC engines will be placed. Moreover, the overall airframe planform and high-lift system of the STV will be similar to the PSC. Thus, with much similarity, the STV will provide the opportunity to demonstrate and evaluate engine noise shielding capability, as well as airframe noise reduction technology, such as slat and gear noise reduction.

4.3.7 Performance

4.3.7.1 Mission Profile

The ERA contract specified a reference mission profile (Figure 136) for PSC performance and sizing. This mission profile specifies that all ranges are to be calculated in still air. Then there are three types of reserves. The first is a 5% block fuel allowance. This is intended to account for things like winds and ATC rerouting. Next there is a missed approach and 200 nm divert. This is to account for bad weather at the destination airport. Finally there is a 30 minute hold. This is to account for an ATC delay in the pattern. This mission profile is also appropriate for STV performance and sizing.

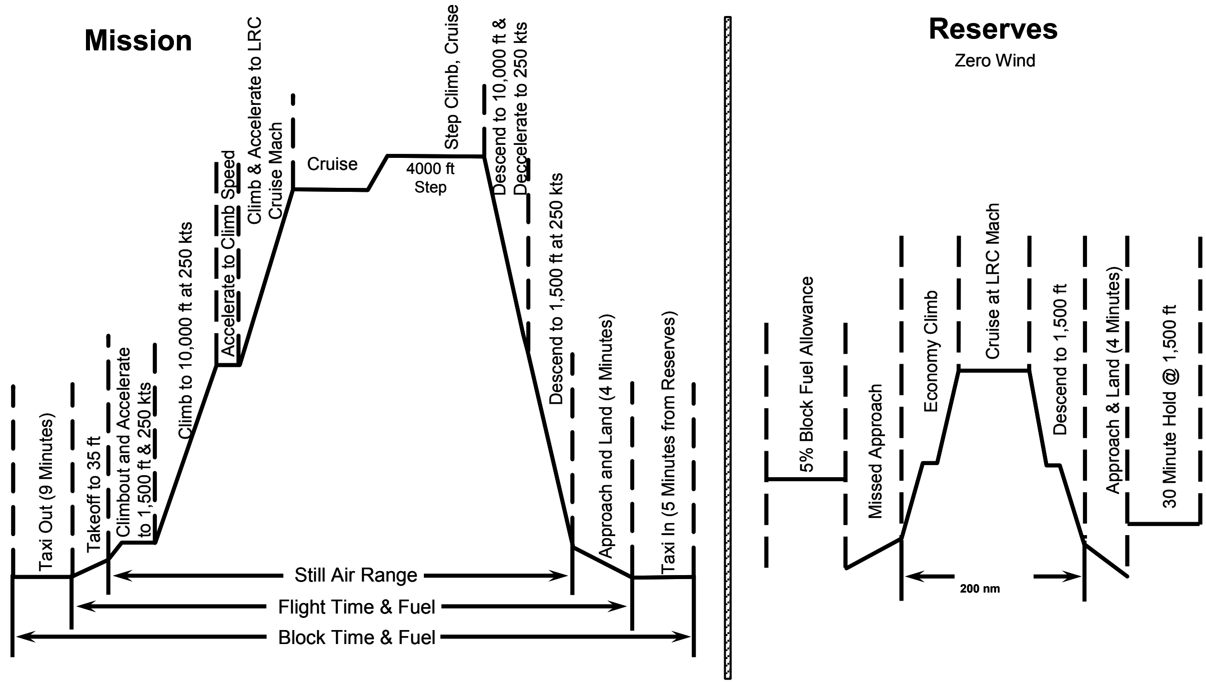


Figure 136 STV Mission Profile

4.3.7.1.1 Range and payload requirements

NASA desires for STV performance are:

- Capable of travelling between all city pairs in lower 48 with design payload, with 95% worst case winds
- Design payload to scale from PSC design payload with aircraft scale.
- Runway requirement: capable of using 100 busiest airports in US with design payload and fuel load capable of meeting the above range requirement with standard day conditions.

The longest city pair distance in the lower 48 is from Miami to Seattle, which is 2736 mi (2378 nm). This will be rounded up to 2400 nm for performance and fuel sizing. This range would assume no ATC rerouting. The payload requirement was derived from the PSC freight requirement of 100,000 lbs multiplied by the cube of the length scale factor (0.65^3). This comes out to 27,463 lbs and will be rounded up to 27,500 lbs for performance and sizing.

4.3.7.2 95% Worst Case Wind Assessment

To assess the 95% worst case wind requirement, world wind data was obtained from the National Center for Atmospheric Research (NCAR) database. This database contains winds from 1948 to 2004 at six hour intervals. Wind speeds can be obtained for 17 altitudes, every 2.5 degrees in latitude and longitude. Two altitudes (37,630 and 43,940 ft) were selected which are within the expected STV cruise altitudes.

Detailed analysis is in Appendix B of this report. In summary, if the head wind persisted throughout the flight (worst case), the range impact would be about 7%. However, a more likely scenario is that the effective head wind speed would be about 50% of the full head wind speed, the range impact would be about 3%. As stated above, the ERA reference mission includes a 5% block fuel allocation for the effect of winds. Boeing recommends that this allocation is sufficient, based on the above wind analysis.

4.3.7.3 STV Baseline Performance Summary

The STV has been sized for a 27,500 lb payload and sufficient fuel for a 2400 nm range (plus all reserves in the STV mission). For similarity with the PSC when doing testing, the STV must also have a maximum takeoff gross weight (MTOGW) high enough to match the PSC takeoff thrust to weight ratio (T/W) and wing loading (W/S).

Performance was analyzed for the STV at DTOGW and MTOGW using a P&W SGTF 1775 parametric engine deck that has not been scaled from the reference Sea Level static thrust of 22,860 lbs. The sizing requirements for takeoff are the same as for the PSC. In the top 100 airport evaluation a considerably shorter distance is required to meet the NASA desires. The STV takeoff performance is considerably better than the requirements. For landing there is no "required" distance. There is a desired distance of 5200 ft. The STV at DTOGW is close to this, but at MTOGW it is longer. At MTOGW, the range payload capability is considerably greater than the sizing requirements.

4.3.7.4 STV Comparison to Current Commercial Aircraft

4.3.7.4.1 Fuel Burn

The STV design mission is to carry 27,500 lbs payload 2400 nmi. Of existing commercial aircraft, the extended range version of the 737-600 comes nearest to matching the STV in performance. The design mission for the 737-600ER is 22,000 lbs payload and 3151 nmi. The range of the STV when carrying 22,000 lbs payload is 3163 nmi, nearly the same as the 737-600ER. For these missions, the STV burns 25% less fuel than the 737-600ER. The average cruise sfc accounts for approximately 14% of that difference.

4.3.7.4.2 Airport Noise

It is of interest to compare the STV to a similar class aircraft flying today to determine what level of noise reduction the STV might be able to demonstrate. Two members of the 737 family of aircraft that match up well to the STV are the 737-800 and 737-900ER. The performance data for the 737-800 are available from the FAA's Integrated Noise Model (INM) aircraft performance database, so this aircraft will be compared to the STV.

The analysis selected noise abatement departure and an arrival procedure performance data for each aircraft representative of normal airport operations. The performance and noise data were generated for the STV INM model.

Figure 137 is a noise footprint comparison of the STV, the 737-800, the MD-90 (the quietest current technology aircraft in its class), and the 737-800 (N+2) technology aircraft. In the NASA Subsonic Ultra Green Aircraft Research (SUGAR) project N+2 and N+3 levels of technology were evaluated. These denote two and three generations beyond the current transport fleet, respectively, which studied aircraft that might enter service out to the 2030 to 2035 time frame.[3] The STV is quieter than the MD-90 and 737 (N+2) technology aircraft on takeoff and as quiet on approach.

The 85 SEL noise contour areas for the STV is 1.5 square miles compared to 7.2, 3.0, and 3.0 for the 737-800, MD-90, and 737-800 (N+2), respectively. In other words the area enclosed in the 85 SEL noise contour of the STV is 80% smaller than that of the 737-800 and 50% smaller than that of the MD-90. This area is also half as much as that of a 737-800 (N+2) technology aircraft. The STV test-bed can also be used to demonstrate additional acoustic reduction technology such as low noise landing gears, advanced slat systems, engine and nacelle treatment improvements, or even different propulsion systems such as the open rotor.

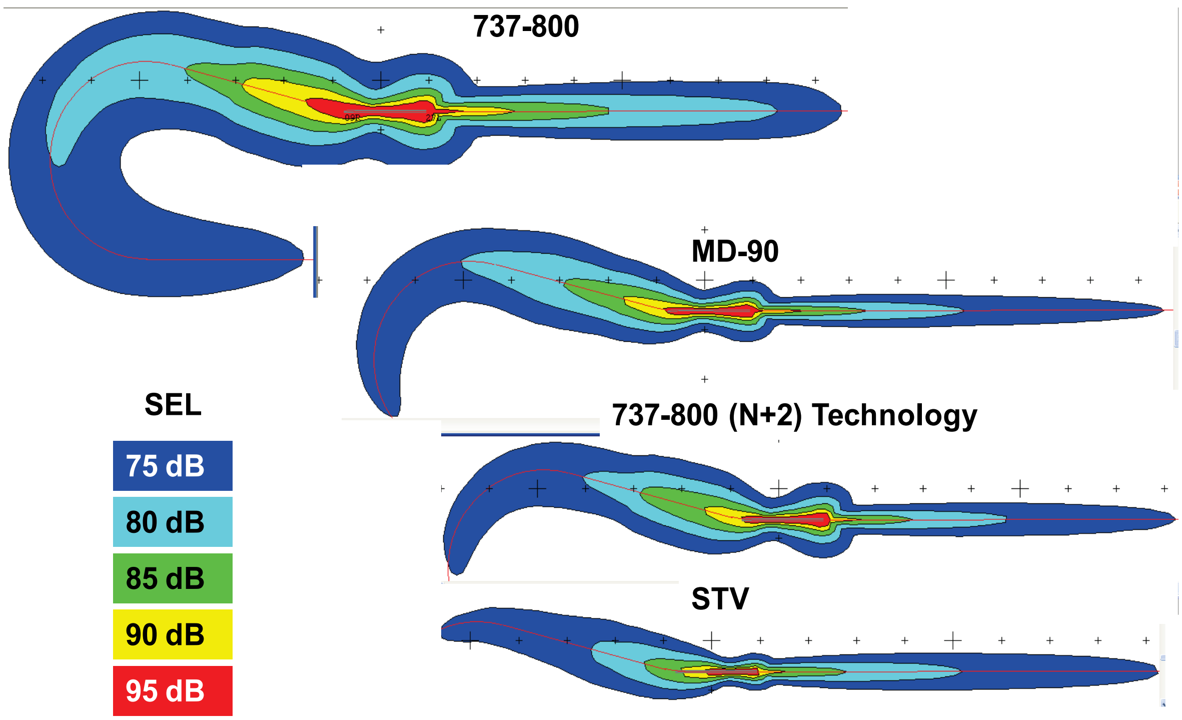


Figure 137 Noise Contour Comparisons

4.3.7.5 Range-Payload

4.3.7.5.1 STV Trade Leading Edge Performance summary

A trade study was conducted for STV leading edge devices. The motivation for this trade was to find a lower cost and lower noise option to the baseline slotted Krueger. The trade was done with the 27,500 lb design payload and 2400 nm design range. Assuming slotted and sealed Krueger, plain flap (droop), and no leading edge device. The results show that all the trade aircraft are capable of meeting the 2.4% engine-out climb gradient, but have up to 35% longer takeoff and landing distances.

It would be possible to begin the STV development with a clean leading edge and then spiral into one of the other leading edge devices. The advantages of a clean leading edge are:

- Lower cost
- Lower noise

The disadvantages of a clean leading edge are longer takeoff and landing distances.

4.3.7.6 100 Busiest Airports – Composite Takeoff and Landing Requirements

An internet search reveals a number of different definitions of "busiest airports" and will result in a slightly different set of airports. For the purpose of this assessment the source for 100 busiest airports (based on passenger boarding's) is CY09 ACAIS Commercial Service Airports (Primary and Non-primary) Updated 11/23/2010 CY09 Passenger Boarding's. This report can be found at: http://www.faa.gov/airports/planning_capacity/passenger_allcargo_stats/passenger/media/cy08_primary_np_comm.pdf. Runway length and elevation, average summer high temperature in the worst month, and a mean summer temperature (deg F) has been added to this database. An excerpt is shown in Table 77 and the entire database is contained in Appendix C of this report.

Table 77 Top 100 Busiest Airport Database (sample)

Rank	RO	ST	Locid	City	Airport Name	Runway Length	Runway Elevation	Average Daily High Temperature worst month(deg F)	Mean Summer Temperature (deg F)
1	SO	GA	ATL	Atlanta	Hartsfield - Jackson Atlanta International	11889	1010	89	78
2	GL	IL	ORD	Chicago	Chicago O'Hare International	13000	653	83	74
3	WP	CA	LAX	Los Angeles	Los Angeles International	12091	100	76	69
4	SW	TX	DFW	Fort Worth	Dallas/Fort Worth International	13401	551	96	85

This database has been plotted in Figure 138. Primarily interest is the runway length variation as a function of runway elevation and temperature. In this case, the average daily high summer temperature in the worst month is shown. If the mean summer temperature was used, the temperature values would be lower. The axes limits are automatically set at the highest value in the database. For runway length it is 14,572 ft. For elevation it is 6090 ft. For temperature it is 109 degrees F. The large blue dots are the data projected into 3-D space and the smaller green, yellow and blue dots are the projections onto the three planes. A few select runways have been labeled, as they are the "outliers" in the cloud of data. For runway elevation they are Colorado Springs (COS), Denver (DEN) and Albuquerque (ALQ). For temperature they are Palm Springs (PSP), Phoenix (PHX), Las Vegas (LAS) and Tuscon (TUS).

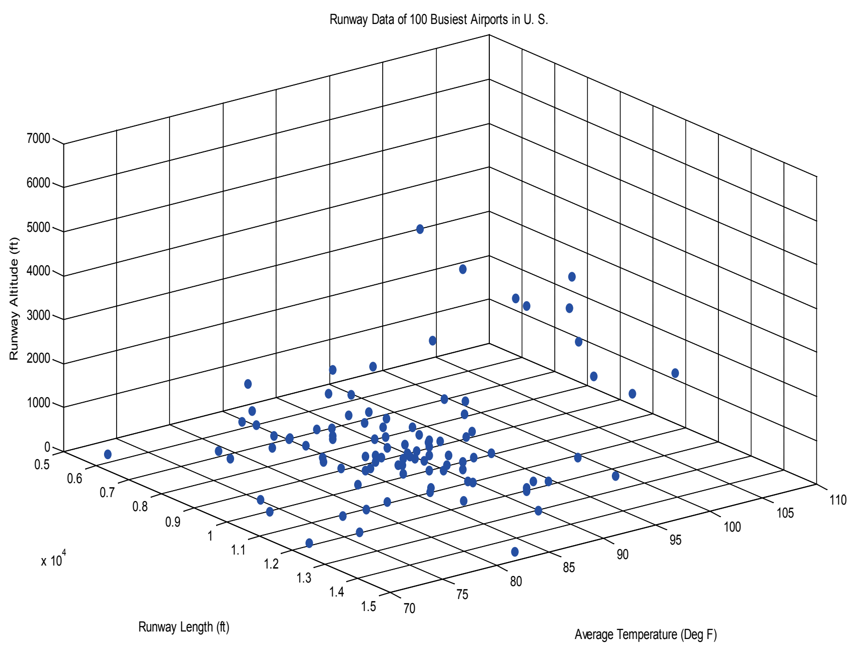


Figure 138 Airport Database as a Function of Length, Elevation, Temperature

Figure 139 shows STV takeoff capability superimposed on the airport database. The takeoff capability is the FAR Part 25 balanced field length. The NASA desires specified standard day for the takeoff capability. Sea Level standar day temperature is 59 deg F and it goes down with increaseing runway elevation. The upper plot shows the STV takeoff performance at 59 deg F, as a function of elevation. The STV is carrying a 27,500 lb payload and sufficient fuel for a 2400 nm range (plus all reserves in the STV mission). The solid magenta line is capability of the baseline STV with a slotted Krueger leading edge.

The STV can takeoff from any airport to the right of the line. The dotted magenta line is the STV capability at 90 deg F. 90 degrees was selected because it is represented of the summer high temperatures experienced at most of the airports in the database. The results show that the baseline STV will be able to takeoff from any of the top 100 airports. The green line is a trade study STV with a clean leading edge. Again, solid is 59 and dotted is 90 deg F. This trade STV cannot takeoff from several of the shortest runways. The lower plot in Figure 139 shows both the baseline and trade STV takeoff performance with temperature. The solid line is Sea Level elevation and the dotted line is 1000 ft runway elevation. The 1000 ft elevation was selected because most of the runway in the database are below that elevation. Again, the baseline STV can takeoff from all the airports under summer conditions. The trade STV at Sea Level will not be able to takeoff from the shortest runways in summer conditions. At 1000 ft elevation in summer conditions, the trade STV will not be able to takeoff from about 10 airports.

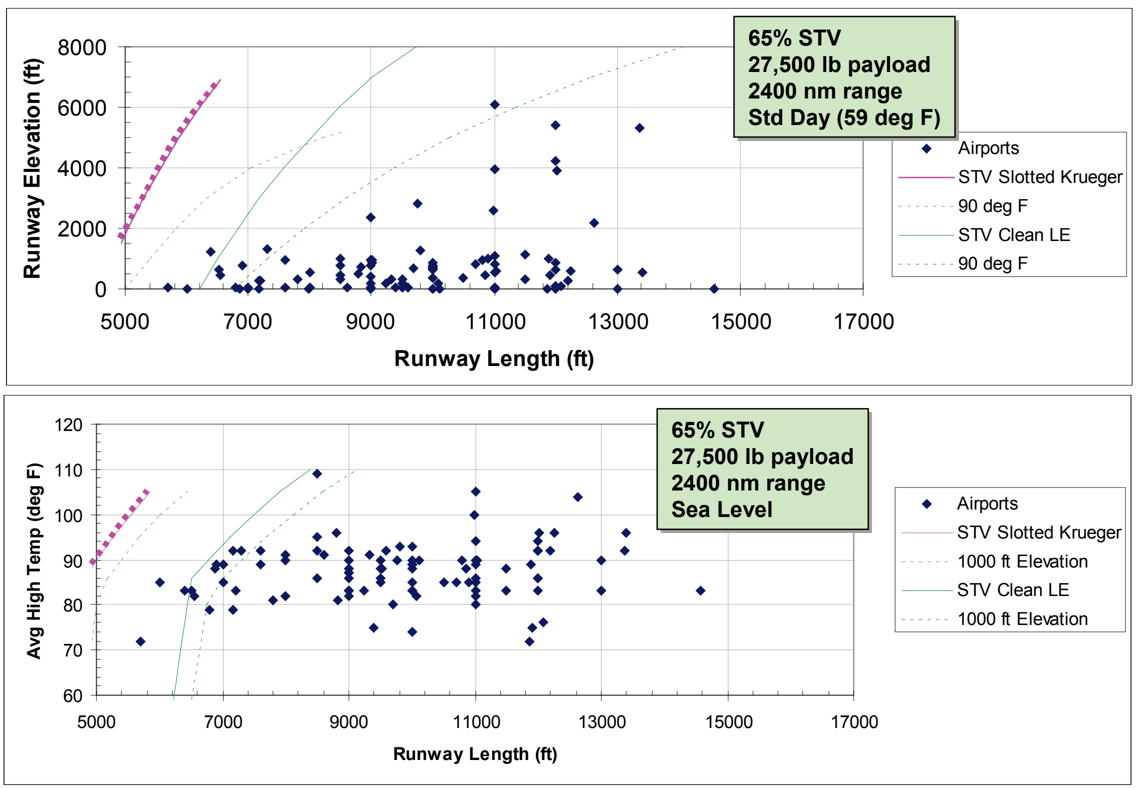


Figure 139 STV Takeoff Performance Superimposed

Figure 140 shows the same type of information for STV landing capability. It should be noted that FAR Part 121, Section 121.195 specifies that the aircraft be capable of landing in 60% of the available runway length from an altitude of 50 ft., so STV landing performance shown accounts for this. The baseline STV is capable of landing at all database airports in standard day and summer conditions. The trade STV will not be able to land at between 3 (standard day) and 10 (summer) of the shorter runways.

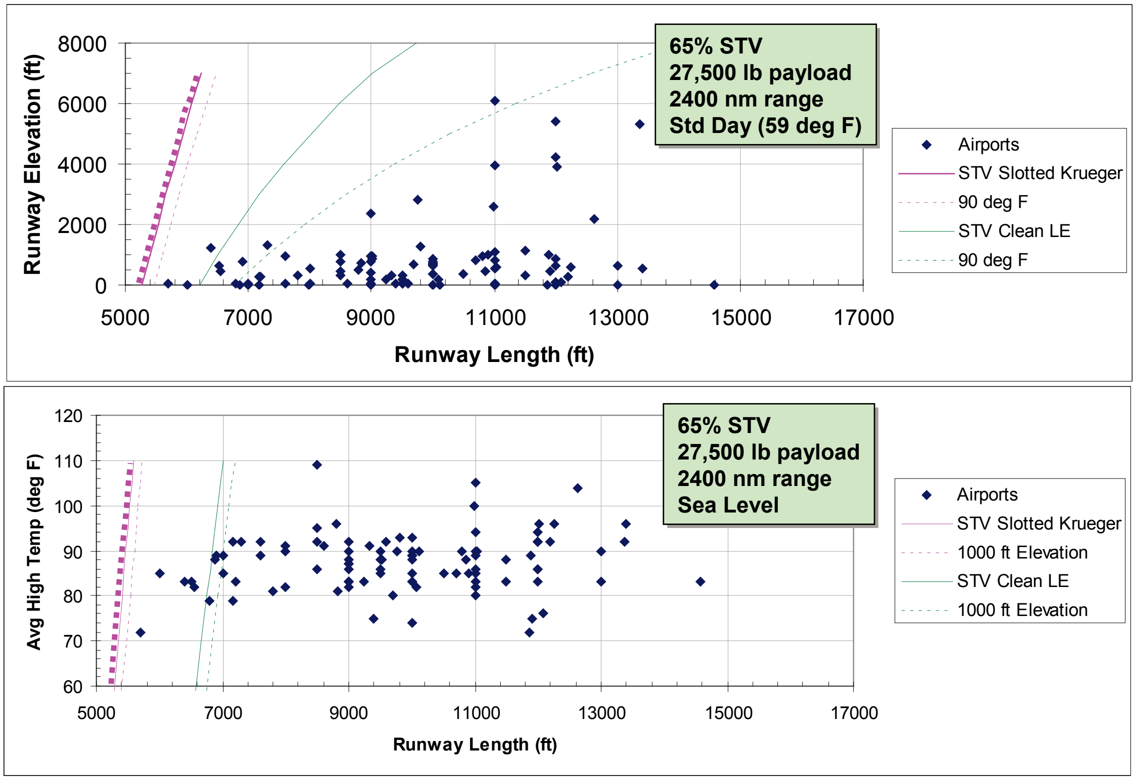


Figure 140 STV Landing Performance Superimposed

4.4 Vehicle Description

4.4.1 Airframe

4.4.1.1 Structural Design Criteria

4.4.1.1.1 SPECIFICATIONS

The following military specifications will be used as structural design guidelines:

MIL-A-8860 (AS)-General Specification for Airplane Strength and Rigidity

MIL-A-8861 (AS)-Flight Loads

MIL-A-8862A (USAF)-Landplane Landing and Handling Loads

MIL-A-8865B (AS)-Miscellaneous Loads

MIL-A-8866C (AS)-Reliability Requirements, Repeated Loads and Fatigue

MIL-A-8867C (AS)-Ground Tests

MIL-A-8870C (AS)-Vibration, Flutter, and Divergence

JSSG-2006-Aircraft Structures

4.4.1.1.2 STRUCTURAL LOAD CRITERIA

The structural load criteria denote those parameters that influence the magnitude and description of the applied air, inertia, and ground loads. These criteria include design weights, design flight speeds and altitude, design sinking speeds, design limit maneuver load factors, maneuver conditions, repeated load spectra, and cabin pressurization.

V-n DIAGRAM

Design maneuver envelopes, V-n diagrams, are shown in Figure 141, airspeed on this diagram are defined in Figure 142.

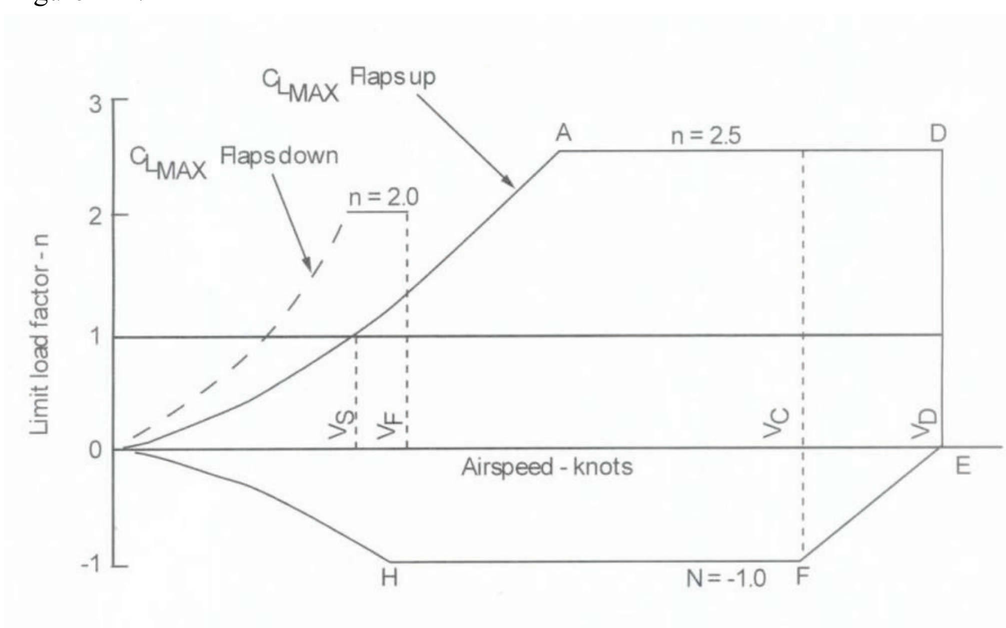


Figure 141 V-n Diagram

MACH NUMBER-ALTITUDE DIAGRAM

Figure 142 presents the airspeed versus altitude diagram for structural design.

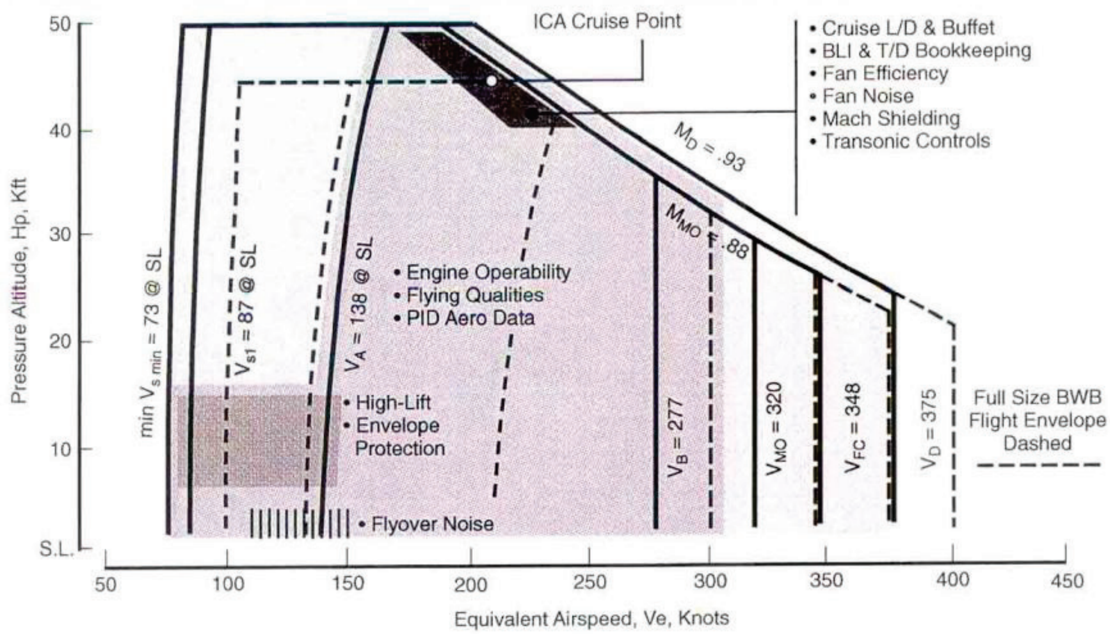


Figure 142 Operational Flight Envelope

4.4.1.1.3 DESIGN LIMIT LOAD FACTORS

The airplane will be designed with sufficient strength to withstand loading conditions at all points within the maneuver envelopes of the V-n diagrams. The requirements of MIL-A-8861 and JSSG-2006 will be used as guide.

STEADY AND ABRUPT PITCHING MANEUVERS

Design symmetrical flight limit load factors at basic flight design gross weight are nz= +9g to -4g for flight up to M=.85, and nz= +5g to -2g for flight speeds greater than M= .85. At weights above the basic design weight, the design load factors will be reduced on a constant nzW basis. See Figure 141 for the weight load factor diagram. These load factors apply for both steady and abrupt pitching maneuvers.

TAKEOFF AND LANDING PULLOUTS

Design limit loads for takeoff and landing. Pullout factors are 0g to 4g.

ROLLING PULLOUT LOAD FACTORS

As defined in MIL-A-8861, the rolling pullout maximum initial load factors are 80 percent of symmetric load factors.

ROLL AND YAW MANEUVERS

MIL-A-8861 maneuvers for transport aircraft will be used

DISCRETE GUST ANALYSIS

The discrete gust analysis specified in MIL-A-8861 will be used as guide

LANDING, TAXI, GROUND HANDLING, AND MISCELLANEOUS LOADS

Landing and taxi load criteria are in accordance with MIL-A-8862A guidelines. Miscellaneous load criteria are in accordance with MIL-A-8865 guidelines.

FATIGUE CRITERIA

Number of hours per life = To be determined

Number of flights per life = To be determined

Scatter factor = To be determined

Safety factor = 1.0

Exceedance data from MIL-A-8866 will be used as guide.

4.4.1.1.4 VIBRATION AND FLUTTER ANALYSIS

FLUTTER

Complete aircraft flutter analysis will be performed to meet the required flight margin.

4.4.1.1.5 EXTERNAL STRUCTURAL LOADS

EXTERNAL LOADS MODEL

An external loads model FEM will be developed for the overall airframe design loads. Theoretical aerodynamic loadings will be used. The Mass Properties Group will supply the weight and inertia data for each grid and the Internal Loads Group will develop symmetric and anti-symmetric matrices.

FLIGHT LOADS

Initial design for the STV concentrated in computing rigid aircraft flight loads at M= .85 at the maximum dynamic pressure of q= xx psf.

GROUND LOADS

Initial design ground load conditions shall be developed using the criteria and methods of MIL-A-8862A.

4.4.1.2 Structure Layout

Figure 143 shows the layout of the structure and major structural components of the STV.

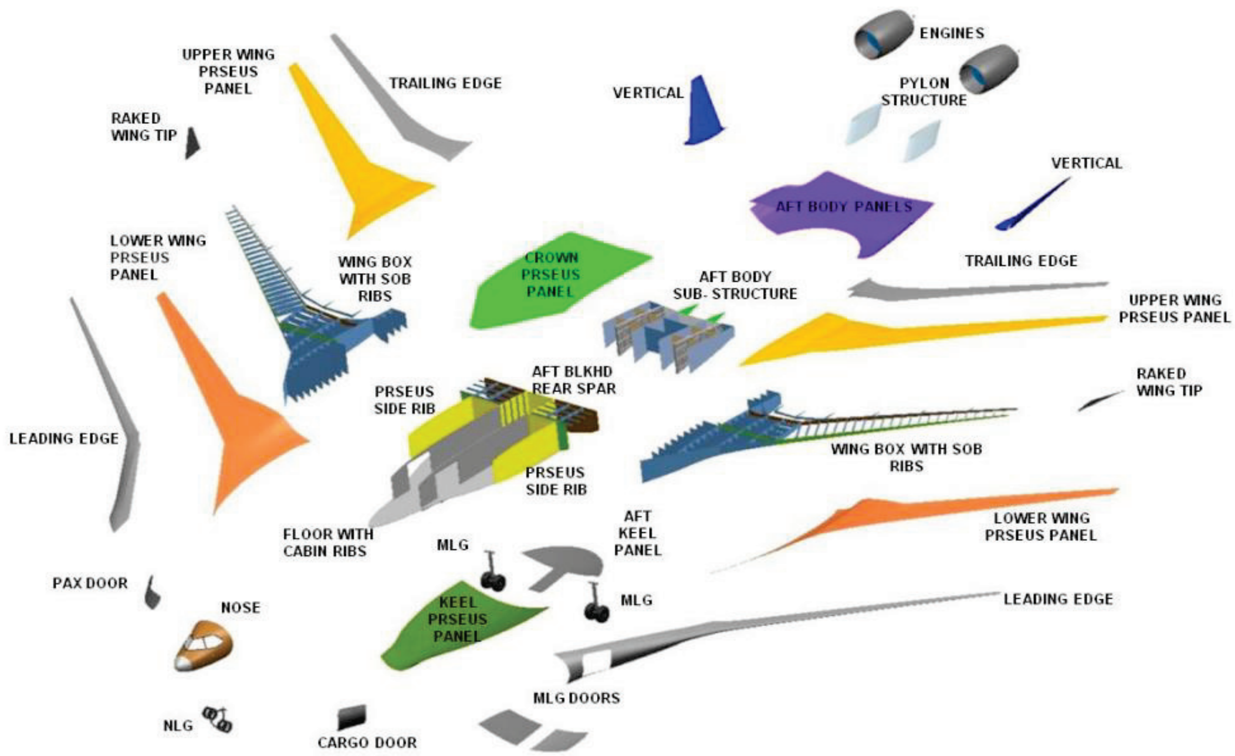


Figure 143 Major Structure Components

4.4.1.3 Wing

The wing has an outboard LE sweep of 38.2 deg and an inboard LE sweep 55.6 deg, aspect ratio 5.55 and is attached to the side of body (SOB) by a shear type joints. Several rib connections at the wing root will have the task of transferring wing bending loads to the center body structure. The primary wing carry-thru connections will be the rear spar and front spar thru the center box.

4.4.1.3.1 Main Box (Section 12)

The outboard wing box panels and spars will be manufactured using stitched resin infused Carbon Fiber Fabric. Aluminum ribs and fittings will be used throughout the wing box with selective usage of titanium in highly loaded areas to be weight efficient. PRSEUS upper and lower panels that include stringers and integrated spar caps will close out the assembly of the wing.

4.4.1.3.2 Main Box Integration

The front and rear spars are aligned with their center body counterparts and are joined at the side of body. The outboard wing box is sealed in order to contain fuel. The main landing gear trunnion is cantilevered off the rear spar and attached to the wing box panels with an external plate. Multiple metal ribs in between the rear and forward spars will attach the wing to the SOB and thus provide wing bending continuity. The rear spar to side-of-body intersection is located between fuselage frames. This accommodates a trapezoidal panel structural arrangement located on the side of the body. The wing is cleaned, sealed and painted (including coves and exterior.)

4.4.1.3.3 Movable Trailing Edge (Section 13)

The movable trailing edge configuration is composed of an inboard flap, an outboard flap, inboard spoilers, outboard spoilers, an inboard roll device (flaperon), an outboard aileron, two rigid hinged panels (similar to spoilers, one over the flaperon and one at the side-of-body), lower cove lip doors, and their respective drive mechanisms and fairings. Construction of the trailing edge flaps will be stitched resin infused (SRI) sandwich structure assemblies, which utilize conventional out of autoclave (OOA) processes. Fittings are to be machined from aluminum forgings/plate. Movable trailing edge surfaces will be supported on aluminum track assemblies to deploy and retract.

4.4.1.3.4 Movable Leading Edge (Section 14)

The STV baseline design has a slotted Krueger leading edge flap on the outboard wing. There are multiple flap segments for each wing that extend from the side of body to the outboard side of the raked wing tip. A moveable leading edge was chosen over no flap for its better performance and to allow for acoustic testing with and without the flap extended. The slotted Krueger was selected due to the compatibility with hybrid laminar flow systems that will be incorporated in the future.

The inboard LE Krueger panels will be supported and driven by linkages. The linkages will be machined aluminum. Krueger flap panels will be located outboard of the fuselage side of body. Construction of Krueger flaps will be fiberglass assemblies, which utilize conventional out of autoclave processes. Fittings are to be machined from aluminum forgings/plate. Slats will be constructed of formed aluminum skins and cove panels, machined aluminum ribs and a bonded aluminum wedge.

4.4.1.3.5 Fixed Trailing Edge (Section 15)

The fixed trailing edge consists of sub-structure between the wing box skin and aft body, a one piece sandwich SRI structure, fuel jettison systems and vapor barrier components. Fabrication of the fixed trailing edge consists of aluminum metallic substructure and a one piece SRI sandwich structure.

4.4.1.3.6 Fixed Leading Edge (Section 16)

The fixed leading edge consists of bull-nose panels, rib substructure, anti-ice provisions, and various systems integration such as for lightning protection. The Fixed LE extends from the side of body to the outboard side of the raked wing tip.

The fixed leading edge consists of a bull nose skin made from aluminum sheet and fiberglass sandwich panels supported by aluminum air load ribs and beams.

4.4.1.3.7 Wing Tip (Section 19)

The wing tip will be a raked configuration. The raked tip is attached to the outboard end of the Section 12 Wing Box. Provisions for all weather radar will be provided on the RHS wing tip.

The raked tip is made from CFRP upper and lower bonded panels from the front spar to the trailing edge, and CFRP channel section spars. Material will be self-adhesive CFRP. The exposed raked tip leading edge is formed aluminum sheet. The root rib is an aluminum hog-out, the leading and trailing edge ribs are machined or built up aluminum, and the tip cap is an aluminum casting or Super Plastic Formed (SPF) aluminum. The colored position light and white anti-collision light are mounted as far outboard on the wing as is practical.

4.4.1.4 Vertical Tail (Section 20)

The canted vertical tails will consist of a vertical fixed section and movable aero surfaces.

4.4.1.4.1 Vertical - Fixed

Construction is for a one piece SRI panels with sandwich or honeycomb core and aluminum support structure. The leading edge will be a bull nose skin made from aluminum sheet.

4.4.1.4.2 Rudder

The rudder is supported by three hinges and is driven by two linear actuators connected to a horn on the lower portion. Construction of the rudder consists of one piece stitched resin infused (SRI) panels with foam sandwich or honeycomb core.

4.4.1.5 Nose (Section 41)

The nose section encompasses the forward portion of the fuselage from the nose to the main cabin splice section of the fuselage. The nose section consists of:

Two-man cabin section

Nose landing gear wheel wells

Emergency egress door

Forward Electrical & Electronic Equipment (E/E)

Transparencies

Nose Cone

Nose landing gear attach points

Cockpit floor with 16g seats

The nose cabin will be pressurized and only the nose landing gear door compartments will be unpressurized. A crew escape hatch made from aluminum construction is located aft of the nose landing gear compartment.

The nose structure will be made from SRI structure with integrated frame caps. Carbon fiber frames will be mechanically attached to the caps. Carbon fiber floor beams with carbon fiber struts will support the nose cabin floor that is made from aluminum floor panels with hat stiffeners. The nose pressure bulkheads are PRSEUS make panels. The nose landing gear bulkheads are aluminum machined structure.

The cockpit features a four-window arrangement. Both the front and side windows are single curvature. The cockpit windows rest on aluminum structure. The windows themselves are as follows: glass double pane forward side windshields and acrylic double pane for the rear side transparencies.

4.4.1.6 Forward Fuselage Transition (Section 42)

The forward transition will also be pressurized and is a continuation of the center body fuselage. This transition will include a 90"W x 76"w cargo door on the left hand side of the fuselage and a 24"W x 48"H crew egress door on the right hand side. Anti-ice provisions and various systems integration such as for lightning protection will be included.

The forward transition bull nose will have and aluminum LE bull-nose skins and fiberglass sandwich panels supported by machined aluminum air load ribs and beams.

The cargo door construction will be conventional, using both composite and metallic materials, as appropriate. The skin will be reinforced to prevent penetration by bird-strike. The cargo door surrounding structure consists of door edge frame, doorsill, and backup intercostals for hinges and latches. The door opening mechanism consists of rotational actuators and scissor links.

4.4.1.7 Center Body Pressurized Fuselage (Section 45)

The center body will be a pressurized cabin section. The center body consists of:

- 21 frames equally spaced at 24 inches
- 42 stringers equally spaced at 6 inches
- 2 outer side ribs
- 2 inner cabin ribs
- Rear spar bulkhead
- Main landing gear attach points
- Main deck floor with cargo roller provisions

The center body crown and keel primary structure panels will be made from PRSEUS technology SRI fabric. The PRSEUS panels will include integrated stringers, caps and Rohacell foam core frames.

Aluminum floor beams and struts will support the main cabin floor that is made from aluminum floor panels with hat stiffeners.

The outer side ribs and rear spar bulkhead will be made from PRSEUS panels. The outer ribs will have aluminum support provisions for the main landing gear points or braces.

The inner cabin ribs will have a core made from Phenolic Hex Core HRP. Composite tubes will provide edge stiffness on the panel opening and attach points. The outer face sheets are fabricated using plain weave pre-preg epoxy cloth with bonded face sheets.

The floor understructure will be supported by both aluminum cross members or aluminum bulkhead panels. Cargo handling tie points made from aluminum and steel forgings will be placed at every floor beam station. Provisions for a cargo net will be included just aft of the nose to center body join to protect the crew and cargo in a 9g crash condition

The center body to aft body transition will consist of titanium stringer to body splices, titanium splice straps and titanium fasteners. Splices will be Determinate Assembly (DA) located on skin-stringer assemblies. Splice straps will require a four-row fastener configuration (two rows on each side of skin gap) for installation.

4.4.1.8 Aft Fuselage (Section 48)

The aft fuselage section will be unpressurized. The aft fuselage consists of:

- Aft body Section
- Vertical support structure
- Power plant pylon support structure
- Maintenance doors

The aft body contains load carrying ribs made of aluminum construction with integral stiffeners. Some ribs will be stitched resin infused integrally stiffened composite panels. These ribs extend from the rear spar to the trailing edge of the fixed structure and provide support for control surfaces and power plants. Incorporation of transverse bulkheads between ribs will support the power plants and skin cover panels. These will be machined from a titanium plate and one serves as a firewall for the APU. Two auxiliary canted ribs made from SRI integrally stiffen panels will support the verticals. The cover panels will be SRI sandwich construction. Fire resistant materials as well as armor protection were required will be applied to protect the structure for engine burst effect. Cutaways for access doors made from aluminum construction will be placed on the lower and upper skin covers for engine and fuselage maintenance.

4.4.1.9 Elevons (Section 49)

There will be three elevons supported by three hinges each and driven by linear actuators. Each elevon consists of one piece SRI panels with foam or honeycomb core construction. Metal base ribs will support the elevons on the aft body attach hinge points.

4.4.1.10 Material Selection

Figure 144 shows the Structure Material Selection for the STV.

Material selection consists mainly of Carbon Fiber (CF) material, Aluminum, and Titanium stock. The dry Carbon Fiber material is the basis for the PRSEUS structure which covers the pressurized fuselage center body and wings. Stitched Resin Infused will used to fabricate the nose and aft body structure. Both PRSEUS and SRI structure will be fabricated using the Boeing CAPRI- OOA process

Metal components will be made from aluminum, titanium and steel aerospace grade material that comply with the Metallic Materials Properties Development and Standardization (MMPDS) data and its predecessor the MIL-HDBK-5.

Joints and splices will be fastened with aerospace grade titanium or steel MD (McDonnell Douglas), BA (Boeing), MS or NAS fasteners. Aluminum fasteners if required will be installed with steel washers to protect the composite against corrosion. Fasteners will be wet installed with sealant.

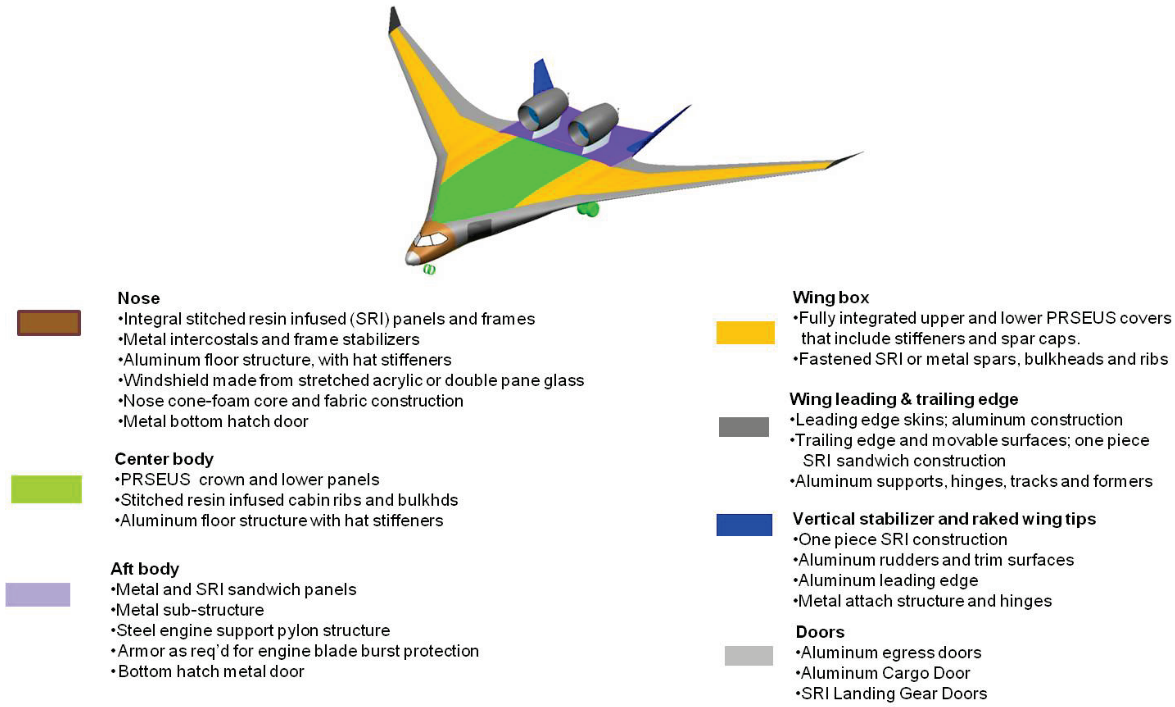


Figure 144 Structure Material Selection

4.4.1.11 Airframe Assembly

The maximum production of STV aircraft is expected to be two vehicles. These airplanes will be highly similar but not necessarily identical because they are intended as research vehicles for various flight science disciplines. Therefore X-shop and prototype assembly methods will be favored over rate tooling and flow production methods.

Major join and final assembly including systems installation will occur in the same facility in a grouping of five co-located work cells.

Work Cell 1- Nose Section 41

Work Cell 2- Center Body Section 42 and 45

Work Cell 3- Aft Body Section 48, 49 and 20

Work Cell 4- Left Wing Section 12, 13, 14, 15, 16 and 19

Work Cell 5- Right Wing Section 12, 13, 14, 15, 16 and 19

4.4.2 Systems

The major systems and capabilities of the STV shown in Figure 145 are discussed in the following sections.

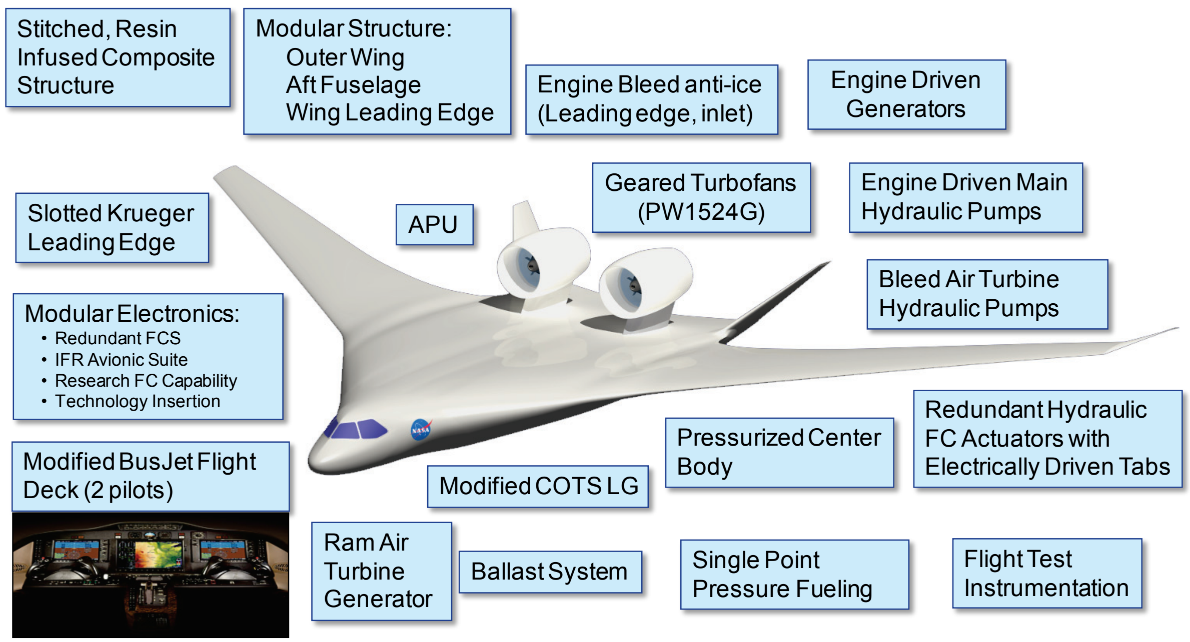


Figure 145 STV Major Systems & capabilities

4.4.2.1 Avionics

Avionic applications include:

- Navigation and guidance
- Communications
- Surveillance
- Flight controls (discuss in separate section)
- Mission avionics
- Vehicle and utility management systems

4.4.2.1.1 Architecture

An Integrated avionic suite consists of COTS hardware and software that is at least one fault-tolerant in all mission critical functions and with capacity for long term growth.

Initial flight test missions will most likely be conducted under visual flight rules (VFR) until operational flight envelope has been cleared. The avionic system is architected so additional capabilities and other advanced technologies can be integrated into the avionic system in the future as required (i.e. IFR, UAS).

A fault tolerant data bus architecture utilizing standard bus protocol are used to share data and system/subsystem signals to ensure that all users within the avionic suite have consistent and timely information.

4.4.2.2 Crew System / Flight Deck

The STV has a two-person, modular flight deck. The flight deck arrangement is similar to a modern conventional commercial/business Aircraft (Figure 146).

Pilot flight inputs are through conventional control wheel and rudder paddle found on all Boeing commercial aircraft. Multifunction flat panel displays will be use to present flight, navigation, and engine information to the pilot. A set of electronic standby instruments will provide backup attitude, airspeed, altitude and heading information.

Figure 146 Example Layout of the Flight Deck

4.4.2.3 Flight Control System

The flight control system will incorporate the following functions; other functions may also need to be incorporated, pending further analysis.

- Stability and control augmented manual aircraft control in all three axes
- Manual airspeed control
- Autopilot/auto throttle functions
- Envelope protection and limiting
- Angle of attack
- Bank angle
- Sideslip
- Over speed
- CG Management
- High lift (leading edge device) configuration control

In order to implement these functions, the flight control system will command all the aerodynamic control surfaces on the aircraft. The top level architecture of the flight control system, the system has the following characteristics:

- Digital fly-by-wire system with no mechanical backup
- Triple redundant electronics
- The three channels will run synchronously
- Each channel will be powered by different power bus
- Each channel will have a dedicated sensor suite; including air data sensors, inertial measurement unit (IMU), cockpit control sensors, and actuator position sensors.
- All inputs and outputs data from each channel will be cross fed to the other two channels
- Triple redundant hydraulic actuators with digital control for the primary(flight critical) flight control surfaces
- Dual redundant electric actuators driving tabs on each primary pitch control elevon to reduce hinge moment on those surfaces
- Simplex hydraulic and/or electric actuators with digital control for the secondary, non flight critical control surfaces (speed brakes, spoilers, etc.)

- The control law architecture will be based on the X-48B/C with update/modification for STV application (extended envelope)
- The system architecture will be open and modular to allow experimentation and technology insertion (hardware and software) over the life of the STV
- Interfaces will be available to allow integration with a flight management system (FMS) to provide autonomous/remote operation capability
- With a single flight control channel failure, there will be no change to aircraft performance and handling characteristic (fail-op).
- With two flight control channels failed, the STV will be able to continue to be controllable and land safely.

4.4.2.3.1 Flight Control Actuation System Driving Requirements

The driving requirement for the flight control system is to provide sufficient control authority during all phases of flight. Each of the flight control surfaces will be actuated by three hydraulic actuators, with each actuator being driven by a separate hydraulic system. The actuation system will be a digital fly-by-wire system with no mechanical backup. The actuators will be sized such that only two of the three actuators are required to provide full control authority. This protects the aircraft from a single hydraulic system failure or a single engine out condition. Each actuator will have two modes of operation, active and bypass. In the active mode, the actuator will be pressurized and providing control authority to the flight control surface. In the bypass mode, the actuator will not be pressurized, and with the use of valves within the actuator manifold that allowing hydraulic fluid to transfer between the extend cylinder and the retract cylinder so that actuator can be back driven. This bypass mode allows the actuators to be back driven when hydraulic pressure is not applied, allowing the other actuators to maintain control of the surface if a hydraulic system fails.

The electric tab actuators will incorporate an internal disengagement device which allows the actuator to be mechanically disengaged at the drive mechanism, allowing the actuator to free float. This disengagement devise prevents an internal actuator jam or malfunction from disabling the operation of the tab by allowing the remaining actuator to operate the surface.

With multiple actuators on a single control surface, the flight control system must be designed to minimize force fighting between the actuators common to the surface. Cylinder pressures from all three of the actuators on a single surface will be monitored and adjusted such that the load differential between the actuators is balanced, therefore, minimizing the force fight between the actuators.

The preliminary flight control actuation system architecture uses the secondary power output capability from the two engines. The left and right engines each drive one engine mounted generator to power the avionics and the powered tabs, one engine mounted hydraulic pump to power the central hydraulic system and one bleed air driven pump to power the left and right hydraulic systems.

4.4.2.4 Autopilot / Auto throttle

4.4.2.5 Propulsion & Fuel System

4.4.2.5.1 Engine

The STV propulsion system will be selected to meet the STV ConOps requirements at minimum cost. The engine will meet the NASA requirement for up to 32,000 lb thrust engines for developing enabling technologies towards simultaneous achievement of ERA N+2 system level goals. The engine will best represent that achievable in the EIS time frame but will be limited by the propulsion technology in available flight qualified engines in 2015. Meeting EIS 2025 emissions and fuel efficiency require an advanced technology core for which technology developments are still under way. The STV can demonstrate and validate airframe fuel efficiency and noise reduction technologies. The absolute FAR 36 cannot be validated for the PSC because FAR 36 noise is a function of TOGW that will not be replicated.

Demonstrating the technologies that could enable meeting the ERA N+2 noise could potentially be met with jet noise compression devices to improve noise shielding. Small scale tests have shown the potential for some concepts. The STV should be tested with and without concepts to validate benefits. Since the engine cannot be flown other than on an airplane, a direct noise comparison with and without propulsion noise shielding cannot be made but the propulsion noise can be measured in a ground test and projected to flight conditions for the assessment. The shielding simulating an Ultra-High ByPass Ratio (UHBPR) engine could be measured by using part power to more closely duplicate the full power characteristics of the UHBPR. The potential difference in noise signature characteristics will need to be addressed with an available engine that most closely matches the PSC propulsion cycle.

The notional engine selected is a Pratt & Whitney geared turbofan based on the engine under development for the Bombardier C Series. The base engine is scheduled to enter commercial service in 2013. The high bypass ratio of the PW1X24G more closely represents the configuration geometry and flow field of the PSC. Engine selection will be re-evaluated during the preliminary design phase.

An open rotor was evaluated but not selected for several reasons. A flight qualified open rotor would be cost prohibitive for availability in the 2015 time frame. Also, determination of the basic BWB airframe drag is best done with a turbofan where the drag is determined from a ground test thrust calibrated engine.

An open rotor could be considered as a spiral follow on for the STV with additional time and cost to develop a flight worthy propulsor. The integrated propulsor performance could then be determined after the airframe drag is known. Consideration could then be given to hybrid propulsion system with a single open rotor retaining a GTF as the second engine for safety.

Another factor considered is the support required if a long term (20 years) usage is required. For such long term usage, availability of spares and spares support needs to be considered. Long term usage should consider drawing from a large production base for this spares support, including potential need for overhaul and replacement engines.

For the reasons above: (1) lowest SFC and noise available for a flight qualified 32K lbs thrust class engine in 2015; (2) a turbofan as to an open rotor is needed to determine in-flight airframe drag and; (3) Large production base to support a 20 year operating life, a Pratt & Whitney engine based on the PW1X24G was selected since the thrust appears to be adequate in the initial assessment.

The performance model and weights and dimensions of the engine were provided by Pratt & Whitney and are used for estimating the STV performance.

All current applications for the PW1000G family are for below the wing mounting on conventional airplane configurations. Studies have been conducted with Pratt & Whitney to determine the best mechanical design architecture for mounting the engine on top of the BWB. Pratt & Whitney has developed a notional engine installation concept.

The propulsion system will enable demonstration/validation of airframe N+2 fuel efficiency and noise reduction technologies. The installation will be designed for all weather operability but it is assumed that operations in severe weather conditions, such as on icy runways will be avoided. Therefore, to minimize initial and 20 year operating cost, a thrust reverser is not included. Thrust reversers have relatively high maintenance costs and would entail a significant development cost for the above the body installation. Investigation of thrust reversing can be considered for a spiral up for the STV to investigate potential airframe integrated concepts.

The existing nacelle designed for under wing mounting will be used as a host to retain as much existing designed hardware as possible. Pneumatic controls, precooler, heat exchangers, filters, and valves will be preserved to the extent possible. Changes will include the engine mounting, outer nacelle lines and the engine/pylon interface connections (electric, fuel, hydraulic, pneumatic). The STV will delete the thrust reverser actuation system preserving the variable area nozzle. The auxiliary inlets and outlets such as fluid drains, pneumatic starter outlet, nacelle cooling, and pre-cooler flow will be reviewed for suitability.

The propulsion installation will address the FAR and JAR 25.903 (d) (1) each state that: "Design precautions must be taken to minimize the hazards to the airplane in the event of an engine rotor failure...’. AC 20-128A provides specific methods for demonstrating compliance with this requirement. An internal Blended Wing Body engine rotor burst study was previously conducted showing requirements to comply with AC 20-128A and will be used as the basis for the STV. Additional consideration will be given for the BWB because AC 20-128A was based on design for T&W configurations.

4.4.2.5.2 Fuel System

The STV fuel system will be designed for operation using Jet-A fuel. The fuel system is designed for fuel transfer between multiple tanks used for aircraft CG control. Studied and analyses will be conducted to define the fuel quantity gauging system. Redundant fuel pumps are used in each tank but a reliability evaluation will be made and an experimental airplane may only require a single AC pump per tank. The system will be designed for continued engine operation with loss of all electric power.

4.4.2.6 Auxiliary Power

For capability of: performing extended simulated airline or cargo service; traveling between all city pairs in the lower 48; and using the 100 busiest airports in the US, it is judged that a ground operable Auxiliary Power Unit (APU) should be included to preclude the need for ground carts that would otherwise be needed for electric and pneumatic power that might not be readily available. In flight power requirements will be studied in detail in the PD phase, however, based on past studies and experience with commercial twinjets, a flight operable APU is desired to provide increased electric power in flight for the primary flight control system and power for main engine starter assist in the unlikely occurrence of a two engine flameout where starter assist would increase the in-flight start envelop beyond windmill starting. A requirements and sizing study will be conducted in the PD phase.

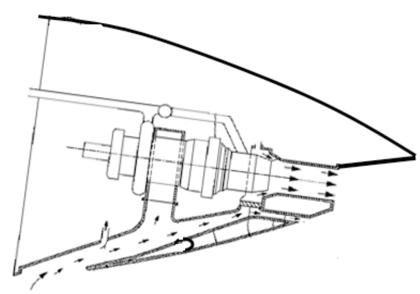


Figure 147 Notional APU Installation

The APU will be an available gas turbine unit capable of operation in flight. Pending further study, the APU will have an electric starter powered from the airplane battery, and be capable of providing ground electric power and pneumatic power for operation of the air conditioning ECS packs and main engine starting. The APU will provide backup electric power in flight and pneumatic power for wind mill starter assist in the event of a main engine flame out.

The APU will operate on Jet A with fuel supply from the main fuel tanks. The installation will be designed to meet ICAO Annex 16 noise requirements.

The notional installation concept is shown in Figure 147 with the APU in the afterbody. The afterbody location reduces the noise and avoids the hot exhaust blowing at the front where most ground personnel activities occur. The inlet has a ram door on the bottom of the BWB and the APU will normally be off during take-off and landing to minimize the potential for FOD. The lower location is more favorable for a higher inlet ram recovery since the boundary layer will be thinner on the lower surface than the upper surface. The exhaust is aft facing to minimize drag and provide the differential pressure needed for in-flight starting. The APU compartment will be kept warm in flight from pressurized compartment outflow air to avoid long APU cold start times. The APU is a fire zone and will be enclosed in a fireproof compartment with fire detection and extinguishing. The unit will either have full rotor failure containment or design precautions for rotor failures.

4.4.2.7 Landing Gear

The landing gear system will integrate existing landing gear components from existing aircrafts with modification when required to minimize development time and cost.

4.4.2.8 Main Landing Gear

Current baseline main landing gear is the 737-900ERW main gear assembly (Figure 148); retract inward as on the 737. The gear is normally extended hydraulically, but can be gravity-deployed (air loads are assisting) if hydraulic power is lost.

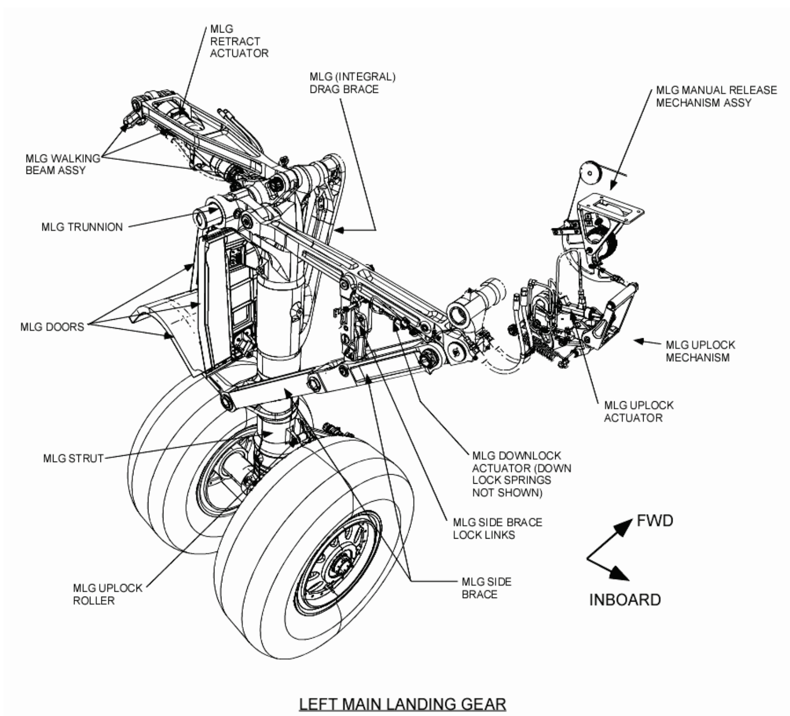


Figure 148 737-900ERW Main Landing Gear Layout

4.4.2.8.1 Main Gear Trade Studies

Several options for the main landing gear were explored, including using 737 main landing gear, 767 nose landing gear, and MD-11 center landing gear. While the 737 is approximately the right size for the STV weight, the 767 and MD-11 options were studied to see if there was an advantage of using their forward/aft retraction mechanism. The landing gear options that were studied are summarized as follows:

Initial Concept: 737 MLG, modified to retract forwards instead of inwards

Pro: 737 gear readily available, maximizes cargo volume.

Con: Modification requires manufacturing collars with new drag and side link clevises. Mod may or may not need re-qual testing – If structural margins on new clevises are large enough, only analysis may be required.

Option 1 (Selected): Unmodified 737 MLG (retract inwards)

Pro: 737 gear readily available, can use unmodified off-the-shelf, cheapest overall cost.

Con: Sacrifice 4 total pallet positions.

Option 2: 767 NLG with 737 wheels, brakes and tires

Pro: 767 NLG readily available, can use standard retraction mechanism.

Con: 767 NLG does not have brakes, may need to be 'beefed up' to handle braking/landing loads. Steering function must be disabled/locked out. May require additional qualification on dyno/drop-test for main-gear load cases.

Option 3: MD-11 CLG with 737 wheels, brakes and tires

Pro: Should not require additional testing (plenty of load capacity), no modification to strut or retraction mechanism.

Con: May require custom axle to mount 737 MLG to MD-11 CLG strut. Heavier than 737 MLG or 767 NLG. May be too big to physically fit in given volume.

4.4.2.9 Nose Landing Gear

4.4.2.10 Electrical System

The STV Electrical System design is driven by the shaft power available on the PW1X24G engines for electrical power generation and flight control actuator power demands. Since the physical size of the STV is similar to the Boeing 737 it was used as a source to derive the flight critical electrical power demand. To minimize electrical power requirement in order to maximize the shaft power available for flight control with the PW1X24G engines, the baseline design will use engine bleed air for anti-icing and for the Environment Control System (ECS). Passenger requirement for Gallery Power and entertainment system requirements were also eliminated from 737 baselines. For emergency landing, the landing gear is gravity dropped to minimize Ram Air Turbine (RAT) and Battery hydraulic power requirements. The baseline has an APU that will pneumatically start the engines and provide electric power during ground operation and can be restarted during flight to provide electrical power in the event of an engine failure.

The STV design has two Pratt Whitney PW1X24G engines capable of provide a total of 120 shaft horsepower per engine and is the primary source of both hydraulics and electrical power for the aircraft. Each engine directly drives a gear driven 60 Hp electric generator and a gear-driven 60 Hp hydraulic pump.

In the improbable case of all engines out, continued flight control for emergency operations will be possible using a dropdown Ram Air Turbine (RAT) generator and the Battery Systems will provide for the tab load in addition to the standard emergency Hp load. Base upon a review of Boeing 737 Electrical Load Analysis the standard emergency power requirement is approximately 4 Hp. Therefore the RAT System and battery will be capable of supplying 60 Hp continuously. The Battery System energy storage requirement is 60 Hp for 1/2 an hour, or 30 Hp for 1 hour or 932A-h.

Allocating the electric power to the direct drive engine shaft provides a more reliable and consistent power source. It is important to note that all AC power generated by different sources are not synced and therefore cannot simultaneously drive the same load. The system can only tolerate one engine failure without impacting flight control handling characteristics After the 1st engine failure the APU will be restarted and recover full flight control authority over two of the three hydraulic system and all tab electric actuators.

After the 2nd Engine failure the flight control aero surfaces will be controlled by the tabs with power provided by the RATs augmented by the Battery system. If transient power demands from the tabs are determined to be significant then the electric system may have to implement an electric accumulator. The electric accumulator is design to store excess power when available and supply this power when demand exceeds supply.

4.4.2.11 Hydraulic System

4.4.2.11.1 Functional Description

The baseline hydraulic system will consist of three independent 5000 psi systems, designated as the Left System, the Central System and the Right System. These independent systems do not share hydraulic fluid to ensure the aircraft has sufficient redundancy. Each of the three hydraulic systems will be driven by multiple variable displacement hydraulic pumps allowing the pumps to be operated based on system demand. The hydraulic pumps will be mechanically driven pumps attached directly to the engines, bleed air driven pumps and electrically driven pumps. The Left and Right Systems will operate on bleed air from the engines thru a turbine pump assembly with backup bleed air available if the APU is running. The Central System will operate on gear driven pumps mounted to power take off pads on each of the engines. Backup power for the central system will be provided by running the APU and driving a hydraulic pump electrically.

The secondary power output capability of the engine is being based on the PW1X24G engine which will provide roughly 60 Hp to the engine mounted electric generator, 60 Hp to the engine mounted mechanical hydraulic pump and 120 Hp to the bleed air hydraulic pump.

4.4.2.11.2 Failure Cases

A single hydraulic system failure or one hydraulic actuator failure on one surface does not degrade the control authority due to the actuation system having the capability to provide full control authority with the remaining hydraulic actuator on each surface.

Loss of one electrical system or one electric actuator on a tab surface does not impact the control authority of the tab surfaces since full tab authority is maintained with one of the two electric tab actuators.

One engine out condition reduces the hydraulic actuation capability but does not affect the tab surface authority since each engine provides sufficient electrical power to operate the tabs. The reduced hydraulic power will affect control authority but by starting the APU, sufficient hydraulic power will be available to maintain full control authority.

A two engine out condition will result in the deployment of the RAT which will be sized to provide sufficient electrical power to drive the tabs surfaces. With tab control only, control authority may be below level 3 handling qualities. If level 3 handling qualities are not achievable with the tabs only, the APU will be used to provide addition control authority. In an emergency landing condition, the landing gear will be deployed using an emergency gravity deployment system.

4.4.2.11.3 Power Concerns

Preliminary sizing of the hydraulic system shows the power required for a traditional hydraulic system is higher than the power requirements for the 737. This high hydraulic system power is being driven by the large control surfaces and fast command rates required to maintain control of the STV aircraft. Studies have been performed to investigate methods of reducing the secondary power requirements for the hydraulic system, which has driven the need to include powered tabs on the control surfaces. Additional power reducing methods are also being studied. These power reduction approaches will add complexity to the flight control system, but may be necessary in order to reduce the secondary power requirement.

4.4.2.12 Environmental Control System

The STV environmental control system will be designed to provide avionics cooling and a shirt sleeve environment in the flight compartment, maintaining a maximum a cabin pressure altitude of 8000 ft. The ECS will maintain crew compartment temperature between 60 and 80 degree F both in the air and on the ground with a minimum of 10 exchanges of crew compartment air per hour.

The pressurization and temperature control will use an available flight qualified pneumatic powered unit with 100% fresh air to the flight compartment. The final configuration definition will be based first determining the ECS design requirements and then conducting an evaluation of available flight qualified units. There is a large base from manufacturers for commercial transports, business jets and fighter aircraft to select from. In general, the ECS units are pneumatic units providing environmentally controlled pressurization but there are also some electric and vapor cycle units available. A notional ECS system is shown in Figure 149 based on using engine bleed air.

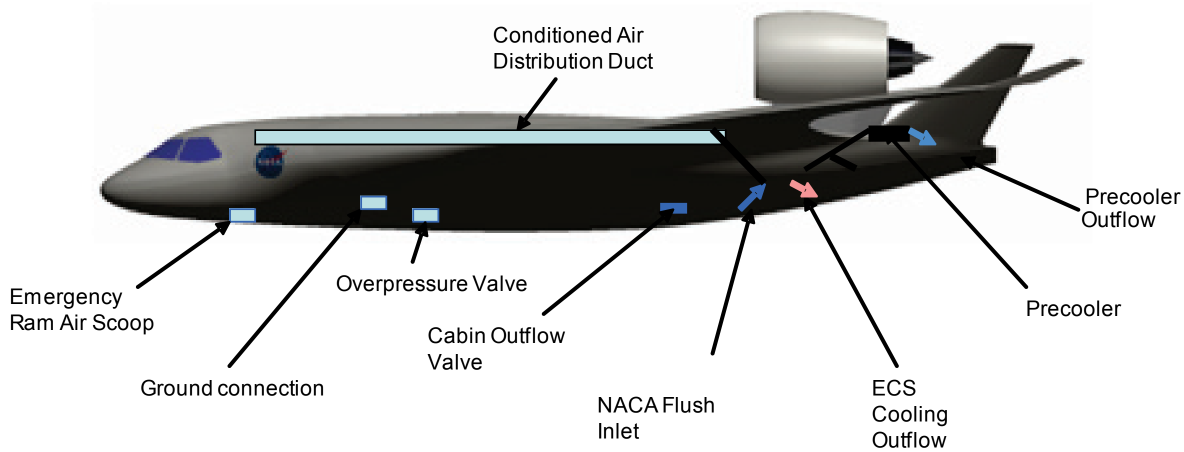


Figure 149 Environmental Control System Layout

4.4.2.13 Flight Instrumentation and Data System

A flight test instrumentation system will be installed in the aircraft to collect, condition, record, and transmit flight test data. The starting point for the STV conceptual design is Boeing's Flight Test Data System (FTDS) that is standard for commercial flight testing.

The instrumentation system will have the ability to collect data from all subsystems onboard the aircraft and have the capacity to record up to TBD of parameters. This includes TBD digital, TBD analog, and TBD discrete parameters.

The instrumentation system will record all voice communication between crew members and external voice communication with ground and/or other aircraft (chase). The system will also record up to TBD channel of video.

The system will record all data on removable media for easy retrieval post flight; a subset of the flight test data collected will be transmitted in real time to a ground facility to allow for real time monitoring of the test flight. As instrumentation requirements are developed during preliminary design, the system will be modified to provide the needed experimental capability and future flexibility.

4.4.2.14 Software

The STV software will be managed using a disciplined, documented development process. The process will be based on the Boeing CMMI Development Model and IEEE EIA 12207 Software Life Cycle Process (Figure 150), with specific tailoring to the needs of the STV air vehicle and ConOps. The major process steps are:

- Requirements definition
- System Definition - Synthesis/Design
- Build
- Integrate and Test
- System Verification and Validation
- Support and Upgrade

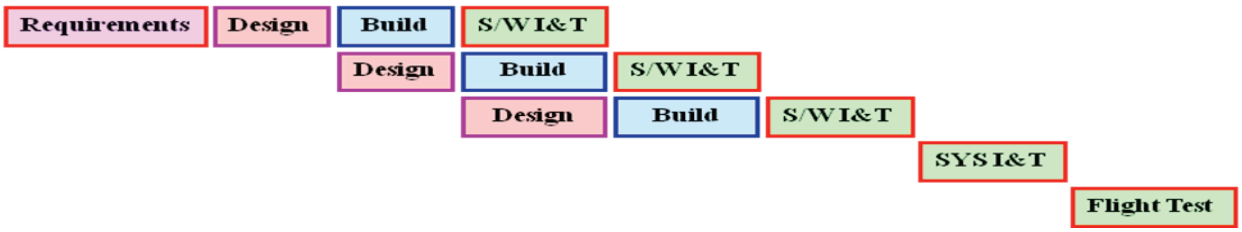


Figure 150 Software Development Process

The software development will use industry and military standards as guides:

- MIL-STD- 498 Software Development and Documentation
- RTCA DO-178B Software Considerations in Airborne Systems and Equipment Certification

STV software components are:

- Avionics
- Flight control
- GN&C
- Redundancy management
- Mission management
- Flight termination, recovery (unmanned ops only)
- Subsystems control/management
- Utility functions
- Integrated Vehicle Health Management

4.4.2.15 Equipment and Furnishings

- Oxygen (loss of pressurization)
- Water/Waste
- Lavatory (for long distance/duration missions)

4.4.2.16 Fire Protection

4.4.2.17 Ice and Rain Protection

4.4.2.18 Lighting

4.4.2.19 Safety

4.4.2.20 Ballast System

4.4.2.21 UAS Systems

One of the objectives of the STV is to serve as a testbed for development and demonstration of capabilities and technologies that allow routine UAS operations within the NAS. The STV design allows for insertion of the hardware and software that are needed for each of these capabilities.

4.4.2.22 System Operation

4.4.2.22.1 Piloted Mode

4.4.2.22.2 Remote /Autonomous Mode

4.4.2.22.3 Command, Control, and Data handling

UAS-specific systems ensuring separation assurance and collision avoidance, robust command, control and communications, environmental hazards detection/avoidance, and resilient flight operations

Flight termination, recovery

Onboard sense and avoid

Communication links

Mission Management (aircraft)

4.4.2.22.4 Ground Operation

4.4.2.23 System Maintenance

4.4.2.24 Technology Spiral Strategy

STV systems are designed to be open and modular to allow easy insertion of new, advanced technologies into the system. Following are a list of technologies that are accounted for during system design and will be introduced into the STV system in a spiral fashion as the technology matures and becomes ready to be flight tested.

- UAV Operation
    - Remote pilot
    - Autonomous mission management onboard
    - Autonomous flight with ground control
- Advanced Aerodynamics
    - Wing hybrid laminar flow system
    - Riblets
    - High lift devices
- Advanced Propulsion
    - Thrust reversing
    - Open rotor engines
    - Secondary power
- Structure/Material
    - Advanced PRSEUS
- Flight Control
    - Research Flight Control
        - Advanced control algorithm
        - Fault tolerant flight control system
    - Actuation System
        - Electro Hydrostatic Actuator (EHS)
        - Electromechanical Actuator (EMA)
- Acoustics
    - Airframe/Engine Noise
    - Quiet wing leading edge devices
    - Quiet airframe components
    - Gear Noise (fairings, etc)

4.5 Future Planning

4.5.1 Overview and Schedule

In the N+2 Advanced Concepts Study, Boeing developed a Preferred System Concept (PSC) aircraft based on the Blended Wing Body (BWB) configuration that simultaneously meets the N+2 fuel burn, noise, and emissions goals. The analysis leading to the selection of the BWB shows that the BWB has substantially better fuel burn and noise performance than other candidate configurations. In Task 5 of the study, Boeing developed a STV configuration, based on that PSC design, which provides an integrated testbed for reducing risk for the PSC and has the capability and flexibility to conduct technology testing for years to come.

Boeing's STV is a 65% scale of the PSC, with OML changes to nacelles to match the engines and to the fuselage nose because pilots don't scale. It is piloted by two crew and expandable to remote piloted and autonomous flight operations, including operations within the national airspace system.

The STV can carry 27,500 lbs of containerized cargo – a capability scaled from the 100,000lb PSC cargo capability – for operational demonstrations and ballast up to a max TOGW for matching full scale flight conditions for noise, performance, and envelope limit tests.

Boeing's STV will:

- Demonstrate maturity of the BWB configuration and its enabling technologies
- Demonstrate maturity of technologies with applications to all aircraft designs
- Validate the methods and models that will be used to develop future BWBs that meet the N+2 PSC design missions and a variety of other applications and missions

Task 5 included development of plans, schedule and cost for future development of the STV. Option 1 is a plan for preliminary design of the STV and successful completion of a PDR. Option 2 is the plan for simulation and ground testing in support of Option 1 to mitigate the key risks associated with the STV. Both Options 1 and 2 are necessary to complete the PDR and demonstrate that the STV design is ready to proceed to detailed design.

4.5.2 Preliminary Design Phase

Option 1 describes the development of a preliminary design for an ERA/UAS subscale testbed vehicle. The objectives of Option 1 are:

- develop a preliminary design of a ERA/UAS subscale testbed vehicle that serves as an integrated technology demonstrator and reduces risk for the PSC developed in the NRA Advanced Vehicle Concepts study.
- provide credibility and traceability to the PSC
- provide credibility and traceability to the 15- year technology maturation roadmap developed as part of the NRA
- mitigate risks identified for the development of a full-size testbed vehicle.

While the Option 1 emphasis is preliminary design of the STV, it will continue refinement of the PSC based on potential improvement studies identified in the advanced concepts study. The refinement will also incorporate changes identified during the more detailed STV preliminary design activity and in the Option 2 testing.

The vehicle design, design reference flight missions, and ConOps that Boeing developed in the advanced concepts study allow testing for performance and noise at conditions approximating full scale vehicle flight. This means only small data corrections are needed in validating the BWB design tools. Option 1 will further refine and update these.

Option 1 will refine and allocate the functional, performance, and interface requirements and verification methods identified in the advanced concepts study. It will also define the testing and instrumentation for data needed to validate the STV vehicle and systems.

4.5.3 STV Work Breakdown Structure (WBS)

A Work Breakdown Structure for the Subscale Test Vehicle was created to guide creation of the Option 1 Plan and cost estimate. It is based on the Boeing Commercial Aircraft template, with modifications to represent the unique features of the STV.

4.5.4 Risk Reduction Ground Testing

Option 2 implements the experimental plan to demonstrate that the major risks associated with producing the ERA/UAS subscale testbed vehicle (STV) have been mitigated, and the STV preliminary design validated the degree that exit criteria for a Preliminary Design Review are satisfied.

The Option 2 plan describes all of the necessary experimental testing (wind tunnel, simulators, structural components, etc.) elements required to sufficiently reduce the risk such that the testbed vehicle is practical, affordable, and has a reasonable chance of meeting the demonstrator flight-test objectives, plus provide the information necessary to validate the subscale testbed vehicle preliminary design methods.

Option 2 has tasks that are essential to the preliminary design effort. Also, Boeing has elected to include in Option 2 all of the analysis required to support the testing and simulation as well. Option 1 and Option 2 are complementary and therefore must be used together to describe the complete STV preliminary design effort.

As it constitutes a large portion of the plan for reducing risk on the PSC, the STV bears most of the risks currently assessed for BWB configurations. The Option 2 studies address the following technology areas that have been identified as issues (and potential risk items) for the BWB configuration:

- BWB Structures
- BWB Aerodynamics
- BWB Propulsion
- BWB Stability & Control, Flight Controls, and Flying Qualities
- BWB Actuation System
- Acoustics

Structures

The BWB Structures development work will develop information needed to design and manufacture the STV using Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) and stitched composite structure technology. This work will reduce the risk of components failing below their design points and reduce the risk of manufacturing problems. Both risks present the possibility of rework which would consume additional schedule and cost in the STV program.

Aerodynamics

The BWB Aerodynamics development work will support risk mitigation in the propulsion and flight control actuation system areas. Engine operability is a propulsion concern for the STV. The aerodynamics work should help determine whether there is a risk of engine operation being adversely affected by the flow field around the engine. The aerodynamics work would seek changes to the BWB aerodynamic design to address that risk. Managing the power demands of the flight control system has been identified as a concern for the BWB. The aerodynamic design of the control surfaces may be part of the solution, including the use of tab surfaces and other means to reduce hinge moment.

Propulsion

There are a few concerns in the BWB Propulsion technology area that affect the PSC, but the main concern affecting the STV is engine operability. While the BWB Aerodynamics work will focus on the STV design, the work under BWB Propulsion would look at opportunities to address the engine operability concern with existing BWB configurations and wind-tunnel models.

Stability & Control, Flight Controls, and Flying Qualities

BWB Stability & Control, Flight Controls, and Flying Qualities (S&C, FC, & FQ) work will develop simulations to determine actuation system requirements and assess high-speed flying qualities. The power requirements currently estimated for the actuation system could potentially be reduced with piloted simulations targeted at getting better requirements. Hinge moment reducing devices, such as tab controls, would need to be accommodated in the control laws, if used. Although no issues are anticipated, control of BWB configurations at high speed needs to be addressed.

Actuation

BWB Actuation System work will explore different options for actuating flight controls while minimizing power demand of the actuation system. Options include hydraulic, electric, and hybrid hydraulic-electric systems.

Acoustics

Work on Acoustics will explore options for increasing acoustic shielding and for reducing airframe noise. This exploration will provide information to guide the design of the STV toward a better demonstration of reduced noise levels.

4.6 Conclusions and Recommendations

As shown in the Technology Maturation Plan (Volume 2 of this report), the next critical step in developing the technology for the Preferred System Concept (PSC) is a flight demonstrator. A flight demonstration vehicle is necessary to test critical technologies in relevant environments that cannot be recreated via ground-based testing including flyover noise, dynamics, and integrated structural scale up. Toward this end, Boeing developed a conceptual design of a Subscale Test Vehicle (STV) that would transition the enabling technologies to TRL 6 and validate that the full-size PSC will meet NASA performance and environmental goals. In addition, the STV is designed with long life and modularity to be a flexible testbed for incorporating future technologies, plus performing flight campaigns to integrate Unmanned Aircraft Systems (UAS) in the National Airspace System.

The STV conceptual design is based on a 65-percent scale version of the PSC. That size was selected in that it best met all Boeing and NASA requirements and objectives while trying to minimize cost. Several factors led to the relatively large scale selected. The square/cube law relationship dictates the structure be near full-scale to be representative. For flight mechanics, achievement of dynamic scaling and Mach scaling with the same airplane again requires near full-scale sizing. Large scale is needed for Strouhal scaling with atmospheric attenuation for acoustics. A large centerbody allows for a reasonably sized flight deck for long-term flight operations. This size STV is a good fit for the planned 26,000 lb-class advanced geared turbofan engines. Finally, large scale is needed so that the design, fabrication and flight test of a manned demonstrator will identify and resolve the many "unknown unknowns" of the BWB concept.

The conceptual design of the STV incorporates an advanced composite airframe. Stitched composites were selected for the centerbody and the wing, with the centerbody making use of the PRSEUS concept that is currently being developed with NASA for testing in their CoLTS facility. Building the STV from advanced composites may add to its cost and schedule. However, the resulting STV will provide the materials, structure, and manufacturing database needed for the full scale PSC.

The detailed plan/schedule for the preliminary design of the STV, including the risk reduction testing needed, shows that PDR can be accomplished with a reasonable level of risk. Near-term tasks have been identified that can be started immediately to address some of the key potential design issues. An early start on these tasks would reduce risk and shorten the schedule to PDR.

The STV as defined here is a robust, large-scale design that meets all of the stated goals and objectives. ROM cost for developing the STV beyond preliminary design were estimated based on historic costs of similar prototype development programs at Boeing. Several opportunities to reduce the estimated cost for the STV have been identified. The best path forward for developing the PSC may be determined by available funding. More work is needed to identify the minimum set of requirements for the STV that is critical to get to the next stage of development leading to the FSD of a real program.

Appendix A - Similarity Ratios and Scaling

Large vehicle scale is essential to properly verify technology readiness of the BWB concept. The square/cube law implies that the structure must be near full-scale to be representative. For aerodynamic and flight mechanic research, achievement of Mach Scaling and Dynamic Scaling with the same airplane requires near full-scale. Large scale is needed for Strouhal scaling with atmospheric attenuation for acoustics. Finally, the design, fabrication and flight test of a large scale manned demonstrator will identify and resolve the many "unknown unknowns" of the BWB concept. This will enable the industry to proceed with confidence to a production program of a BWB subsonic transport.

Choosing the vehicle scale factor is the most important of the conceptual design trade studies. The only way that a test bed vehicle can match all relevant experiment parameters is if it were built full scale. This is probably cost prohibitive, so subscale vehicle testing is used. Unfortunately, this requires compromising some of the relevant experiment parameters. The goal is to strike the correct balance between cost and creating a relevant flight environment for the experiments.

Vehicle similarity relationships have been well understood for many years (Reference: Chester H. Wolowicz, James S. Bowman, Jr., and William P. Gilbert, "Similitude Requirements and Scaling Relationships as Applied to Model Testing," NASA TP-1435, August 1979) and is the basis for all subscale vehicle testing. Different vehicle similarity relationships need to be used depending on the test objectives. Before going into detail about specific sets of similarity relations, it is important to list and prioritize the test objectives for the ERA STV demonstrator:

1) Perform experiments to substantiate the significant fuel burn improvement of the STV, including showing the incremental benefits of spiral developments like HLFC

2) Perform experiments to substantiate the significant noise reduction of the STV

3) Perform transonic handling qualities experiments to make certain the STV performs as pilots expect in this flight regime

4) Perform terminal area handling qualities experiments to establish that the STV handles as pilots expect in the most severe of takeoff and landing scenarios.

While the X-48B was a significant step forward in proving that a BWB configuration can be viable, it was not designed to test any of the above objectives. All of these experimental objectives require a significantly larger vehicle with more precise instrumentation. The last two items require that the pilot be on-board the airplane. With the objectives established, sets of similarity relations can be chosen that best meet these individual test objectives.

Table 78 shows the three sets of similarity relations that are relevant to STV testing.

Table 78 Similarity Relationships

Scale Factor = *K* Density Ratio = *D*	Static Mach Scaling	Dynamic Mach Scaling	Conventional Dynamic Scaling
Test Objective (Test Priority)	**Cruise Perf. (1) and Acoustics (2)**	**Transonic Handling (3)**	**Terminal Area Handling (4)**
Length, *l*	K	K	K
Angle, θ	1	1	1
Froude Number, (V^2/lg)	K^{-1}	1	1
Acceleration, *g*	1	K^{-1}	1
Velocity, *V* or *M*	1	1	$K^{1/2}$
Time, *t*	$K^{1/2}$ to K	K	$K^{1/2}$
Angular Velocity, θ'	$K^{-1/2}$ to K^{-1}	K^{-1}	$K^{-1/2}$
Angular Acceleration, θ''	K^{-1} to K^{-2}	K^{-2}	K^{-1}
Density, ρ	D	D	D
Mass, *m*	DK^2	DK^3	DK^3
Inertia, *I*	DK^4	DK^5	DK^5
Force, *F*	DK^2	DK^2	DK^3
Moment, *T*	DK^3 to DK^2	DK^3	DK^4

The table lists the test objectives identified above for which the specific similarity relations are valid. It is important to note that the density ratio, D, does not have the same meaning as the density ratio for the atmosphere, commonly referred to as sigma. The atmospheric density ratio is defined as the air density at the test condition divided by the air density at sea level standard day conditions. The airplane density ratio, D, is defined as the mass density of the subscale test airplane divided by the mass density of the full scale airplane. As the table shows, this also corresponds to the air density where the subscale test must be conducted divided by the air density for the full scale airplane test condition that will be matched.

The first set of similarity relations, labeled Static Mach Scaling, preserves the test Mach number and velocity. Mach number and flow velocity are primary driving parameters in airplane performance testing and acoustic measurements. These quantities will identically match the same test on the full size PSC. Once these primary items to be matched are chosen, the other similarity relations can be derived. The items in red text represent areas where this particular set of similarity relations breaks down relative to the full scale PSV vehicle. The Froude number is not preserved, which leads to dynamic relations farther down the column having multiple possible similarity relations depending on how they are derived. This clearly cannot be the case in the real world and so these dynamic variables cannot be matched for this type of testing. In addition to preserving Mach number and airspeed, the acceleration is also preserved, which allows for testing in a normal one g gravity environment. Measured forces can be appropriately scaled back to the full size vehicle, but not moments. So, Static Mach Scaling cannot be used when the airplane is not in trim moment balance because the resulting moments will be incorrect. A byproduct of the forces being appropriately scaled is that the lift coefficient, C_L, and the drag coefficient, C_D, are identically matched to the full sized airplane.

The second set of similarity relations is labeled Dynamic Mach Scaling. The primary motivation behind all forms of dynamic scaling is to accurately match the aerodynamic and inertial forces on the vehicle so that the resulting motion is also scaled. This type of scaling is sometimes also called movie scaling because it is used by the film industry to allow subscale vehicles to simulate much larger vehicles. Note that the scaling relations include the scaling of time. For movie production, the subscale vehicle is filmed at higher frame rate. When played at normal speed, the resulting motion looks like how a full sized vehicle would move. For Dynamic Mach Scaling, Mach number and velocity are preserved relative to the full scale airplane, but so is the Froude number. When the Froude number is preserved, it means that the complete set of dynamic (non-trim) testing variables will have well behaved scaling relationships relative to the full scale airplane. But, one parameter in this set is not properly scaled relative to the full scale vehicle and that is the acceleration. In order to perform testing where the Mach number and the airplane dynamics are properly scaled, the airplane must be operated in a state with accelerations greater than one g. This set of similarity relations is appropriate for testing dynamic handling qualities at transonic conditions, but the proper test condition will have to be reached in turning flight with the proper g level that scales to the full scale airplane g level for that test condition.

The last set of similarity relations is labeled Conventional Dynamic Scaling. Here, the Froude number and the acceleration are matched identically with the full scale airplane. But, as with all of the other similarity relations, something will not be properly matched in the subscale test. In this case, it is the Mach number and velocity. As expected when the Froude number is matched, all of the dynamic parameters have well behaved scaling relations. This set of similarity relations is appropriate when the objective is to do dynamic tests at low Mach number conditions, such as takeoff and landing. This is the set of scaling relations that were used in the design and construction of the X-48B so that it would have proper flight dynamics for testing low speed flight control algorithms. The motions recorder by its onboard sensors can be directly scaled to the motions of a full scale BWB.

Ideally, the ERA STV airplane would be able to accomplish all of the test objectives outlined above. This would mean designing the airplane so that it could be loaded on a particular test day to match the proper set of similarity relations for the testing scheduled. The flight test program would be structured in phases with similar tests grouped on a set of flights with the airplane loaded a particular way. Once one set of tests are completed, the airplane could be set up for a different set of test using a different set of similarity relationships. But, this is only possible in practice if the airplane is large and flexible enough to be able to meet all three sets of similarity relations.

The Static Mach Scaling relationships result in a much heavier test vehicle than Dynamic Mach Scaling or Conventional Dynamic Scaling. Both the Static and Dynamic Mach Scaling require more thrust than needed for Conventional Dynamic Scaling. So, it is impossible to simultaneously meet these requirements at the same test condition unless the vehicle is full scale. If the STV can be designed to have the low weight required for both types of Dynamic Scaling, but the high thrust required for both types of Mach scaling, then it can be operated with de-rated thrust for Conventional Dynamic Scaling tests and ballasted to higher test weights for Static Mach Scaling tests. This may also not be fully practical in one airplane design. By bringing in an additional degree of freedom, test altitude, it may be possible to strike a reasonable compromise between the three sets of scaling relations. If the airplane cannot reach the minimum weight for Dynamic Scaling, then a low altitude test mission can still simulate Dynamic Scaling at a higher altitude. Similarly, if the airplane cannot be ballasted to the full weight required for Static Mach Scaling, then the airplane can fly higher to simulate the correct Mach and C_L conditions of the full scale airplane cruise.

At the start of the STV design process, a study was undertaken to figure out the minimum vehicle scale that would allow sufficient flexibility to achieve all of the test objectives. The single most expensive COTS item on any airplane is the engine. These only come in discrete sizes and it is important for the scaling study to use engines that are either available today or will be available within the design timeframe of the STV vehicle. Three candidate engines were chosen for the study with characteristics that would be beneficial for the STV performance and acoustics testing. Three candidate STV vehicles were then crudely sized to match the candidate engines. Then, each candidate STV was evaluated using the similarity relations relative to the full scale PSC to see if they could perform the appropriate tests.

The Scaled Initial Cruise Weight is the highest weight at which transonic testing is desired. For the Cruise Performance testing, this weight is about 4,000 lbs below the MTOGW, which gives a fuel allowance to climb to altitude. Even if the airplane burns more fuel getting to altitude, the initial cruise test point will be close to the scaled value. The load factors at the test condition and to reach the buffet condition are the same as for the full scale PSC.

For the Transonic Handling Qualities evaluation, the airplane needs to be lighter than for Transonic Cruise testing. The weight required is still well within the practical airplane weight envelope. As discussed earlier, the pilot will need to pull load factor to reach the correct test condition. At 65% scale, this requires 1.54g of load factor to reach the equivalent of a 1.0g test condition for the PSC. To reach the buffet condition requires pulling 2.0g on the 65% scale STV. This is considered about as high as is practical without undue stress on the pilot and airframe.

Other issues besides the similarity relations may dictate the final vehicle size. As discussed earlier, there will be a definite minimum size in order to have a usable cockpit for the pilots, but not grossly violate the PSC loft. The structure must be close to full scale if it is going to provide substantial risk reduction for the jump to a production vehicle. Available propulsion systems and other commercial-off-the-shelf components may also dictate the vehicle size. Engines tend to come grouped in particular thrust classes and there are definite gaps between these sizes. Existing landing gear must be found that not only retract in the desired manner, but support the weight of the test vehicle. The advanced fly-by-wire control system requires actuators with enough hinge moment, bandwidth, and rate to properly stabilize the vehicle. Hinge moments grow as the cube of the vehicle size, so actuator requirements increase rapidly with vehicle size. All of these are long lead items for a vehicle program and have significant impact on the design. The search and selection of off-the-shelf components for these items may save significant cost, but also could box the design into an undesirable corner. These trades need to be investigated early and components selected wisely. On the X-48 program, the biggest problems were caused by the off-the-shelf items and not the ones that were custom designed for the airplane. This may point to the use of custom designed components as a way to free up the vehicle design space and to lower final integration costs, but careful cost trades are required.

In summary, the 65% scale STV is well positioned in size to meet all ERA and BWB development experiment objectives. A smaller airplane would be cheaper, but it would be difficult to fit test crew and equipment inside, and would not meet some of the test objectives. This is a case where a bargain approach would not turn out to be a bargain in the end. The 65% scale STV is the necessary development step to making a BWB type PSC possible.

Appendix B – Mission Wind Analysis

To assess the 95% worst case wind requirement, world wind data were obtained from the National Center for Atmospheric Research (NCAR) database. This database contains winds from 1948 to 2004 at six hour intervals. Wind speeds can be obtained for 17 altitudes, every 2.5 degrees in latitude and longitude. Two altitudes (37,630 and 43,940 ft) were selected which are within the expected STV cruise altitudes. Figure 151 shows the 95th percentile winds at the lower altitude and Figure 152 shows winds at the higher altitude.

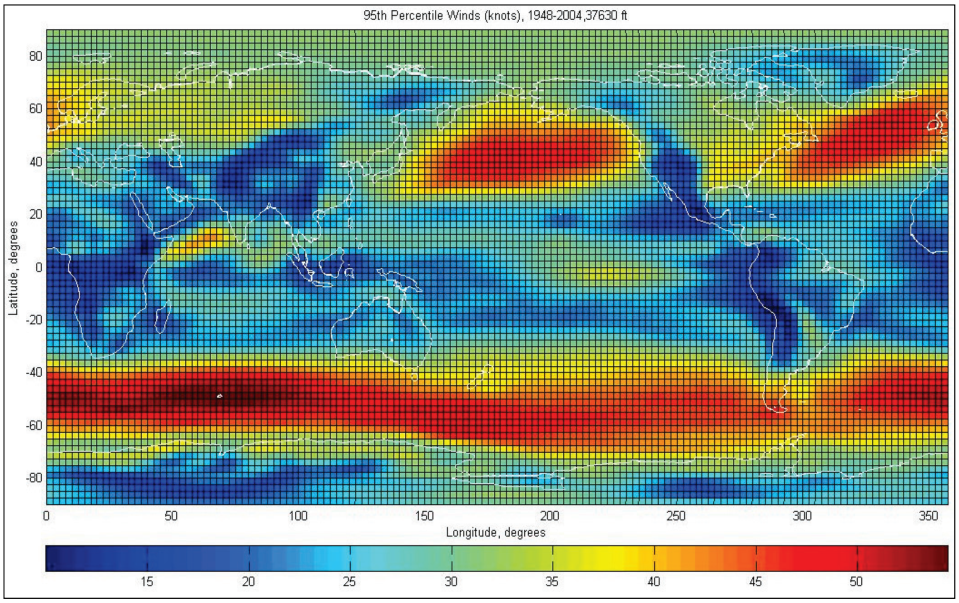


Figure 151 95th Percentile Winds at 37,630 ft

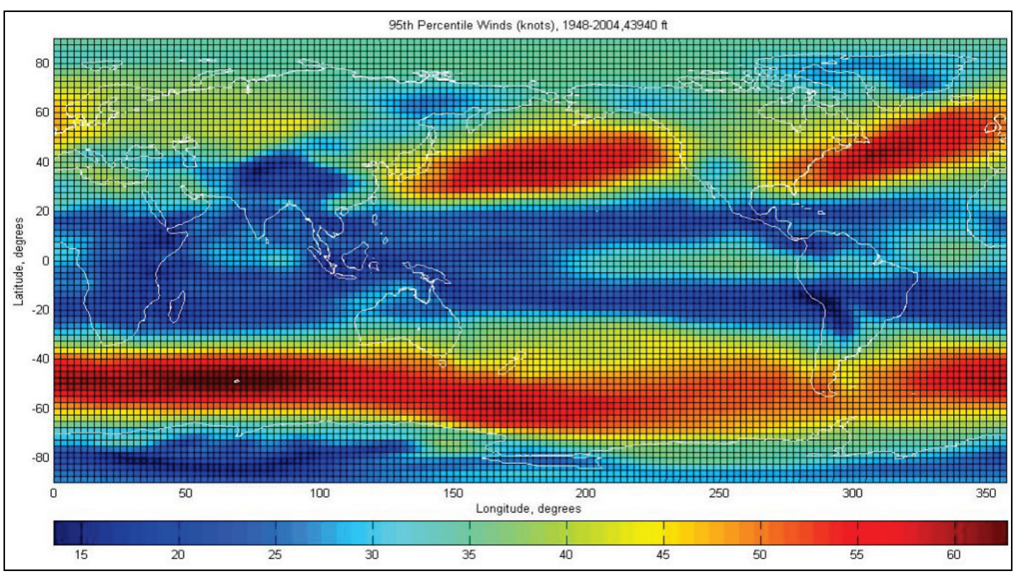


Figure 152 95th Percentile Winds at 43,940 ft

For the STV assessment, the winds in the lower 48 were selected (shown in Figure 153). To assess the winds along the longest city pair route, a line has been drawn from Miami to Seattle (longest range route) and the speed of each pixel determined and averaged along the route. At the lower altitude the average wind speed is 27 kts. At the higher altitude it is 39 knots. When these two altitudes are combined, the average wind speed is 33 knots. The flight path of the STV will likely not experience direct head wind, so the effective 95th percentile wind speed will be somewhat lower than this during the Miami to Seattle flight.

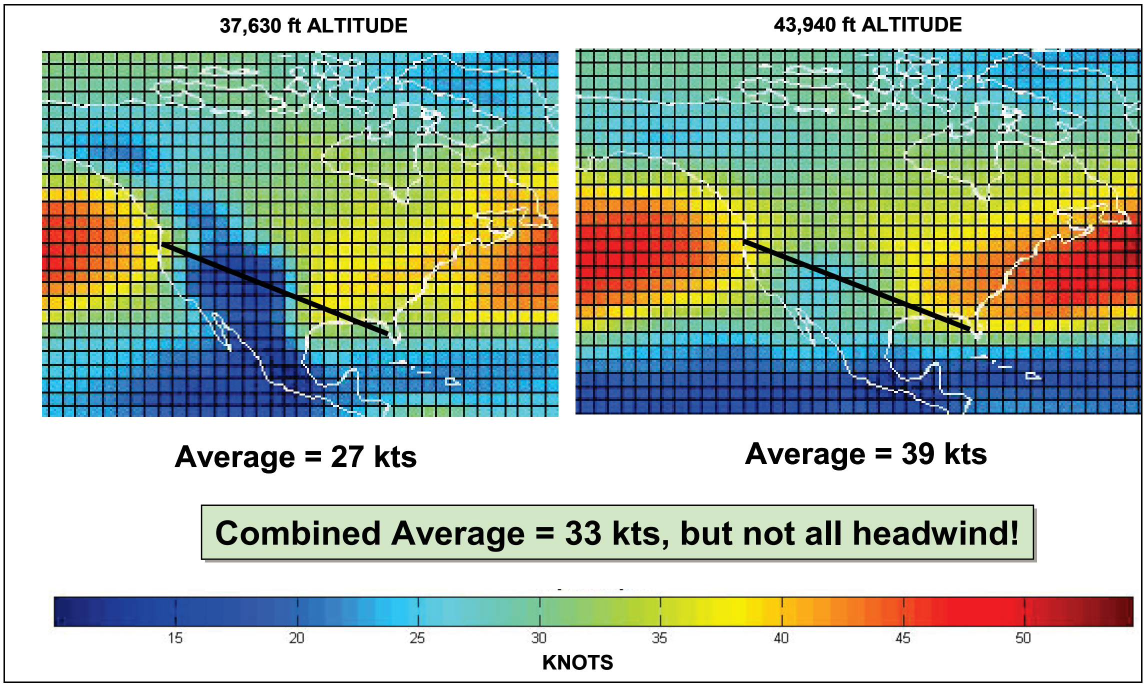


Figure 153 Average Winds (Miami to Seattle)

Next step is to determine the impact of the 95th percentile winds on range. Figure 154 shows a parametric analysis of how head winds affect the range. To do this analysis the cruise true airspeed was determined at Mach 0.85 and 39,000 ft. Various winds were applied to this airspeed and the resulting increase in time to complete a specified range was determined. This time increase was multiplied by the cruise speed to determine the effective range increase. The percent increase in range is observed to be independent of the base range, so the factor can be applied to any range. An additional calculation made at Mach 0.85 and 35,000 ft. showed very little difference from the Figure 154 results. Figure 154 also shows the effect of the winds not blowing all of the time, or not being direct head wind.

If the head wind persisted throughout the flight (worst case), the range impact would be about 7%. However, a more likely scenario is that the effective head wind speed would be about 50% of the full head wind speed, the range impact would be about 3%. As stated above, the ERA reference mission includes a 5% block fuel allocation for the effect of winds. Boeing recommends that this allocation is sufficient, based on the above wind analysis.

To determine the 95th percentile wind impact on STV range, the results of Figure 153 and Figure 154 are combined. This is shown in Figure 155, for an average wind speed of 33 kts.

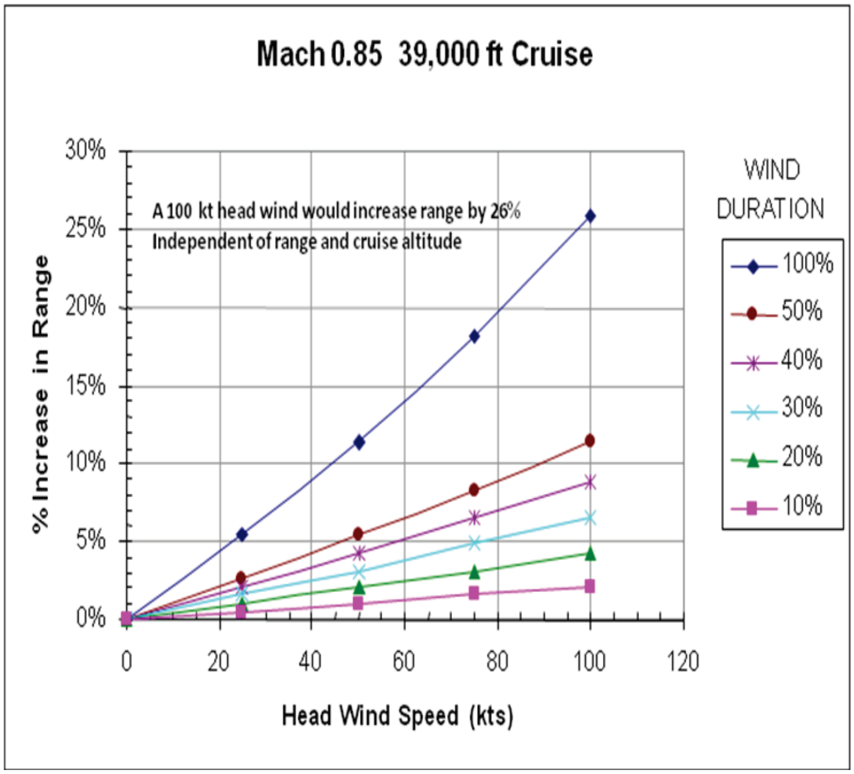


Figure 154 Wind Impact on Range

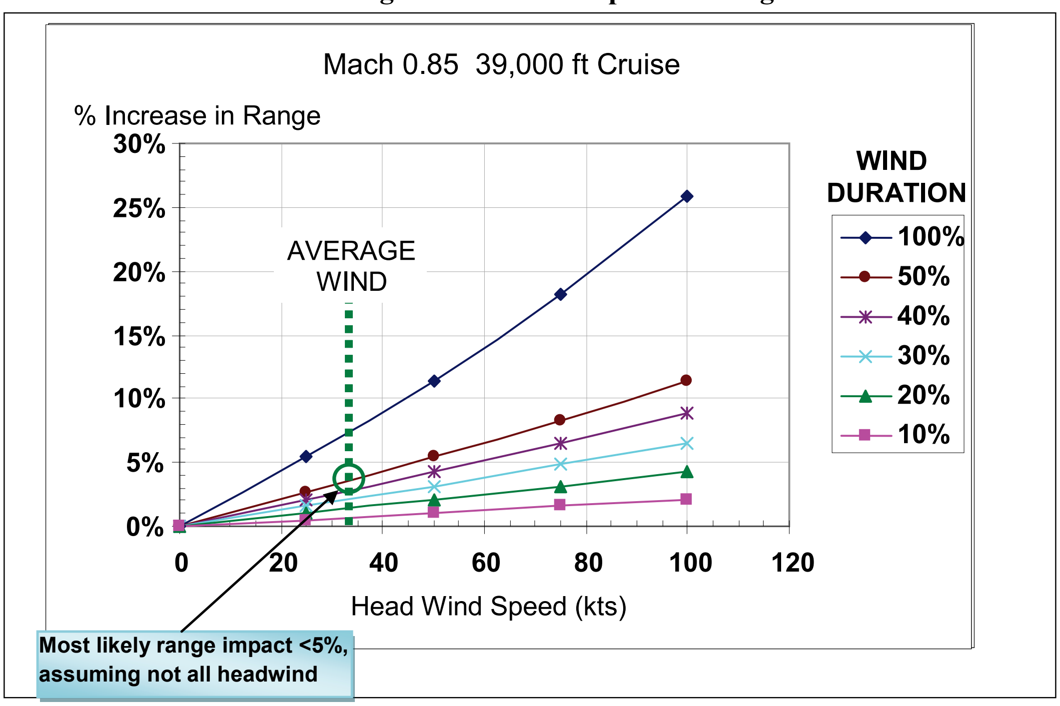


Figure 155 Expected Average Wind Impact on Range

Appendix C – 100 Busiest Airport Database

The 100 busiest airports were obtained from the report CY09 ACAIS Commercial Service Airports (Primary and Nonprimary), updated 11/23/2010 using CY09 Passenger Boardings. There are several criteria by which "busiest" can be determined. This database uses passenger boardings as the criteria and can be obtained from: http://www.faa.gov/airports/planning_capacity/passenger_allcargo_stats/passenger/media/cy08_primary_np_comm.pdf.

The report lists the airports by rank and their boardings, but does not contain any data useful to performance analysis, such as runway length, elevation, and temperature data. These runway length and elevation data were obtained from www.world-airport-codes.com . Airport temperature data was obtained from a Boeing Corporate resource named Atmospheric Physics. The NASA requirement stated that the top 100 continental United States (CONUS) airports be included. This database included United States airports outside of CONUS (such as Honolulu, HNL). These eight non-CONUS airports were stripped out and the database continued past the 100 rank. Features of the top 100 airports are listed in Table 79 below.

Table 79 Top 100 CONUS Airports

Rank	RO	ST	Locid	City	Airport Name	Runway Length (ft)	Runway Elevation (ft)	Average Daily High Temperature worst month (deg F)	Mean Summer Temperature (deg F)
1	SO	GA	ATL	Atlanta	Hartsfield - Jackson Atlanta International	11889	1010	89	78
2	GL	IL	ORD	Chicago	Chicago O'Hare International	13000	653	83	74
3	WP	CA	LAX	Los Angeles	Los Angeles International	12091	100	76	69
4	SW	TX	DFW	Fort Worth	Dallas/Fort Worth International	13401	551	96	85
5	NM	CO	DEN	Denver	Denver International	12000	5431	86	73
6	EA	NY	JFK	New York	John F Kennedy International	14572	16	83	75
7	WP	NV	LAS	Las Vegas	McCarran International	12636	2162	104	91
8	SW	TX	IAH	Houston	George Bush Intercontinental/Houston	12001	96	94	82
9	WP	AZ	PHX	Phoenix	Phoenix Sky Harbor International	11001	1110	105	93
10	WP	CA	SFO	San Francisco	San Francisco International	11870	8	72	62
11	SO	NC	CLT	Charlotte	Charlotte/Douglas International	10000	700	89	78
12	EA	NJ	EWR	Newark	Newark Liberty International	11000	30	86	77
13	SO	FL	MCO	Orlando	Orlando International	12004	91	92	81
14	SO	FL	MIA	Miami	Miami International	13000	12	90	82

Rank	RO	ST	Locid	City	Airport Name	Runway Length (ft)	Runway Elevation (ft)	Average Daily High Temperature worst month (deg F)	Mean Summer Temperature (deg F)
15	GL	MN	MSP	Minneapolis	Minneapolis-St Paul International/Wold-Chamberlain	11006	834	83	73
16	NM	WA	SEA	Seattle	Seattle-Tacoma International	11900	450	75	64
17	GL	MI	DTW	Detroit	Detroit Metropolitan Wayne County	12003	633	83	73
18	EA	PA	PHL	Philadelphia	Philadelphia International	10500	361	85	75
19	NE	MA	BOS	Boston	General Edward Lawrence Logan International	10081	161	82	72
20	EA	VA	IAD	Dulles	Washington Dulles International	11501	313	88	78
21	EA	NY	LGA	New York	La Guardia	7000	11	85	76
22	EA	MD	BWI	Glen Burnie	Baltimore/Washington International Thurgood Marshal	9519	196	88	77
23	SO	FL	FLL	Fort Lauderdale	Fort Lauderdale/Hollywood International	10000	10	89	83
24	NM	UT	SLC	Salt Lake City	Salt Lake City International	12003	4222	92	78
26	EA	VA	DCA	Arlington	Ronald Reagan Washington National	6869	10	88	79
27	WP	CA	SAN	San Diego	San Diego International	9400	26	75	70
28	SO	FL	TPA	Tampa	Tampa International	11002	19	90	81
29	GL	IL	MDW	Chicago	Chicago Midway International	6519	623	83	75
30	NM	OR	PDX	Portland	Portland International	11011	21	80	67
31	CE	MO	STL	St. Louis	Lambert-St Louis International	11019	535	89	79
32	SO	KY	CVG	Greater Cincinnati International Airport	Cincinnati/Northern Kentucky International	12000	869	86	75
33	SO	TN	MEM	Memphis	Memphis International	9319	318	91	81
34	CE	MO	MCI	Kansas City	Kansas City International	10801	973	90	81
35	GL	OH	CLE	Cleveland	Cleveland-Hopkins International	8998	770	83	73
36	WP	CA	OAK	Oakland	Metropolitan Oakland International	10000	5	74	64
37	WP	CA	SMF	Sacramento	Sacramento International	8600	27	91	79

Rank	RO	ST	Locid	City	Airport Name	Runway Length (ft)	Runway Elevation (ft)	Average Daily High Temperature worst month (deg F)	Mean Summer Temperature (deg F)
38	SO	NC	RDU	Raleigh	Raleigh-Durham International	10000	376	89	76
39	SO	TN	BNA	Nashville	Nashville International	11030	580	90	79
40	WP	CA	SNA	Santa Ana	John Wayne Airport-Orange County	5701	50	72	66
41	WP	CA	SJC	San Jose	Norman Y. Mineta San Jose International	11000	56	82	69
43	SW	TX	HOU	Houston	William P Hobby	7602	49	92	84
44	SW	TX	AUS	Austin	Austin-Bergstrom International	12248	597	96	84
45	EA	PA	PIT	Pittsburgh	Pittsburgh International	11500	1150	83	72
46	SW	LA	MSY	Metairie	Louis Armstrong New Orleans International	10104	3	90	81
47	GL	WI	MKE	Milwaukee	General Mitchell International	9690	672	80	71
48	SW	TX	SAT	San Antonio	San Antonio International	8502	794	95	84
49	GL	IN	IND	Indianapolis	Indianapolis International	10005	792	85	75
50	SW	TX	DAL	Dallas	Dallas Love Field	8800	486	96	86
51	SO	FL	RSW	Fort Myers	Southwest Florida International	12000	15	92	81
52	GL	OH	CMH	Columbus	Port Columbus International	10701	812	85	74
53	SO	FL	PBI	West Palm Beach	Palm Beach International	7989	18	90	82
54	SW	NM	ABQ	Albuquerque	Albuquerque International Sunport	13375	5326	92	78
55	SO	FL	JAX	Jacksonville	Jacksonville International	8000	23	91	81
56	EA	NY	BUF	Buffalo	Buffalo Niagara International	8828	705	81	71
57	NE	CT	BDL	Windsor Locks	Bradley International	9502	160	85	73
59	WP	CA	ONT	Ontario	Ontario International	12198	287	92	76
60	WP	CA	BUR	Burbank	Bob Hope	6902	775	89	75
62	NE	RI	PVD	Warwick	Theodore Francis Green State	7166	3	79	71
63	CE	NE	OMA	Omaha	Eppley Airfield	8500	980	86	77
64	WP	NV	RNO	Reno	Reno/Tahoe International	11000	3933	94	78
65	WP	AZ	TUS	Tucson	Tucson International	10990	2584	100	86

Rank	RO	ST	Locid	City	Airport Name	Runway Length (ft)	Runway Elevation (ft)	Average Daily High Temperature worst month (deg F)	Mean Summer Temperature (deg F)
66	EA	VA	ORF	Norfolk	Norfolk International	9000	16	87	79
67	SW	OK	OKC	Oklahoma City	Will Rogers World	9802	1280	93	81
68	EA	VA	RIC	Highland Springs	Richmond International	8999	164	87	78
69	SO	KY	SDF	Louisville	Louisville International-Standiford Field	10850	477	88	78
70	NE	NH	MHT	Manchester	Manchester	9250	193	83	70
71	SW	TX	ELP	El Paso	El Paso International	12010	3918	96	82
72	NM	WA	GEG	Spokane	Spokane International	9000	2356	83	68
73	SO	AL	BHM	Birmingham	Birmingham-Shuttlesworth International	10000	620	90	80
74	SW	OK	TUL	Tulsa	Tulsa International	10000	668	93	83
75	WP	CA	LGB	Long Beach	Long Beach /Daugherty Field/	10000	383	83	71
76	NM	ID	BOI	Boise	Boise Air Terminal/Gowen Field	9763	2838	90	75
77	EA	NY	ALB	Albany	Albany International	7200	285	83	72
79	EA	NY	ROC	Rochester	Greater Rochester International	8001	547	82	72
81	GL	OH	DAY	Dayton	James M Cox Dayton International	10900	995	85	75
83	SW	AR	LIT	Little Rock	Adams Field	7173	257	92	82
84	SO	SC	CHS	Charleston	Charleston AFB/International	9001	38	90	81
85	EA	NY	SYR	Syracuse	Syracuse Hancock International	9003	421	82	71
86	EA	NY	HPN	White Plains	Westchester County	6548	440	82	73
87	NM	CO	COS	Colorado Springs	City of Colorado Springs Municipal	11021	6090	85	70
88	EA	NY	ISP	Islip	Long Island MacArthur	5999	11	85	76
89	GL	MI	GRR	Grand Rapids	Gerald R. Ford International	10000	707	83	72
90	NE	ME	PWM	Portland	Portland International Jetport	6800	57	79	69
91	SO	NC	GSO	Greensboro	Piedmont Triad International	10001	886	88	77
92	CE	IA	DSM	Des Moines	Des Moines International	9001	957	86	76
93	SO	FL	SFB	Sanford	Orlando Sanford	9600	57	92	82

Rank	RO	ST	Locid	City	Airport Name	Runway Length (ft)	Runway Elevation (ft)	Average Daily High Temperature worst month (deg F)	Mean Summer Temperature (deg F)
					International				
94	SO	TN	TYS	Alcoa	McGhee Tyson	9008	949	88	77
95	SO	GA	SAV	Savannah	Savannah/Hilton Head International	9003	46	92	81
96	GL	WI	MSN	Madison	Dane County Regional-Truax Field	9005	858	83	72
97	WP	CA	PSP	Palm Springs	Palm Springs International	8500	448	109	92
98	CE	KS	ICT	Wichita	Wichita Mid-Continent	7302	1321	92	81
99	GL	OH	CAK	Akron	Akron-Canton Regional	6397	1208	83	72
100	SO	SC	MYR	Myrtle Beach	Myrtle Beach International	9502	33	88	81
101	NE	VT	BTV	Burlington	Burlington International	7807	332	81	70
102	SO	FL	PNS	Pensacola	Pensacola Gulf Coast Regional	7002	30	89	82
103	SO	FL	SRQ	Sarasota/Bradenton	Sarasota/Bradenton International	9500	30	90	83
105	SO	MS	JAN	Jackson	Jackson-Evers International	8500	330	92	80
106	SO	SC	GSP	Greer	Greenville Spartanburg International	7600	973	89	78
107	EA	PA	MDT	Harrisburg	Harrisburg International	9501	338	86	75

Appendix D – STV Objectives and Requirements

Requirements for the STV have been developed from top level requirements and objectives from two primary sources. The first source is Appendix D of the NRA solicitation. These have been grouped into 4 objective categories:

1. Demonstrate technologies that enable the PSC to meet the ERA goals
2. Demonstrate technologies that enable UAS operations in the NA
3. Provide a flexible test bed for other advanced technologies
4. Other objectives and requirements from the NRA

The second source is a list of 12 ConOps items provided by NASA during the study (NASA ERA N+2 Advanced Vehicle Concept Study, Subscale Testbed Vehicle (STV) ConOps, Version 1.0, April 12, 2011). These are listed under item 5 below.

These starting point requirements and the flow-down and derived requirements are documented in a "STV System Requirements Document.

Starting Point Requirements and Objectives from the NRA

NRA Appendix D source page in parentheses.

Demonstrate technologies that enable the PSC to meet the ERA goals

- a subscale version of the design team's PSC (D-5) (D-14)
- sufficient scale to
  - support current noise reduction scaling methodology
  - demonstrate high Reynolds number requirements for aerodynamic efficiency
  - this means approximately a 50% scale vehicle (D-23)
- Provide critical validation data for predictive methods required for design of a full scale PSC (D-5)
- present a clear and quantifiable developmental path to the PSC from the ERA/UAS subscale testbed vehicle. (D-14)
- traceable to, and reduce the risk of, the PSC (D-14)
- flight research would reduce the risk associated with designing and building a full scale vehicle based on the proposer's PSC. (D-14)
- incorporating in an integrated fashion key enabling technologies required to simultaneously meet the ERA noise, emissions, and fuel burn goals. (D-5) (D-14)
- designed to test integrated technologies that are critical to the success of the PSC (D-10) (D-14)
- Reduce the risk for the technologies / integrations that are critical enablers for the proposed 2025 entry into service (EIS) of the PSC (D-5)
- cruise Mach number of the ERA/UAS subscale testbed vehicle must match the PSC design cruise speed. (D-14)
- vehicle shall demonstrate controlled flight throughout the full flight envelope of the PSC vehicle. (D-23)
- provide quantitative evidence that the N+2 fuel burn, emissions and noise goals can be met by the PSC (D-5)

Demonstrate technologies that enable UAS operations in the NAS

- second objective for the proposed subscale flight test vehicle is as a testbed and demonstrator of UAS in the NAS capabilities and technologies that will be developed under this new project. (D-5)
  - desired that the design of the subscale testbed vehicle accommodate the insertion of these technologies for both development and demonstration purposes in the 2015 and beyond timeframe. (D-5)

- vehicle design should allow for insertion of developing technology and avionics that would enable the routine operation of UAS in the NAS …addressing issues related to
    - separation assurance
    - collision avoidance
    - robust command, control and communications
    - remote pilot-vehicle interface issues
    - environmental hazards detection/avoidance (D-5) (D-10) (D-14)
    - resiliency to environmental hazards. (D-23)

- provide a flexible testbed for future flight campaigns for integrating UAS into the NAS. (D-10) (D-14)
- testbed vehicle should be capable of operation in piloted, remotely piloted, and fully autonomous modes in order to demonstrate UAS operations in the NAS (D-10) (D-14)
- expected that the ERA/UAS subscale testbed vehicle will eventually be remotely piloted or autonomous, in order to demonstrate UAS operations in the NAS. (D-14) (D-23)
- These flight campaigns will … evaluate technologies needed for integrating UAS into the NAS. (D-5)
- Avionics packages will be modular and allow for integration to either the NASA Aviation Safety Program (AvSP) or Airspace Systems Program (ASP) activities (D-23)
    - Integrated Vehicle Health Management Project
    - Integrated Intelligent Flight Deck Project
    - Integrated Resilient Aircraft Control Project
    - Aircraft Aging and Durability Project

Provide a flexible test bed for other advanced technologies

- a flexible ERA/UAS vehicle test bed for future flight test campaigns (spiral flight test activities, nominally in 5-6 year blocks) that might involve
    - integration of a future advanced propulsion system
    - new vehicle control laws
    - remotely piloted or autonomous flight in the NAS (D-22)
- flight control system will be digital with research flight control system capability to allow for flexibility in assessing technologies such as advanced flight control laws. (D-23)

Other objectives and requirements

- vehicle must have retractable landing gear (D-14)
- Options for initial operation (manned, remotely piloted, autonomous) should be explored during the study with factors such as cost, operational flexibility and research potential taken into account. (D-14)
- It should have an endurance of at least 3 hours (longer preferred). (D-23)
- avionics will be integrated to a data acquisition system for development of high quality flight test data. (D-23)
- particular attention will be paid to possible integrated vehicle health monitoring applications for diagnostics and detection of structural integrity issues. (D-23)

NASA ConOps, Version 1.0, April 12, 2011

1. Piloted, with provision for two pilots
2. Capable of reconfigurable avionics/cockpit to accommodate eventual safety pilot and/or remote pilot operations.
3. Capable of all weather operations – anti ice systems, appropriate avionics, etc.
4. Capable of travelling to various air shows.
5. Capable of performing EXTENDED simulated airline or cargo service.

6. Scaled to at least 50 percent of reference vehicle size. (About 100 ft. or larger wing span.) Design payload to scale from PSC design payload with aircraft scale.
7. Range requirement: capable of travelling between all city pairs in lower 48 with design payload, with 95% worst case winds.
8. Runway requirement: capable of using 100 busiest airports in US with design payload and fuel load capable of meeting range requirement in 7 with standard day conditions.
9. Pressurized cargo area.
10. Up to 32,000 lb thrust engines (consistent with scaling description in 6). Best technology available - Must enable aircraft system to demonstrate simultaneous achievement of ERA system level goals. Could be developmental engines, but must have sufficient life.
11. 20-year and 10,000 hr projected useful life for STV aircraft. Determine sensitivity of STV cost to both the 20-year and 10,000 hr projected useful life.
12. Identify major systems and technologies used on the STV that can be removed and replaced with updated systems or different technologies in future test spirals of the aircraft. Identify what changes (i.e. structural concept – yes, OML – no, etc) can be made to major components (wings, fuselage, control surfaces, propulsion) in future test spirals to test technologies that enable simultaneous achievement of the noise, emissions and fuel burn goals.

Options: Ramp – Not required, unless the STV is based off of a cargo version of the PSC that has a ramp.

Appendix E - Executive Summary of Cranfield Aerospace Study for the Environmentally Responsible Aviation Programme

Technical Note

CRANFIELD AEROSPACE

Executive Summary of Cranfield Aerospace Study for the Environmentally Responsible Aviation Programme on behalf of Boeing R&T.

Issue:	1.0	*Compiled by:*	G. Dickman Dr Robert Jones Prof Ian Poll
Date:	5th December 2011		
Ref:	CAe/BNG/ERA/R005		

1. INTRODUCTION

Cranfield Aerospace Limited (CAe) were requested to provide a contribution to Boeing's work under ERA addressing two specific areas. These were:

Task 1: Integration of Unmanned Aircraft Systems (UAS) into US and European Airspace

Task 2: Environmental Characteristics of Conceptual Aircraft Emissions

The work performed on these topics and major findings resulting from this is summarised below, and reported in full in the study final report[1].

2. TASK 1: INTEGRATION OF UNMANNED AIRCRAFT SYSTEMS (UAS) INTO US AND EUROPEAN AIRSPACE

The motivation behind study of this subject for the Boeing ERA work was that a potential approach for progression of work on this programme in the future could involve production of a sub-scale demonstrator of a selected civil transport aircraft configuration. This aircraft would be used to fly demonstration operations but it would, crucially, be intended to operate, under normal circumstances, as a UAS. Therefore, it would be important to understand whether and how such an aircraft could operate, in the intended fashion as a UAS, within the general airspace that would be necessary to perform the demonstration operations.

The overall task was divided into seven specific sub-tasks. These attempted to cover the recognised important aspects of attempting to operate a single, or potentially multiple, UAS within the airspace environment that presently exists within Europe and the US but also taking account of the projected developments in the way airspace and its control/management is expected to change in the foreseeable future. This would provide the basis for the Concept of Operations (CONOPS) for a potential sub-scale UAS flight demonstrator aircraft to perform risk reduction and address technology gaps whilst operating in the expected airspace management and control systems.

Allowing any type of UAS to operate within airspace such that it is not segregated from normal manned aircraft and away from areas where, if a failure caused it to come to ground, it would not have the potential to endanger people or property is a subject that has been exercising all the relevant aviation organisations and bodies for many years. Therefore, a major aspect of the approach taken to gather the necessary knowledge on exactly where things stand on the subject at present and how matters are likely to develop in future was to use CAe's membership and connections to the relevant initiatives in Europe to attend workshops and meetings being held over the period of study. In particular, proceedings at the gatherings of three initiatives were drawn upon. These were:

Meetings of EUROCAE's Working Group 73

Workshops of the E4U Initiative

Workshops of the European Commissions UAS Panel

CAe is a member of the European aviation equipment manufacturers association, EUROCAE's, Working Group 73. This was founded in 2006 and tasked by the European Aviation Safety Agency (EASA) with addressing and providing recommendations for the safe integration of UAS into European airspace. Its organisation and terms of reference have altered over the period

[1] CAe/BNG/ERA/R004 Issue 1.0, ERA N+2 UAS and Aircraft Emissions Study - Purchase Contract No: 448350 - Final Report: October 2011

since its inception but, in general, progress towards its aims has been disappointingly slow for several reasons. These include lack of funding for its work and consequent poor attendance, failure to achieve consensus particularly between airworthiness authorities and industry members and postponement of meetings. However, WG73 does have a wide base of membership from the entire global aviation community as well as links to the efforts of other relevant organisations outside Europe. Therefore, it does provide a good opportunity to gauge the present situation. In addition, it is through membership of WG73 that CAe has been invited to take part in other relevant initiatives.

E4U (EREA for UAS) is an initiative that took place over 2011 to perform a scoping and prioritisation study of topics for a programme aimed at achieving insertion of UAS into general airspace. This results from European Defence Ministers launching an attempt to ensure that funding for defence R&T was better aligned with that on civil security and space provided by the European Commission EC and European Space Agency (ESA). The European Defence Agency (EDA) were subsequently tasked with preparation of a UAS programme prioritising technical topics and presenting a business case to participating Member States (pMS) that resulted in funding of the E4U study.

EREA (European Research Establishments Association) was tasked with performing the E4U study and in doing so organised a series of three workshops to involve the widest range of potential stakeholders in the subject of UAS air traffic insertion. CAe was invited to these workshops and provided with correspondence and access to material produced. The final workshop took place in September 2011. At this the study personnel presented and led discussions on their identified priorities of topics for address and a business case based on two Goal Options to achieve flight of UAS in un-segregated airspace within a five year timeframe. Whilst the identified Goal Options and priorities appeared sensible, there was scepticism expressed over the timeframe and budgets defined (0.5 to 1 billion Euro), particularly as there was no indication that the pMS were prepared to support anything in the present financial climate. A decision is due on whether any work will go ahead in early 2012 following discussion with the pMS.

In 2009 the Directorate General of the EC concerned with mobility and transport (DG-MOVE) conducted a hearing on UAS. This led, via a high level conference in 2010, to the launch of an EC process at the Paris Air Show in 2011 to consider uses and what institutional and infrastructure alterations would be necessary to allow UAS to fly in non-segregated airspace. In order to collect the information to produce a strategy paper for future UAS in Europe, the EC instituted a UAS Panel and called for contributions and organised workshops on five distinct subjects:

Economic Importance of UAS
Insertion into non-segregated airspace (including radio frequency management)
Safety related issues, airworthiness.
Societal dimension
Research and Development

Workshops on the first four of these have taken place with the final one due to occur early next year. For each workshop written contributions have been called for, relevant literature collated and a discussion paper produced and distributed prior to the event.

CAe attended the 2nd, 3rd and 4th workshops of this initiative and these have proved to be very helpful. Not only have they provided further detail on the present and likely future with regard to the possibilities for integration of UAS into non-segregated airspace but they have also exposed some of the less obvious considerations that will need to be addressed by anyone wishing to attempt to operate a UAS. From the EC UAS Panel workshops and supporting information, it is clear that we are some way from the possibility of anything approaching routine operation of UAS in un-segregated. In fact, to-date there are no true examples of UAS flying as General Air Traffic (GAT), under ICAO rules, in such airspace in a completely non-segregated fashion. To allow this to happen will require significant changes in many areas which extend well beyond the obvious airworthiness and technical areas into areas such as ethics and public acceptance.

In addition to highlighting the difficulties of operation of UAS, the UAS Panel workshops also identified some aspects where the proposed developments in airspace control and management could be of benefit to UAS operations and possibly provide greater benefits to UAS than manned aircraft. In addition, the technologies and related aspects that need to be developed for UAS operation may also be of benefit to what is required for the changes to airspace control and management. For example, the Single European Sky (SES) and US equivalent NextGen proposed arrangements will need to rely on facilities that are not under the direct control of the local Air Traffic Management (ATM) authority, if any ATM authority. This is similar to the way a UAS operating Beyond (radio) Line Of Sight (BLOS) may need to rely on satellite or other communication relays that are not under its direct control.

All of the three European initiatives above have set up their own web sites for collation and exchange of relevant information and, although the WG73 site is password protected, those of the E4U study and EC UAS Panel are intentionally available to anyone who wishes to consult them. Links have been provided to these sites within the main Final Report detailing CAe's contribution to ERA.

Building on the information gained from the European initiatives and other relevant literature, each of the sub-task areas defined under the overall task of studying UAS integration into non-segregated airspace has been addressed specifically.

The first sub-task requests an initial CONOPS including the consideration of the various constituent parts of the UAS system. In response, it was indicated that CONOPS could be generated, perhaps based on one of the Goal Options identified the E4U study. However, given the present and presently foreseen situation any CONOPS produced would be largely academic because if it is achievable, it will not be acceptable to those bodies that need to sanction it and, if it is acceptable to relevant bodies, it is highly unlikely to be achievable within a reasonable timeframe.

The handling of UAS by European and US Air Traffic Management was the subject of the second sub-task. This is difficult to answer at present due to the lack of any true examples of it in the context of non-segregated airspace. Although there are examples of small UAS being allowed to fly in general airspace, they are limited to an altitude below that used by almost all air traffic in the areas allowed. In addition, such operations have only been allowed in specific locations at specific times. There is some experience with UAS being allowed into general airspace as Operational Air Traffic (OAT), such as the Swiss Ranger UAS and proposed operations of the European version of Global Hawk. However, even these operations are not routine and are limited to a single country. Before they are allowed to be routine, several changes to regulations are required.

The difficulties in allowing operation of a single UAS, even on an occasional basis, mean that the possibility of the operation of multiple or large numbers of UAS alongside conventional air traffic, to be considered under the third sub-task, is even less likely and would require even further advances in the confidence of the authorities to allow it. With larger numbers of UAS there is bound to be a greater possibility for difficulties and, even if these difficulties result from a problem with a conventional manned aircraft, there is the problem of the UAS always being blamed because it is the new system. An example of this is the recent incident involving a military transport aircraft and a UAS where the latter was immediately blamed, even by the aviation press, when it was not at fault.

Any environmental and safety requirements unique to UAS were the subject of the fourth sub-task and this was answered with the view that, provided the airworthiness authorities view prevails, for all but possibly very small UAS, there will be no differences from manned aircraft. Despite studies, some even commission by FAA themselves, that have concluded that the potential for incidents resulting in fatalities caused by ground impacts or mid-air collisions involving UAS is very location dependent, the airworthiness authorities are minded to apply the same regulations to UAS as presently apply to manned aircraft of equivalent size. Using this approach, once considered safe to do so, a UAS could fly in the types or airspace it is cleared for whether that is over a deserted or heavily populated area, close to an airway or airport or well away from any other likely air traffic.

Although there is general recognition that a UAS is a system and consists of other important elements that effect and contribute to its safety, such as a ground control station and data links, ICAO is at present proposing to limit airworthiness considerations to the air vehicle. The responsibility for the safety of and consequent liability for ensuring all the constituent parts of the UAS work together would be placed on the registered Operator through the Operator's Certificate. The reason for this is that it is the Operator that is likely to remain in a single country whilst the air vehicle and even ground control may move to others during an operation. However, it should be pointed out that this approach is currently the topic of fierce debate within the member organisations that constitute ICAO.

There is no reason to believe UAS will be treated in any way that differs from manned aviation in terms of its environmental effect, e.g. emissions and noise.

The fifth sub-topic required consideration of what a UAS might require of the proposed future airspace control and management arrangements under NextGen and SES. The official position is that UAS will have to fit seamlessly into the prevailing ATM system and therefore UAS will not be allowed to 'require' anything special from the future systems. However, as indicated at the EC UAS Panel workshops, there are potential synergies between UAS and the future airspace arrangements proposed.

Both UAS operating BLOS and the proposed ATM systems will probably need to make use of facilities not under their direct control and need to address the issues associated with this. The SES approach will rely heavily on the SWIM (System Wide Information Management) system that will support much greater information exchange than supports ATM at present. However, this will, for a manned aircraft, have a weak link between ground and aircraft. In the case of a ground based pilot of a UAS, he will be much more easily integrated into the SWIM system. However, many envisaged operational uses of UAS will need some minor changes to what NextGen and SES offer for manned operations, in terms of catering for operations that are often not point to point flights but involve flying specific patterns in specific locations.

The sixth sub-topic relates to NextGen and SES requirements on UAS, which again should actually differ little from those that they will place on manned aviation. In fact, a UAS is likely to have a head start with regard to the need to provide accurate information on location and condition because this will most probably be needed to allow a UAS to operate within any air traffic management environment. In addition, the ease with which a UAS might be integrated into the SWIM system and the requirement that this will place on other airspace users to provide accurate information will add to the information available to a UAS pilot in performing his role.

The first six sub-tasks can be viewed as providing the basis for the final sub-task that requires consideration of how a sub-scale UAS demonstrator might operate within NextGen and SES proposed systems, reducing risks and addressing technology gaps.

Although the sub-task definition indicates the UAS may have a ground based pilot or be autonomous, it should be viewed against a stated intention to operate such a UAS with a safety pilot actually onboard the air vehicle. This is seen as the most plausible approach to addressing the two major technologies issues generally defined for UAS in the reliability of the data-link and a Detect & Avoid system. By placing a safety pilot on board a UAS, if the data link fails, the safety pilot is able to take over control and is able to perform the function of detecting and avoiding potential collisions in exactly the same way as the pilot of a manned aircraft. Therefore, placing a safety pilot on board a UAS offers an approach to addressing the concerns in allowing UAS operations in non-segregated airspace.

CAe has some experience relevant to the approach of an onboard safety pilot on a UAS, sometimes termed a 'surrogate UAV'. It should noted that it does not ally all the concerns of the airworthiness authorities, who will still take great interest in the safeguards placed on what the aircraft does when acting as a UAS and whether it is always possible for the safety pilot to regain complete control without the aircraft achieving a state or condition from which it can not be retrieved.

Presence of a safety pilot onboard a UAS places several requirements on the air vehicle which are not always achievable. The air vehicle needs to be large enough for the pilot and all his support systems, as well as those necessary to operate as a UAS, to be contained within it. It must allow for the pilot to have the necessary vision and controls to act as a normal pilot. However, provided the size of the sub-scale demonstrator concerned allows this, the approach allows the possibility of building-up operation of a UAS, in terms of both the systems being used and the phases of flight in which they operate, it a stepwise fashion. In particular, it allows the system to operate as a UAS when en-route in the air but with the option of converting to a normal manned aircraft during near ground and particularly on ground operations, which are seen as much more challenging for UAS operation.

3. TASK 2: ENVIRONMENTAL CHARACTERISATION OF CONCEPTUAL AIRCRAFT EMISSIONS

The study performed under Task 2 focussed on three elements. The first covered the performance of the aircraft. The second provided an overview of the current understanding of the impact of aviation from the atmospheric science perspective, whilst the third looked at the expected evolution of global aviation from an operations and an economic perspective.

In the first element, it is argued that the environmental impact of aviation is related to the amount of fuel burned and the altitude at which the aircraft flies. This covers two of the most important aspects of environmental impact at the global level; namely the amount of carbon dioxide emitted and the formation of contrails. Reducing the amount of fuel used to carry a given payload a given distance clearly reduces the environmental impact due to carbon dioxide and it has the added advantage of improving the operating economics as the price of fuel increases with time. Therefore, a focus on reducing the fuel burn is considered to be particularly important from the manufacturer's perspective.

A first principles analysis is developed and this shows how the performance of a modern "tube and wing" civil transport aircraft is constrained by anthropological, geometric and aerodynamic relationships to such an extent that the potential for improving fuel efficiency can be estimated with surprisingly good accuracy by a very simple analysis. It is argued that the most appropriate figure of merit for a design is the "energy to revenue work ratio" (ETRW). This is closely related to the more familiar fuel burned per unit payload per unit distance travelled.

Improved engine efficiency has a first order effect upon ETRW, i.e. all other things being equal, a 1% improvement in engine efficiency gives a 1% improvement in ETRW. However, with 60 years of progressive advances in engine technology already delivered, the prospect for big improvements in the future is limited; not least by the 2nd Law of Thermodynamics. For the current "all turbulent" aircraft, the most powerful parameter available to the designer is the wing aspect ratio (= $(\text{span})^2/\text{gross wing area}$). In percentage terms, a 10% increase in aspect ratio at a fixed material technology level would give a 2.5% improvement in the ETRW. If additional light weight material could be introduced into the wing design so that the weight growth with increasing aspect ratio was eliminated, the benefit would increase to almost 5%. It is also shown that if light weight material was just used to make an aircraft with the same wing aspect ratio lighter, ETRW would improve by just 2%. Therefore, if the benefit to fuel consumption is to be maximised, advances in material technology require parallel advances in aerodynamic technology. The potential for additional improvement to ETRW by using techniques such as "surface riblets" to reduce the skin friction drag due to fully turbulent flow and laminar flow control are also considered. It is argued that, at best, riblets can only offer improvements in the region of 2%. It is also argued that the benefits of laminar flow control are limited; with a 5% improvement in ETRW requiring a 30% reduction in the drag of the wing. A reduction of this magnitude would be a monumental engineering achievement and would bring with it a number of serious operational and regulatory issues. Therefore, the true price of this additional 5% is very high. The inescapable conclusion is that the tube and wing configuration is reaching the end of its evolutionary road, with the benefits getting smaller and the cost of each additional improvement increasing dramatically.

The final option is to abandon the "tube and wing" arrangement and develop a shape that is not subject to the same design constraints. The BWB is the obvious candidate. However, the BWB is not without issues; for example anthropological and airport related geometric restrictions mean that the all important aspect ratio is necessarily much lower for this configuration and this gives it a 10% initial handicap compared to tube and wing. As a result of the much increased complexity of the case for the BWB versus the tube and wing is beyond the scope of this study.

In the second element, the effect of aviation's emissions on the atmosphere is considered with a focus on issues at the global level. The problem is shown to be very complex. In addition to the nature and the amount of the emissions, time is an important variable and, in certain cases, the location in which the emission occurred in also important. Effects resulting from emissions occur on timescales that vary from minutes in the case of contrails to millennia in the case of carbon dioxide. The formation of contrails and, possibly, cirrus cloud depend strongly on the aircraft altitude and the local meteorological conditions whilst the effect depends upon the time of day. On the other hand, the effects of carbon dioxide are essentially independent of where, or when, the emission took place. Consideration is also given to the effects of emissions of the oxides of nitrogen, water vapour, soot and sulphates whose effects are both complex and, at present, difficult to quantify. The consequence of emissions is described primarily in terms of the consequences for the concept of "radiative forcing". However, radiative forcing is an imperfect measure of environmental impact and a number of more complex metrics that are, arguably, more relevant to climate change and to climate change policy are described. It is clear that there is some way to go before the full impact of aviation on the future average surface temperature and on climate is understood. It is also clear that there is more to solving the problem than simply reducing carbon dioxide emissions, since, even if carbon dioxide emissions were totally eliminated, e.g. by the use of appropriately sourced bio fuels, some very important effects would remain and would need to be addressed.

Having shown that the total impact of aviation on the environment depends upon the size and composition of the global civil aircraft fleets, the third part of this report considers how the global fleet is expected to evolve over the next 30 years. The number of aircraft in service is expected to grow, the distribution around the world is expected to change and the distribution of aircraft size and range is also expected to change. All these variations will have an impact on the environment. The strongest growth is expected to be in Asia as the economies in this area expand and with it the need to travel. Consequently, the emissions are being moved into different latitudes. In parallel with the growth, the efficiency of the global fleet increases as old aircraft are replaced by new. Therefore the annual rate of aircraft retirement of aircraft is an important contributor to fleet efficiency. Clearly, all these effects need to be combined in order to get a complete and accurate picture of the challenge.

Finally, there is currently a great deal being said and written about the future use of biofuels as a means of reducing carbon dioxide emissions. At the technical level, the use of appropriately formulated, synthetic kerosene is straightforward. However, the economic arguments and the ethical arguments are far from simple and some of these, e.g. the price of biofuel versus oil derived fuel, the cost of production, the willingness of oil companies to invest in bio fuel rather than oil exploration and the availability of such fuels to aviation in competition with other industries who may be able to pay considerably more for fuel, are discussed. It is concluded that, from an economics perspective, the future use of biofuel in aviation is far from clear.

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