NASA N+3
MIT Team
Final Review

23 April 2010

NASA Langley Research Center
Agenda

• Executive summary (message)
• Scenario and aircraft requirements
• Overall program approach
• D Series (Double-bubble fuselage) concept – Features and Results
  – D8.1 – “Current Technology” aircraft: The benefits of configuration
  – D8.5 – Advanced Technology aircraft
• H Series (Hybrid wing body) concept
• Concept trades: payload, range, cruise Mach number
• Risk assessment and technology roadmaps
• Reprise and closing
NASA N+3 MIT Team Final Review
Executive Summary
Team Accomplishments

• Defined documented scenario and aircraft requirements
• Created two conceptual aircraft: D (double-bubble) Series and H (Hybrid Wing Body) Series
  – D Series for domestic size meets fuel burn, LTO NOx, and balanced field length N+3 goals, provides significant step change in noise
  – H Series for international size meets LTO NOx and balanced field length N+3 goals
  – D Series aircraft configuration with current levels of technology can provide major benefits
• Developed first-principles methodology to simultaneously optimize airframe, engine, and operations
• Generated risk assessment and technology roadmaps for configurations and enabling technologies
Project Enabled by University-Industry Collaboration

- MIT
  - (GTL) Propulsion, noise, (ACDL) aircraft configurations, systems, (ICAT) air transportation, and (PARTNER) aircraft-environment interaction
  - Student engagement (education)
- Aurora Flight Sciences
  - Aircraft components and subsystem technology
  - Aerostructures and manufacturing
  - System integration
- Pratt & Whitney
  - Propulsion
  - System integration assessment
NASA Subsonic Fixed Wing N+3 Objectives

• Identify advanced airframe and propulsion concepts, and enabling technologies for commercial aircraft for EIS in 2030-35
  – Develop detailed air travel scenario and aircraft requirements
  – Advanced concept study
  – Integrated airframe/propulsion concepts supported by detailed analysis
  – Key technologies are anticipated to be those which end up on the aircraft
  – Anticipate changes in environmental sensitivity, demand, and energy
• Use results to aid planning of follow-on technology programs
## NASA System Level Metrics

**... technology for dramatically improving noise, emissions, performance**

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<td>Noise</td>
<td>- 32 dB (cum below Stage 4)</td>
<td>- 42 dB (cum below Stage 4)</td>
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<td>LTO NOx Emissions (below CAEP 6)</td>
<td>-60%</td>
<td>-75%</td>
<td>better than -75%</td>
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<td>Performance: Aircraft Fuel Burn</td>
<td>-33%**</td>
<td>-40%**</td>
<td>better than -70%</td>
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<tr>
<td>Performance: Field Length</td>
<td>-33%</td>
<td>-50%</td>
<td>exploit metro-plex* concepts</td>
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- Energy intensity metric for comparison of fuel burn
- Add a **climate impact** metric for evaluation of the aircraft performance
  - Global temperature change as a result of the emissions
### N+3 Scenario and Requirements Drive the Design

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Two Scenario-Driven Configurations

Double-Bubble (D series): modified tube and wing with lifting body
Baseline: B737-800
Domestic size

Hybrid Wing Body (H series)
Baseline: B777-200LR
International size

Fuel burn (kJ/kg-km)

Field length

Noise

LTO NOx

100% of N+3 goal

9
Three Major Results from N+3 Program

• Development and assessment of two aircraft configurations:
  – D Series for domestic size meets fuel burn, LTO NOx, and balanced field length N+3 goals, provides significant step change in noise
  – H Series for international size meets LTO NOx and balanced field length N+3 goals

• Comparison of D Series and H Series for different missions (domestic and international)

• Trade study identification of D Series benefits from configuration vs. advanced technologies
**D Series – Double Bubble Configuration**

- Modified tube and wing configuration with wide “double bubble” fuselage offers significant benefits
- Fuselage provides lift and offers advantageous flow geometry for flush-mounted engines on aft body
- Unswept wing benefits from reduced structural loads and accommodates elimination of high-lift devices
- With **advanced technology insertion** D8.5 achieves 3 of 4 N+3 objectives
- With **minimal technology insertion**, D8.1 offers N+2 level reductions in fuel burn, noise, and emissions
**D8 Configurations: Design and Performance**

D8.1  
(Aluminum)

D8.5  
(Composite)

- Fuel Burn (kJ/kg-km)
- Noise (EPNdB below Stage 4)
- Field Length (feet)
- LTO NOx (g/kN) (% below CAEP 6)

100% of N+3 Goal

50%

75%
## D8.5 – Double Bubble Configuration

**Mission**
- Payload: 180 PAX
- Range: 3000 nm

### Table of Metrics

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<tr>
<th>Metric</th>
<th>737-800 Baseline</th>
<th>N+3 Goals % of Baseline</th>
<th>D8.5</th>
</tr>
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<tbody>
<tr>
<td>Fuel Burn (PFEI) (KJ/kg-km)</td>
<td>7.43</td>
<td>2.23 (70% Reduction)</td>
<td>2.17 (70.8% Reduction)</td>
</tr>
<tr>
<td>Noise (EPNdB below Stage 4)</td>
<td>277</td>
<td>202 (-71 EPN db Below Stage 4)</td>
<td>213 (-60 EPNdB Below Stage 4)</td>
</tr>
<tr>
<td>LTO Nox (g/kN) (% Below CAEP 6)</td>
<td>43.28 (31% below CAEP 6)</td>
<td>75% below CAEP 6</td>
<td>10.5 (87.3% below 6)</td>
</tr>
<tr>
<td>Field Length (ft)</td>
<td>7680 for 3000 nm mission</td>
<td>5000 (metroplex)</td>
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D8.5 Airframe Technology Overview

Operations Modifications:
- Reduced Cruise Mach
- Optimized Cruise Altitude
- Descent angle of 4°
- Approach Runway Displacement Threshold

- Natural Laminar Flow on Wing Bottom
- Reduced Secondary Structure weight
- Health and Usage Monitoring
- Boundary Layer Ingestion
- Active Load Alleviation
- Lifting Body
- Faired Undercarriage
- Advanced Structural Materials
**D8.5 Engine Technology Overview**

- High Bypass Ratio Engines (BPR=20) with high efficiency small cores
- LDI Advanced Combustor
- Distortion Tolerant Fan
- Tt4 Materials and advanced cooling
- Advanced Engine Materials
- Variable Area Nozzle
## H3.2 Performance

![Mission Image]

*Mission*
- Payload: 354 PAX
- Range: 7600 nm

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<th>Metric</th>
<th>777-200 LR Baseline</th>
<th>N+2 Goals % of Baseline</th>
<th>N+3 Goals % of Baseline</th>
<th>H3.2</th>
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<tbody>
<tr>
<td><strong>Fuel Burn (PFEI) (KJ/kg-km)</strong></td>
<td>5.94</td>
<td>3.58 (40% Reduction)</td>
<td>1.79 (70% reduction)</td>
<td>2.75 (54% reduction)</td>
</tr>
<tr>
<td><strong>Noise (EPNdB below Stage 4)</strong></td>
<td>288</td>
<td>246 (-42 EPNdb)</td>
<td>217(-71 EPNdB)</td>
<td>242 (-46 EPNdB Below Stage 4)</td>
</tr>
<tr>
<td><strong>LTO Nox (g/kN) (% Below CAEP 6)</strong></td>
<td>67.9</td>
<td>24.5 (75% below CAEP 6)</td>
<td>&gt;24.5 (75% below CAEP 6)</td>
<td>18.6 (81% below CAEP 6)</td>
</tr>
<tr>
<td><strong>Field Length (ft)</strong></td>
<td>10,000</td>
<td>4375 (50%)</td>
<td>metroplex</td>
<td>9000</td>
</tr>
</tbody>
</table>
**H3.2 Technologies Overview**

- Variable Area Nozzle with Thrust Vectoring
- Advanced Combustor
- Drooped Leading Edge
- Health and Usage Monitoring
- Lifting Body with leading edge camber
- Distributed Propulsion Using Bevel Gears
- Tt4 Material and advanced cooling
- Boundary Layer Ingestion
- Ultra High BPR Engines, with increased component efficiencies
- Active Load Alleviation
- No Leading Edge Slats or Flaps
- Noise shielding from Fuselage and extended liners in exhaust ducts

**Operations Modifications:**
- Optimized Cruise Altitude
- Descent angle of 4°
- Approach Runway Displacement Threshold
D and H Series Fuel Burn for Different Missions

- D Series has better performance than H Series for missions examined
- H Series performance improves at international size
D Series Configuration is a Key Innovation

D8 configuration
Airframe materials/processes
High bypass ratio engines
T metal engine material and advanced cooling processes
Natural laminar flow on bottom wing
Engine component efficiencies

Airframe load reduction
Secondary structures weight
Advanced engine materials
Approach operations
Fairied undercarriage
LDI combustor

% Fuel burn reduction relative to baseline
% LTO NOx reduction relative to CAEP6
%0 %10 %20 %30 %40 %50 %60

% Fuel burn reduction relative to baseline
% LTO NOx reduction relative to CAEP6
%0 %10 %20 %30 %40 %50 %60

Balanced Field Length for all designs = 5000 feet

EPNdb Noise reduction relative to Stage 4

Fuel burn
Noise
LTO NOx
Concept and Technology Risk Assessment

- For the two configurations
  - Assessment of risks and contributions associated with configuration
  - Analysis of risks vs. contributions to each N+3 metric for enabling technologies
- Technology roadmaps
  - Developed 14 roadmaps following Delphi method
  - Verified using technology trend extrapolation when historical data was available
**TASOPT (Transport Aircraft System OPTimization)**

- First-principles innovative global optimization for aircraft design
- Simultaneously optimizes airframe, engine, and operations parameters for given mission
- Developed in modules so easily integrated with other tools
- Generate required output files for detailed aeroelastic and aerodynamic analysis
- Allows aircraft optimization with constraints on noise, balanced field length, and other environmental parameters
HWBOpt (HWB OPTimization)

- Developed from tools and methodology created during Silent Aircraft and N+2 NRA's
- Simultaneously optimizes airframe, engine, and operations parameters for a HWB configuration
- Structural model based on Boeing proprietary code
- Examine large range of propulsion system configurations: podded and distributed, with mechanical and electrical transmission systems, conventional fuel and LNG
External Interactions / Reviews

• Regular interactions with Dr. N. A. Cumpsty (former Chief Technologist, RR), R. Liebeck (Boeing BWB designer)
• Non-advocate review on 29 May
  – J. Langford – CEO, Aurora Flight Sciences
  – S. Masoudi, Program manager, P&W
• NASA Glenn NOx Workshop on 7 August
• P&W Workshop on 7 August (Lord, Epstein, Sabnis, 12 other technical specialists)
• Electrical system review (NASA OSU Adv. Magnet Lab)
• NASA SFW Workshop on 29 September to 1 October
• NASA Green Aviation weekend workshop on 25-26 April
University-Industry Collaboration

• University perspective, skills
  – Impartial look at concepts, analysis, conclusions
  – Educating the next generation of engineers

• Industry perspectives, skills
  – Aircraft, engine design and development procedures
  – In-depth product knowledge

• Collaboration and teaming
  – Assessment of fundamental limits on aircraft and engine performance
  – Seamless teaming within organizations AND between organizations

• Program driven by ideas and technical discussion
  ⇒ many changes in “legacy” beliefs
The Focus of the Presentation

Double-Bubble (D series): modified tube and wing with lifting body

Baseline: B737-800
Domestic size

Hybrid Wing Body (H series)

Baseline: B777-200LR
International size
Mission Scenario and Aircraft Requirements
N+3 Scenario Design Process

Scenario Dimensions
- Demand
- Operations
- Infrastructure
- Energy
- Environment

Scenario Time Frame
2025 TRL 6, 2035 EIS

Current Trends → Projected Drivers → Scenario

Design Requirements
- Size
- Speed
- Range
- Emissions
**Demand for Air Travel**

- Overall passenger demand expected to double by 2035
- Spatial distribution of US flights will not change significantly
- Significant growth expected in developing regions such as India and China
- Partial shift of short haul demand to alternative modes
- Highest domestic demand for 500-2500 nm stage lengths
- Continued demand for long haul intercontinental missions

Airline Operations

- Airline business models will not change significantly
- Similar route structures with some shift to secondary airports
- Price-driven ticket purchasing and increased security delays reduce the importance of high cruise speed
- Drive for reduced Cost per Available Seat Mile (CASM)
- Fuel will become a more significant part of DOC
- Some increase in gauge, while still filling thin demand routes
- Reduction of short haul operations
Infrastructure

- Congestion at key metropolitan airports (e.g. NY)
- Limited ability to expand or build new airports in US
- Restrictions at congested airports will suppress short haul demand
- NextGen in place, providing some capacity improvement
- Significant growth in secondary and tertiary airport utilization
- Adequate pool of potential airports with 5,000+ ft runways
Energy

Alternative fuels could:
- Reduce emissions
- Expand energy supplies
- But only if amenable to large-scale production

To evaluate potential, need to:
- Examine fuel energy per unit mass and volume, freeze point, volatility, etc.
- Consider life cycle well-to-wake greenhouse gas emissions*
- Remember vast infrastructure investment → considerable justification required to switch to cryogenic alternative fuel

* Stratton, Wong, and Hileman; PARTNER Report 2010-001.
Environment

- Increased concern on global and local emissions
- Expected restrictions on carbon and NOx
- Carbon emissions from aviation will increase
- Other modes will reduce emissions faster than aviation, increasing pressure
- Increase in effective cost of fuel
- Noise constraints limit airport operations and terminal area procedures

Greenhouse Gas Emissions

Transport

Each square represents 1% of total emissions inventory

Non-Transport
- Electric Utilities
- Industry
- Agriculture
- Commercial
- Residential

Transport
- Transportation
- Aviation

Cumulative Noise Restriction History – B737-700 (150,000 lbs)

Year


Cumulative EPNdB

220 240 260 280 300 320

Stage 2 - 1969
Stage 3 - 1975
Stage 4 - 2006
N+1
N+2
N+3
Potential Fleet-Wide Impact of N+3 Goals

Specifications defined for the two size classes which would have greatest fleet-wide impact

- Domestic vehicle – Increase from 737 seat class: 180 pax
- International vehicle – 777-200LR as baseline: 354 pax

One year of domestic emissions by aircraft type
NASA 2006 baseline emissions inventory, Volpe National Transportation Systems Center
**N+3 Requirements Summary**

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Passenger Capacity

- Domestic 130-180 passenger aircraft dominate inventory (2005 data)
- International 250-450 passenger aircraft have lower numbers but high utilization
Cargo Requirements Vary with Range

- Domestic aircraft utilize small fraction of belly freight capacity
- International aircraft have higher belly freight load factors
- Domestic data for 2007

Data from U.S. BTS Form 41 data, 2007.
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**Candidate Reference Missions**

- Missions represent challenging operations and popular routes

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<th>Great Circle Distance (nm)</th>
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<td>MIA-SEA</td>
<td>2,365</td>
<td>Transcontinental headwind</td>
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<tr>
<td>DCA-LAX</td>
<td>2,000</td>
<td>Short runway</td>
</tr>
<tr>
<td>JFK-HKG</td>
<td>7,000</td>
<td>Transpacific</td>
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<tr>
<td>LAX-SYD</td>
<td>6,520</td>
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- Domestic range requirement of 3,200 nm based on:
  - MIA to SEA during winter, facing 65 kts headwind
  - NBAA IFR Reserves (including 200 nm diversion)
- Long range 7,600 nm mission emulates 777-200LR transpacific capability
Available Seat Mile Distribution

- Based on one day of global operations
- Retrieved from AEDT/SAGE (Aviation Environmental Design Tool/System for Assessing Global Emissions)
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Domestic Cruise Mach Number

- Opened design space to consider lower Mach number for performance improvement

- Evaluated impact of reduced Mach number on aircraft utility and scheduling
  - 10% Mach number reduction leads to 15 minutes of average daily schedule shift
  - Recommend min Mach 0.72

- Impact of Mach reduction could be mitigated by reduced load/unload time

Cruise Mach History

![Graph showing various aircraft's certification years and their long range cruise speed. The X-axis represents the certification year from 1965 to 2010, and the Y-axis represents the long range cruise speed at 35,000 feet. Various aircraft models are plotted on the graph, such as 747-200, 757-200, 767-200, 777-200, A319, A320, A330, CRJ-200, and others. The red dotted line represents the N+3 minimum speed.](image-url)
# N+3 Requirements Summary

| Size          | Domestic: 180 passengers @ 215 lbs/pax (737-800)  
|              | International: 350 passengers @ 215 lbs/pax (777-200LR)  
|              | Multi-class configuration  
|              | Increased cabin baggage |
| Range        | Domestic: US transcontinental; max range 3,000 nm with reserves  
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| Speed        | Domestic: Minimum of Mach 0.72  
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| Runway Length | Domestic: 5,000 ft balanced field  
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| Fuel & Emissions | N+3 target: 70% fuel burn improvement  
|                | Meet N+3 emission target (75% below CAEP/6 NOx restriction)  
|                | Consider alternative fuels and climate impact |
| Noise        | N+3 target: (-71 dB cumulative below FAA Stage 4 limits) |
| Other        | Compatibility with NextGen  
|             | Wake vortex robustness  
|             | Meet or exceed future FAA and JAA safety targets |
Runway Accessibility

- Minimum additional utility below 5,000 ft

* Major airports excluded
### N+3 Requirements Summary

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Other Capability

• Aircraft will be NextGen compliant
  – RNP, ADS-B, Datalink …
• Take advantage of NextGen operational flexibility
  – Cruise climbs
  – Continuous descent approaches
• Wake Vortex (Robustness and Mitigation)
• Meet or exceed future FAA and JAA safety requirements
# N+3 Requirements Summary

## Size
- **Domestic**: 180 passengers @ 215 lbs/pax (737-800)
- **International**: 350 passengers @ 215 lbs/pax (777-200LR)
- Multi-class configuration
- Increased cabin baggage

## Range
- **Domestic**: US transcontinental; max range 3,000 nm with reserves
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## Speed
- **Domestic**: Minimum of Mach 0.72
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- Driven by fuel efficiency

## Runway Length
- **Domestic**: 5,000 ft balanced field
- **International**: 9,000 ft balanced field

## Fuel & Emissions
- N+3 target: 70% fuel burn improvement
- Meet N+3 emission target (75% below CAEP/6 NOx restriction)
- Consider alternative fuels and climate impact

## Noise
- N+3 target: (-71 dB cumulative below FAA Stage 4 limits)

## Other
- Compatibility with NextGen
- Wake vortex robustness
- Meet or exceed future FAA and JAA safety targets
Overall Design Process
Design Objectives

• Seek globally-optimum airframe/engine/ops combinations
• Determine global sensitivities of fuel burn to technology

FPR, $T_{t4}$

Pratt’s, GE’s design domain

Existing Engines

Common apparent (false) optimum

Fuel economy isocontours

Existing Airplanes

Boeing’s, Airbus’s design domain

W/S, $M_{\infty}$
N+3 Program Process Overall Flow

Inputs

Concept selection and detailed design

Configuration Assessment and Performance Determination

Configuration Documentation and Risk Assessment
N+3 Program Process

- Technologies
  - TASOPT, HWBOpt
  - Configuration
  - Integration
  - Sizing
  - Optimization

- Mission Scenario Requirements

- NASA N+3 Goals

- Adjust Technology selection, Configuration

- Evaluation Against Goals
  - Noise
  - LTO NOx
  - Fuel burn
  - Bal. field length
  - Climate
  - Risks

- Acceptable?

- Final Configuration

- TMPs
TASOPT (Transport Aircraft System OPTimization)

• First-principles innovative aircraft design optimization global method

• Simultaneously optimizes airframe, engine, and operations parameters for given mission

• Developed in modules so easily integrated with other tools

• Generate required output files for detailed aeroelastic and aerodynamic analysis

• Allows aircraft optimization with constraints on noise, balanced field length, and other environmental parameters
TASOPT: Design and Development Methodology

• Preparatory offline design work:
  – Cabin and cross-section layout designed by hand
  – Fuselage nose and tailcone cambers designed via Vortex Lattice
  – Wing airfoil family designed by CFD multi-point optimization

• Optimization case setup:
  – Design variable selection (AR, Λ, t/c, λ, $C_L$, $h_{CR}$, FPR$_D$, BPR$_D$, $T_{t4_{cr}}$, $T_{t4_{ta}}$)
  – Design parameter specification ($W_{pay}$, $R_{max}$, $M_{cr}$, $N_{lift}$, $\sigma_{cap}$, $\rho_{cap}$, SM…)
  – Objective selection (Fuel Burn)
  – Constraint specification ($l_{BF}$, $W_{fuel_{max}}$)

• Sizing and optimization execution by TASOPT, producing:
  – Wing and tail dimensions, positions
  – Structural gauges, weights
  – Engine areas, design speeds and mass flows, cooling flows
  – Flight parameters for each mission point
  – Engine flowpath quantities for each mission point
  – Mission fuel weight
  – Output files for detailed aeroelastic and aerodynamic analysis
**TASOPT Components**

- Collection of fully coupled low-order physical models
- Weight-iteration algorithm to meet specified mission
- Optional outer descent loop seeks minimum mission fuel in selected design space
- Physical Models
  - Primary structure weight via load/stress/material fundamentals
  - Secondary structure, equipment, etc via historical weight fractions
  - Wing drag from airfoil database $c_d(c_l, t/c, M, R_e)$, sweep theory
  - Fuselage drag from geometry, via viscous CFD $C_D_{\text{fus}}(A(x), M_\infty, Re)$
  - Stability and trim from weight- and aero-moment buildup
  - Component-based turbofan model $F(FPR, BPR, OPR, M_\infty, T_{t4})$
  - Major-component turbofan weight model $W_{\text{eng}}(m\text{core}, OPR, BPR)$
  - Trajectory equations for $W_{\text{fuel}}$, $I_{BF}$
Primary Structure-Fuselage Beam

- Pressure vessel with added bending and torsion loads
- Bending loads from distributed payload, point tail
Primary Structure - Fuselage Section

- Double-bubble section, with floor-load model
- Single-tube section is special case ($w_{db} = 0$)
- Gauges sized by stresses at worst-case load for each element
Primary Structure – Wing or Tail Section

- Double-taper planform, with or without strut
- Double-taper aero loading with fuselage and tip mods
Wing or Tail Surface cross section

- Box beam: curved bending caps with shear webs
- Non-structural slats, flaps, spoilers, fairings
- Box interior defines maximum fuel volume
- Gauges sized via material stresses
Load Cases used for Sizing Primary Structure

- \( N_{\text{lift}} \): wing bending spar caps and shear webs
- \( \Delta p_{\text{max}} \): fuselage skin tension
- \( L_{VT}_{\text{max}} \): tailcone skin shear, side stringers, tail caps and webs
- \( L_{HT}_{\text{max}} \): added top/bottom stringers, tail caps and webs
- \( N_{\text{land}} \): added top/bottom stringers, fuselage floor beams
Airfoil Parameterization

- Key tradeoffs are in $M_\infty$, $\Lambda$, $t/c$, $c_l$ design space (fixed $t/c$, $c_l$ would give sub-optimal aircraft)
- Family of airfoils over range of $t/c = 0.09...0.14$
- Each is designed for good Mach drag rise behavior.

<table>
<thead>
<tr>
<th></th>
<th>NC090</th>
<th>NC100</th>
<th>NC110</th>
<th>NC120</th>
<th>NC130</th>
<th>NC140</th>
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<td>area</td>
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<td>0.07464</td>
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<tr>
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<td>0.10000</td>
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<td>0.12000</td>
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<td>0.02036</td>
<td>0.01930</td>
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<td>0.01457</td>
<td>0.01489</td>
<td>0.01522</td>
<td>0.01556</td>
<td>0.01590</td>
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<tr>
<td>$\Delta \theta_{TE}$</td>
<td>11.78°</td>
<td>11.74°</td>
<td>11.71°</td>
<td>11.66°</td>
<td>11.64°</td>
<td>11.62°</td>
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Swept Wing Profile Drag

- Airfoil performance database + infinite sweep theory
- Wing-root corrections for shock unsweep

\[
\begin{align*}
\{C_{d_f}, C_{d_p}\} &= F\left(C_{l_{\perp}}, M_{\perp}, \frac{t}{C}, Re_c\right) \\
C_{D_{\text{wing}}} &= F\left(C_{L}, M_{\infty}, \Lambda, \frac{t}{C}, Re_c\right)
\end{align*}
\]
High-Fidelity Fuselage Drag Model (I)

- Potential flow via compressible source line, using $A(x)$
- Boundary layer + wake flow via compressible integral method, with lateral divergence (body perimeter) effects, using $b_0(x)$
- Strongly coupled together via source-blowing model
- Used for fuselage drag and BLI calculations

$$C_{D_{fuse}} = \frac{2\Theta_{wake}}{S}$$
High-Fidelity Fuselage Drag Model (II)

- Typical BL calculation shown gives BL state at engine inlet for BLI accounting
**Turbofan Performance Model**

- From Kerrebrock, extensively enhanced with variable $c_p(T)$, BLI, fan and compressor maps, turbine cooling, VAN.

Used online for...
- Engine sizing at design point (cruise)
- Engine performance at off-design (takeoff, climb, descent)
Turbine Cooling Sub-model

- Modified Horlock model, with two prediction modes:

\[ \alpha_c = F(T_{metal}, T_{t3}, T_{t4}; St_A, \theta_f, \eta_c) \] (cooling flow sizing)

\[ T_{metal} = F(\alpha_c, T_{t3}, T_{t4}; St_A, \theta_f, \eta_c) \] (\(T_{metal}\) prediction)
Operation Models - Mission Profiles

- Numerically integrated ODEs for altitude and fuel profiles:

\[
\tan \gamma = \frac{dh}{dR} = \frac{F'}{W \cos \gamma} - \frac{D'}{L} - \frac{1}{2g} \frac{d(V^2)}{dR}
\]

\[
\frac{dW}{dR} = F' \frac{PSFC'}{\cos \gamma}
\]
Weight Iteration/Sizing Procedure

Initial weight guesses

Surface spans, areas

Loads, Shears, Moments

Structural gauges

Volumes and Weights

Drag, Engine size+weight

Trajectory, Fuel Weight

Total Weight converged?

Y

Configuration, Weight, Fuel Burn, T/O perf...

Inputs

( Mach, Nmax, fstress, OPR, Tmetal, IBFmax, Sweep, Altitude, FPR, BPR, Tt4, ... )
Weight Iteration/Sizing with Outer Optimization

Design Parameters

- Mach, Nmax, fstress, OPR, Tmetal, IBFmax ...

Design Variables

- Sweep, Altitude, FPR, BPR, Tt4 ...

Initial weight guesses

Surface spans, areas

Loads, Shears, Moments

Structural gauges

Volumes and Weights

Drag, Engine size+weight

Trajectory, Fuel Weight

Total Weight converged?

Y

Optimize Design Variables

N

Configuration, Weight, Fuel Burn, T/O perf...

Fuel burn minimized?

Y

Sweep, Altitude, FPR, BPR, Tt4
Selectable Design Variables (Optimization Outputs)

- $C_{L_{cr}}$ cruise lift coefficient
- $AR$ overall aspect ratio
- $\Lambda$ wing sweep angle
- $(t/c)_o$ airfoil thickness at $\eta_o$ (wing root)
- $(t/c)_s$ airfoil thickness at $\eta_s$ (planform break or strut-attach)
- $\lambda_s$ inner panel taper ratio
- $\lambda_t$ outer panel taper ratio
- $r_{c_s}$ clean-configuration $c_{l_s}/c_{l_o}$ at $\eta_s$ (planform break)
- $r_{c_t}$ clean-configuration $c_{l_t}/c_{l_o}$ at 1 (tip)
- $OPR_D$ design overall pressure ratio
- $FPR_D$ design fan pressure ratio
- $BPR_D$ design bypass ratio
- $h_{CR}$ start-of cruise altitude
- $T_{t4_{cr}}$ cruise turbine inlet temperature
- $T_{t4_{to}}$ takeoff turbine inlet temperature
Typical TASOPT Uses

- Size aircraft (inner loop only), get sensitivities to inputs, e.g.

\[
\frac{\Delta W_{\text{fuel}}}{\Delta M_{\text{CR}}}, \frac{\Delta W_{\text{fuel}}}{\Delta AR}
\]

- Size/optimize aircraft (outer, inner loops), get sensitivities to parameters, e.g.

\[
\frac{\Delta W_{\text{fuel}}}{\Delta M_{\text{CR}}}, \frac{\Delta AR_{\text{opt}}}{\Delta M_{\text{CR}}}
\]

Note:
- Point sensitivity differs from post-optimum sensitivity,

\[
\frac{\Delta W_{\text{fuel}}}{\Delta M_{\text{CR}}} \neq \frac{\Delta W_{\text{fuel}}}{\Delta M_{\text{CR}}}
\]

- \(AR_{\text{opt}}\) is an output, so \(\Delta(\ )/\Delta AR_{\text{opt}}\) has no meaning
Metrics
N+3 Program Process
**N+3 Noise Metric**

- Noise sources calculated from Matlab scripts created based on ANOPP
- Shielding noise estimated using method developed by MIT under N+2 NRA as subcontractor from Boeing
- Acoustic liner attenuation estimated from peak value based on SAI results
- N+3 design philosophy: Choose a configuration with low noise attributes and then optimize the configuration to minimize fuel burn
• ICAO LTO NOx is total mass of NOx (g) produced at various conditions and time modes divided by rated engine thrust (kN)

• Goal: more than 75% below CAEP 6
Payload Fuel Efficiency Intensity Metric

\[ PFEI = \frac{\text{fuel energy consumed}}{\text{total payload \times great circle distance}} \]

- Objective: Compare ‘fuel burn’ for different aircraft (conventional, alt fuel, cryogenic, electric, etc.) over varied mission (payload and range)
- Goal = 70% reduction from baseline
N+3 Balanced Field Length Metric

- Field length for N+3 consideration defined by balanced field length
- Goal: Metroplex performance
Environmental Impact of Aviation

Combustion Emissions

- CO₂: 71%
- Water: 28%
- CO, HC, NOₓ, SOₓ, Primary PM₂.₅: < 1%

Atmospheric Chemistry and Physics

- Primary PM₂.₅
- Secondary PM₂.₅
- SOₓ
- NOₓ
- UHC
- CO
- O₃
- CH₄
- H₂O
- CO₂

Global Climate Change

- Cooling Effects
- Warming Effects

Emissions from Fuel Production

Population Exposure and Health Impacts
Climate

Assessment Process: Calculate emissions of one aircraft flying one mission; includes:

- Change in concentration
- Radiative forcing
- Temperature change

Life Cycle Emissions:

- Well-to-tank CO₂
- Well-to-tank CH₄
- Combustion emissions

Metric: Global Temperature change

More information on Climate Model used:
- Marais et al Met Z., 2008
- Mahashabde, MIT PhD dissertation, 2009
- http://apmt.aero
D8 Aircraft Concept

D8.1 Design
D8.5 Design
**D8.1 Major Design Features**

- Noise shielding from fuselage/tails
- Flush-mounted engines
- Centerbody BLI
- Aluminum aircraft
- Extended liners on exhaust ducts
- No leading edge slats
- Double bubble with lifting nose and pi-tail

**Propulsion system**

Three direct drive turbofans Bypass Ratio of 6

**Mission**

B737-800

**Cruise**

Mach: 0.72
Altitude: 40636 – 43329 ft
L/D: 22.1
Static margin: 5 % (limit), 15%(typ.)
CG travel: 7.4 ft (2.4 m)
Engine SFC: 0.45 lb/(lbf hr)

**Airframe**

Span: 149.9 ft (45.6 m)
OEW/MTOW: 0.54

**Engine**

OPR: 35
T_{metal}: 1200 K
Max. thrust: 53.9 kN
**D8.5 Major Design Features**

Noise shielding from fuselage/tails  
Flush-mounted engines  
Extended liners on exhaust ducts  
No leading edge slats  
Double bubble with lifting nose and pi-tail  
Centerbody BLI  
Composite aircraft  
N+3 Advanced Technologies  
Propulsion system  
Three geared turbofans Bypass Ratio of 20

---

**Mission**

- **B737-800**: D8.5
- **Payload, 1000 kg**: Range, km

---

**Cruise**

- Mach: 0.74
- Altitude: 44653 – 46415 ft
- L/D: 25.3
- Static margin: 0 % (limit), 10%(typ.)
- CG travel: 8.9 ft (2.7 m)
- Engine SFC: 0.37 lb/(lbf hr)

---

**Airframe**

- Span: 169.9 ft (51.8 m)
- OEW/MTOW: 0.51

---

**Engine**

- OPR: 50
- $T_{metal}$: 1500 K
- Max. thrust: 37.7 kN

---
**D8.5 Airframe Technology Overview**

- **Natural Laminar Flow on Wing Bottom**
- **Reduced Secondary Structure weight**
- **Active Load Alleviation**
- **Boundary Layer Ingestion**
- **Health and Usage Monitoring**
- **Lifting Body**
- **Faired Undercarriage**
- **Advanced Structural Materials**

**Operations Modifications:**
- Reduced Cruise Mach
- Optimized Cruise Altitude
- Descent angle of 4°
- Approach Runway Displacement Threshold
D8.5 Engine Technology Overview

- High Bypass Ratio Engines (BPR=20) with high efficiency small cores
- LDI Advanced Combustor
- Distortion Tolerant Fan
- Tt4 Materials and advanced cooling
- Advanced Engine Materials
- Variable Area Nozzle
- Multi-segment rearward liners
**D8 Concept Overview**

Highly synergistic combination of following physical features:

- "Double-bubble" fuselage cross-section
- Lifting nose
- Nearly-unswept wing
- Rear-mounted engines with BLI fans
- Lightweight pi-tail

These enable numerous other features…
Benefits of Wide Double-Bubble Fuselage with Lifting Nose

- Increased optimum carryover lift and effective span
- Built-in nose-up trimming moment
- Partial span loading
- Shorter landing gear, lower noise
- Roomier coach cabin
- Reduced floor-beam weight
- Weight advantage of fewer windows
Benefits of Reduced Mach Number and Sweep

- Reduction of wing weight for given span
- Reduction of induced drag
- Elimination of LE slats
- Natural laminar flow on wing bottom
- Shorter landing gear via larger $\frac{dC_L}{d\alpha}$
- Propulsion efficiency benefits
Benefits of Engine/Pi-Tail Unit with Flush-Mounted Engines

- Improves propulsive efficiency via fuselage BLI
- Lightweight minimal nacelles
- Expectedly immune to bird strike
- Fan noise shielding noise by fuselage and pi-tail

- Fin strakes synergistically exploited:
  - Function as mounting pylons for engines and tail
  - Usual strake’s added yaw power at large beta
- Small vertical tails from small engine-out yaw
- Lightweight horizontal tail from 2-points support
**B737 ➔ D8.1 “Morphing” Study**

- Shows benefits of D8 configuration alone, with current tech:
  - Aluminum structure
  - Standard load factors, allowables
  - CFM-56 class engines, with BLI
- Identifies physical origins of benefits
- Allows reality checks on feasibility during evolution
**B737 ➔ D8.1 “Morphing” Steps**

- Modifications are introduced sequentially in 8 steps
  - 0. B737-800, CFM56, $M = 0.80$, $l_{BF} = 8000$ ft, not optimized
  - 1. B737-800, optimized airframe+ops (engine fixed)
  - 2. Fuselage replacement from tube+wing to double bubble configuration
  - 3. Reduced cruise Mach number $M = 0.76$
  - 4. Reduced cruise Mach number $M = 0.72$
  - 5. Engines moved from wing to rear and mounted flush with top fuselage
  - 6. Optimized airframe+ops+*engines*, with 15-year engine improvements
  - 7. Remove slats (less weight and excrescence drag)
  - 8. Reduced $l_{BF} = 5000$ ft
B737-800 Starting Point – Case 0
D8.1 Ending Point – Case 8
- B737-800, CFM56, $M=0.80$, $l_{BF}=8000$ ft, not optimized
B737 → D8.1 “Morphing” – Case 0 - 1

- B737-800, CFM56, $M=0.80$, $l_{BF}=8000$ ft, not optimized
- B737-800, optimized airframe + ops (engine fixed)
• B737-800, optimized airframe + ops (engine fixed)
• Fuselage replacement from tube + wing to double bubble configuration
Fuselage replacement from tube + wing to double bubble configuration

Reduced cruise Mach number $M=0.76$
- Reduced cruise Mach number $M=0.76$
- Reduced cruise Mach number $M=0.72$
- Reduced cruise Mach number $M=0.72$
- Engines moved from wing to rear and mounted flush with top fuselage
- Engines moved from wing to rear and mounted flush with top fuselage
- Optimized airframe+ops+engines, with 15-year engine improvements
B737 ➔ D8.1 “Morphing” – Case 6 - 7

- Optimized airframe+ops+engines, with 15-year engine improvements
- Remove slats
Remove slats
- Reduced $l_{BF}=5000$ ft


**B737 ➔ D8.1 Gross and Fuel Weight Evolution**

![Graph showing the evolution of gross and fuel weight for different configurations of the B737. The graph compares max takeoff weight (lb) against fuel weight (lb). The configurations include B737-800 M=0.8, B737-800 optimized, Double-bubble fuselage, M=0.76, M=0.72, Engines to rear, Optimize engines, Misc. mods, BFL=5000 ft. The graph shows a clear trend of decreasing fuel weight and max takeoff weight.](image-url)
B737 ➔ D8.1 Component Drag Evolution
**B737 ➔ D8.1 C_L snd TSFC Evolution**
B737 ➞ D8.1 Sweep, AR, L/D Evolution
**B737 ➔ D8.1 Fuel Burn Evolution**

D8 configuration gives 49% fuel burn reduction.
B737 ➔ D8.1 Morph Study—Main Observations

- Improvement arises from integration and exploitation of indirect benefits – there is no one “magic bullet”
- Design methodology allows exploration of interactions
- D8 fuselage alone is slightly draggier than B737's, but enables…
  - lighter wing
  - smaller lighter tails
  - enables fuselage BLI
  - smaller, lighter engines
  - shorter, lighter landing gear
  - … etc
- BLI itself has indirect benefits…
**BLI and Engine Integration Benefits**

- Ingested fluid has its wake dissipation eliminated
- Overall engine size shrinks
- Optimized BLI engine has larger $FPR$ and smaller $BPR$ (= less weight) than non-BLI engine with same core

<table>
<thead>
<tr>
<th></th>
<th>$FPR$</th>
<th>$BPR$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-BLI</td>
<td>1.45</td>
<td>14.0</td>
</tr>
<tr>
<td>BLI</td>
<td>1.58</td>
<td>7.5</td>
</tr>
</tbody>
</table>
**D8 BLI Approach**

- Entire upper fuselage BL ingested
- Exploits natural aft fuselage static pressure field
  - Fuselage's potential flow has local $M = 0.6$ at fan face
  - No additional required diffusion into fan
  - No generation of streamwise vorticity
  - Distortion is a smoothly stratified total pressure
Optimum Cruise Altitudes (I)

- Real objective is to move fuselage + payload 3000 nmi, at a minimum drag or energy cost
  \[ E_{\text{fuse}} = D_{\text{fuse}} \times \text{Range} = \left( \frac{1}{2} \rho V^2 A_{\text{fuse}} C_{f_{\text{fuse}}} \right) \times \text{Range} \]

- Aside from laminar flow, the only option to reduce \( E_{\text{fuse}} \) is to reduce \( r \) (fly higher)

- But flying high incurs “energy-use overhead”:
  - Larger and heavier wings, tails, engines
  - Thicker pressure vessel skin

\[ \Rightarrow \] Optimum cruise altitude is where \( E_{\text{fuse}} \) is balanced by the overhead
Optimum Cruise Altitudes (II)

- Current jets
  \[ \Rightarrow 35 \text{kft cruise is optimum tradeoff} \]
- D8.1 dilutes the overhead factor mainly via configuration:
  - Low-sweep wing
  - Fuselage lift and nose-up moment
  - Pi-tail with 2-point horizontal tail mounting
  - Reduced nacelle wetted area and weight, etc.
    \[ \Rightarrow 40 \text{kft cruise is optimum tradeoff} \]
- D8.5 dilutes the overhead further:
  - Better materials, SHM, GLA, etc.
  - Lighter engines, better components, etc.
    \[ \Rightarrow 45 \text{kft cruise is optimum tradeoff} \]
- Side benefit of higher cruise is “oversized” and thus quieter engines
D8 Configurations: Design and Performance

<table>
<thead>
<tr>
<th></th>
<th>Cruise Mach</th>
<th>L/D</th>
<th>OEW/MTOW</th>
<th>TSFC (g/kNs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D8.1</td>
<td>0.72</td>
<td>22</td>
<td>0.54</td>
<td>12.8</td>
</tr>
<tr>
<td>D8.5</td>
<td>0.74</td>
<td>25</td>
<td>0.51</td>
<td>10.5</td>
</tr>
</tbody>
</table>

Fuel Burn (kJ/kg-km)
Field Length (feet)
Noise (EPNdB below Stage 4)
LTO NOx (g/kN) (% below CAEP 6)

D8.1 (Aluminum)
D8.5 (Composite)
**Improved Load/Unload Time and Airport Capacity**

- **Improved Load/Unload Time.** D8.5 provides reduction in block time during load and unload and approach operations

  B737-800  
  30 x 6 per aisle  
  (35 min. load, unload)  
  D8.5  
  23 x 4 per aisle  
  (20 min. load, unload)

<table>
<thead>
<tr>
<th>Flight time (hr)</th>
<th>Trip time (hr)</th>
<th>Flight time (hr)</th>
<th>Trip time (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B737</td>
<td>D8.5</td>
<td>B737</td>
<td>D8.5</td>
</tr>
<tr>
<td>NYC-LAX</td>
<td>4.81</td>
<td>5.29</td>
<td>5.98</td>
</tr>
<tr>
<td>NYC-ORD</td>
<td>1.55</td>
<td>1.73</td>
<td>2.71</td>
</tr>
<tr>
<td>BOS-DCA</td>
<td>0.93</td>
<td>1.06</td>
<td>2.09</td>
</tr>
</tbody>
</table>

- **Airport capacity.** D8 could allow for increased airport capacity due to wake vortex strength reduction
Strut-Braced Wing Study

- D8 fuselage was combined with strut-braced wings
  - SD8.1, aluminum
  - SD8.5, composite
- Optimized with TASOPT
- Preliminary aeroelastic analyses with ASWING
SD8.1 Strut-Braced Wing Configuration, Aluminum

Mach = 0.72
Area = 1282 ft²
Span = 182 ft
MAC = 7.72 ft
AR = 25.9
L/D = 22.9
MTOW = 123310 lb
Wfuel = 18270 lb
Range = 3000 nmi
Field = 6000 ft

Dfan = 49 in
FPR = 1.58
NPR = 7.1
OPR = 35.8

22.23 rows
180 seats
19'x33'

N+3 SD8.1
SD8.5 Strut-Braced Wing Configuration, Composite

- Dfan = 52 in
- FFR = 1.42
- BPR = 20
- QFR = 90

- 22.21 rows
- 180 seats
- 19"x13"

N+3 SD8.5
- Mach = 0.74
- Area = 1040 ft²
- Span = 188 ft
- HGC = 6.10 ft
- AR = 33.92
- L/D = 26.1
- MTOW = 97970 lb
- Wfuel= 10650 lb
- Range= 3000 nmi
- Field= 4650 ft
Strut-Braced Wing Evaluation

- Fuel burn changes from baseline:
  - SD8.1: -53% ( -4% better than D8.1)
  - SD8.5: -73% ( -2% better than D8.5)
- More complex structure, larger spans and aspect ratios
  - Larger manufacturing costs
  - More restrictions on airport gate operations
- Significant added risks compared to cantilever versions
  - Complex and more numerous failure modes
  - Aeroelasticity concerns, nonlinear flutter conceivable
⇒ Small fuel gains deemed unjustified with offsetting factors
**D8.5 – Double Bubble Configuration**

Mission
- Payload: 180 PAX
- Range: 3000 nm

<table>
<thead>
<tr>
<th>Metric</th>
<th>737-800 Baseline</th>
<th>N+3 Goals % of Baseline</th>
<th>D8.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Burn (PFEI) (KJ/kg-km)</td>
<td>7.43</td>
<td>2.23 (70% Reduction)</td>
<td>2.17 (70.8% Reduction)</td>
</tr>
<tr>
<td>Noise (EPNdb below Stage 4)</td>
<td>277</td>
<td>202 (-71 EPN db Below Stage 4)</td>
<td>213 (-60 EPNdb Below Stage 4)</td>
</tr>
<tr>
<td>LTO Nox (g/kN) (% Below CAEP 6)</td>
<td>43.28 (31% below CAEP 6)</td>
<td>75% below CAEP 6</td>
<td><strong>10.5 (87.3% below 6)</strong></td>
</tr>
<tr>
<td>Field Length (ft)</td>
<td>7680 for 3000 nm mission</td>
<td>5000 (metroplex)</td>
<td><strong>5000 (metroplex)</strong></td>
</tr>
</tbody>
</table>
D8.5 Take-off Noise Estimate

Sideline: 75.6 EPNdB

Flyover: 63 EPNdB

Technologies for reduced take-off noise:
- UHBR engine
- Near sonic fan tip speed
- Reduced jet velocity through BLI and low FPR
- Airframe shielding for forward noise
- Multi-segment rearward acoustics liners
- Operations for reduced noise
Technologies for reduced approach noise:

- Eliminate slats
- Undercarriage fairing
- Airframe design for enhanced low speed performance
- Airframe shielding for fan forward noise
- Low engine idle thrust
- Descent angle of 4 degrees and Runway Displacement Threshold
**D8.5 LTO NOx**

Technologies for reduced LTO NOx:
- Improved engine cycle and ultra high bypass ratio engine
  - Lower TSFC
- Lean Direct Injection (LDI) Combustor

LTO NOx for D8 configuration with advanced technologies is 10.5 g/kN and cruise NOx emission 4.2 g/kg

*(87.3% Reduction with respect to CAEP 6)*
PFEI for D8 configuration with advanced technologies is 2.17 kJ/kg-km (70.8% Reduction with respect to baseline B737-800)
D8.5 Fuel Burn for different missions

- Bureau of Transportation Statistics (BTS) database examined to find actual variation in payload/range for B737-800
- Fuel burn varies between 2.89 and 2.17 kJ/kg-km for ranges between 500 to 3000 nm
**D8 Climate Performance**

- Climate metric of interest = $\Delta T\text{-yrs}$
  - Globally averaged, time-integrated surface temperature change
  - Normalized by productivity (payload*distance)
  - Used 800 year time-window to capture full CO$_2$ impact

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Payload (kg)</th>
<th>Distance (km)</th>
<th>$\Delta T$-years ($^\circ K$-yrs)</th>
<th>Normalized Climate Impact ($^\circ K$-yrs / (kg x km))</th>
</tr>
</thead>
<tbody>
<tr>
<td>B737-800</td>
<td>19958</td>
<td>3723</td>
<td>1.37E-08</td>
<td>18.4E-17</td>
</tr>
<tr>
<td>N+3 Goals</td>
<td>19958</td>
<td>3723</td>
<td>4.07E-09</td>
<td>5.48E-17</td>
</tr>
<tr>
<td>D8.1</td>
<td>38700</td>
<td>5556</td>
<td>7.61E-09</td>
<td>3.54E-17</td>
</tr>
<tr>
<td>D8.5</td>
<td>38700</td>
<td>5556</td>
<td>4.33E-09</td>
<td>2.01E-17</td>
</tr>
</tbody>
</table>

- D8.1 $\rightarrow$ 81% improvement; D8.5 $\rightarrow$ 89% climate improvement
- Benefit mostly attributable to fuel burn savings
D8.5 Contribution of Different Technologies to Noise

- D8 configuration provides greatest benefit
- Ultra high bypass ratio engines reduces fan and jet noise through near sonic tip speeds and jet velocity reduction
- Change in approach trajectories reduces approach noise through increased distance to the observer

-60 EPNdB reduction relative to Stage 4
**Contribution of Different Technologies to LTO NOx**

- D8 configuration provides greatest benefit due to optimized engine cycle
- Advanced combustor technology
- Ultra high bypass ratio engines due to reduced engine TSFC

### 87.3% reduction relative to CAEP 6

<table>
<thead>
<tr>
<th>Technology</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>D8.1 - Configuration Only</td>
<td>51.85%</td>
</tr>
<tr>
<td>Advanced Combustor Technology (LDI)</td>
<td>18.29%</td>
</tr>
<tr>
<td>High BPR Engines (High Efficiency Small Cores)</td>
<td>15.55%</td>
</tr>
<tr>
<td>Compressor Efficiency</td>
<td>0.8%</td>
</tr>
<tr>
<td>Turbine Efficiency</td>
<td>0.66%</td>
</tr>
<tr>
<td>Fan Efficiency</td>
<td>0.07%</td>
</tr>
<tr>
<td>Combustor Pressure Drop</td>
<td>0.07%</td>
</tr>
<tr>
<td>Cooling and Tmetal materials</td>
<td>-0.04%</td>
</tr>
</tbody>
</table>

Total: 87.3% reduction relative to CAEP 6
D8.5 Contribution of Different Technologies to Fuel Burn

- D8 configuration provides greatest benefit
- Airframe advanced materials and processes for structural weight reduction
- Ultra high bypass ratio engines for increased engine TSFC

70.8% Fuel Burn reduction relative to B737-800
Bypass Ratio Trades: Noise and Fuel Burn

Increase in BPR:
- Decrease in noise by decrease of fan tip speed and jet velocities
- Decrease in Fuel Burn by increase of propulsive efficiency
**Trades between Balanced Field Length, Noise, and Fuel Burn**

For short balanced field length (around 3200 feet)

- Decreased cutback noise due to increased distance to the observer, and reduced FPR. Decrease approach noise due to decreased flight speed
- Increased winspan comparable to B777 so not suitable for metroplex
**D Series Challenges**

Recommended Key Technology Focus Areas for D8 Series Development to TRL-4

- Small Core Size Engine Technology
- Boundary Layer Ingesting (BLI) Propulsion
- Propulsion-Airframe Integration/ Exhaust System
Core Size Challenge: Axial, Mixed NA+C, or Centrifugal HPC?

Current Small Engine Technology: OPR ~ 25-30, BPR ~ 5

Axial HPCs

NA + C

Adv Technology: OPR ~ 50, BPR ~ 10-20

Dseries engine
Fuselage BLI ➔ “Flat Distortion” into the Fan

**Throat Section**

2.5 L/D Inlet high offset

**AIP Section**

D8 Series external diffusion inlet

- **Challenges**: fan performance, operability, blade stress, system performance
Propulsion-Airframe Integration & Aeroacoustics for D8 Series

- **Challenges:** multiple close-coupled exhaust, ensure low installed drag
H Aircraft Concept
**H3.2 Major Design Features**

- Advanced structural design
- Centerbody: LE camber
- No leading edge slats
- Fairied undercarriage
- Extended liners on exhaust ducts
- Noise shielding from fuselage
- Variable area nozzle
- Thrust vectoring
- Flush-mounted engines
- 40% span centerbody BLI

**ENGINES**

High bypass ratio (BPR: 20) turbofans: 2 cores-4 fans
Bevel gear transmission

<table>
<thead>
<tr>
<th>Mission:</th>
<th>Cruise:</th>
<th>Airframe:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boeing 777-300ER</td>
<td>Mach: 0.83</td>
<td>Span: 213 ft (65 m)</td>
</tr>
<tr>
<td>Boeing 777-200LR</td>
<td>Altitude: 34921 – 40850 ft</td>
<td>OEW/MTOW: 0.44</td>
</tr>
<tr>
<td></td>
<td>L/D: 24.2</td>
<td>Engine:</td>
</tr>
<tr>
<td></td>
<td>Static margin: 6.9 %</td>
<td>OPR: 50</td>
</tr>
<tr>
<td></td>
<td>CG travel: 3 ft (0.9 m)</td>
<td>$T_{\text{metal}}$: 1500 K</td>
</tr>
<tr>
<td></td>
<td>Engine SFC: 0.50 lb/(lbf hr)</td>
<td>Max. thrust: 261 kN</td>
</tr>
</tbody>
</table>

**Engine Specifications:**

- Max. thrust: 261 kN
- OPR: 50
- $T_{\text{metal}}$: 1500 K
- Engine SFC: 0.50 lb/(lbf hr)
- CG travel: 3 ft (0.9 m)
- Static margin: 6.9 %
- L/D: 24.2
- Altitude: 34921 – 40850 ft
- Mach: 0.83
H3.2 Technologies Overview

- Variable Area Nozzle with Thrust Vectoring
- Advanced Combustor
- Drooped Leading Edge
- Health and Usage Monitoring
- Lifting Body with leading edge camber
- Advanced Materials
- Fairied undercarriage
- Ultra High BPR Engines, with increased component efficiencies
- Active Load Alleviation
- No Leading Edge Slats or Flaps
- Noise shielding from Fuselage and extended liners in exhaust ducts

Operations Modifications:
- Optimized Cruise Altitude
- Descent angle of 4°
- Approach Runway Displacement Threshold
3-View of H3.2 Configuration
Leveraging HWB Design Knowledge

• Leveraged SAI and N+2 methodology and in-house HWB design codes along with SAI, N2A/N2B aerodynamic design of centerbody\(^1\)

• SAI codes reviewed by Boeing Commercial Airplanes, Boeing Phantom Works, Messier Dowty, Rolls-Royce, ITP and NASA

• Leveraged Boeing Phantom Works Wingmod for HWB structural model

• Provides test-bed for comparing novel technologies and impact of mission

HWB Design Methodology (HWBOpt)

Final Configuration

Adjust Technology Selection, Configuration

Aircraft Development HWBOpt

Generate 3D Planform

Weight Estimation

Size Propulsion

Cruise Aero Performance

Trimmed?

Fuel Burn Calculation

Adjust Wing Twist

Converged Weight

Acceptable?

yes

no

Technologies

Mission Scenario Requirements

N+3 Goals

Evaluation against goals

Noise LTO Nox Fuel Burn Bal. Field Climate Risk

LTO Analysis

Stall Speed Analysis

Generate 3D Planform

Weight Estimation

Size Propulsion

Cruise Aero Performance

Trimmed?

Fuel Burn Calculation

Adjust Wing Twist

Converged Weight

yes

no

no

no

yes

no
**H3.2 Cabin Design**

**Cabin**
- Detailed cabin design
  - A350 Interior Rules
  - Fixed cabin box geometry
- 354 PAX (3-Class)

**Cargo**
- 22 LD3 containers + 8 LD7 Long Pallets Cargo (194 m² / 56500 lb)
- Typical payload for comparable aircraft consists of ~40-50% cargo
HWBOpt: Propulsion System Configuration

- Propulsion system configuration consists of transmission system, number of fans, number of cores, fuel type
- Calculated transmission system efficiencies from best available data and models
- Considered conventional fuel and LNG for all configurations
- Configuration chosen based on tradeoff between BLI and engine cycle performance
HWBOpt: Propulsion System Design Methodology

- Used TASOPT engine cycle model
- Extent of boundary layer ingestion matches engine size and determines inlet pressure recovery
- BPR locally optimized for cruise SFC for given cycle parameters
- Variable area nozzle enables flexible choice of engine off-design operating point
**HWBOpt Weight Model**

**Structural weight model**
- SAX40 response surface model based on WingMod, Boeing proprietary code
- Optimistic 30% weight reduction for N+3 timeframe using advanced materials and load alleviation

**Propulsion weight**
- Granta 3401 (SAX 40) bare engine weight scaling
- NASA* gear weight correlation
- Correlation model developed for electric transmission

**Fixed weight and furnishings**
- Roskam correlations

---

1 *NASA TM-2005-213800
**HWB Design**

- Centerbody used on SAX-40, N2A, N2B HWB designs
  - Carved leading edge
  - Not optimized
- Centerbody nose lift trims lift of supercritical outer wings
  - BWB uses inefficient reflex for trim
- Elliptical lift distribution during cruise
- Increase induced drag for quiet approach

**HWBOpt Model**

- 2D viscous analysis for outer wings
- Hoerner correlations for centerbody
- Vortex lattice analysis for lift and induced drag

---

**HWBOpt Optimization**

**Objectives**
- Combination of Fuel Burn and approach airframe noise

**Design Variables**
- Planform geometry / Twist distribution
- Cruise altitude
- Engine cycle / Prop. configuration

**Design Parameters**
- Mach: SAX40F drag divergence study
- Airfoils: SAI, N2A/B centerbody
- Cabin geometry: Detailed design

**Multi-objective mixed-integer programming problem**
- Non-linear objective and constraints
- Islands of feasibility
- Hybrid genetic algorithm
Choice of propulsion system and fuel

- Tradeoff between BLI and engine performance
  - More BLI $\rightarrow$ reduced wake and jet dissipation $\rightarrow$ better aero performance
  - More BLI $\rightarrow$ reduced engine intake pressure recovery $\rightarrow$ worse engine performance
  - Full centerbody BLI requires heavy, distributed propulsion system

- Jet A chosen over LNG
  - Cold sink not required due to elimination of electric transmission
  - Marginal benefits from laminar flow on bottom wing and increased fuel specific energy ($\sim$5% benefit in Fuel Burn)
  - Large risk involved with LNG, relative to Jet A and synthetic fuels from natural gas
**HWB Payload Range Impact**

To quantify impact of payload and range, different HWB designs optimized using HWBOPT framework

- Scale has a significant impact of performance
  - Considered three missions (domestic, intermediate, international)
  - N+3 goals change with mission

- Analysis used detailed cabin design

- Mach number set to 0.83 for all three missions
Discussion of Cabin Size

<table>
<thead>
<tr>
<th>Class</th>
<th>SAX40 OML Scale</th>
<th>Total Cabin Width (m)</th>
<th>Total Seat Capacity</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>0.86</td>
<td>11.28</td>
<td>180</td>
<td>All Economy</td>
</tr>
<tr>
<td>H2</td>
<td>1.00</td>
<td>11.73</td>
<td>256</td>
<td>3 Class</td>
</tr>
<tr>
<td>H3</td>
<td>1.10</td>
<td>16.99</td>
<td>354</td>
<td>3 Class</td>
</tr>
</tbody>
</table>
H1 Performance

- Cabin aisle height requirements
- Longitudinal static stability constraints
- Airport constraints

<table>
<thead>
<tr>
<th>Class</th>
<th>PAX</th>
<th>Revenue Cargo (m²)</th>
<th>Range (nm)</th>
<th>Fuel Burn (kJ/kg-km)</th>
<th>OEW/MTOW</th>
<th>L/D</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>180</td>
<td>-</td>
<td>3,000</td>
<td>4.41</td>
<td>61.5</td>
<td>20.7</td>
</tr>
</tbody>
</table>
**H2 Performance**

Larger aircraft reduces impact of white space

- Cabin aisle height requirements
- Longitudinal static stability constraints
- Airport constraints
- Increased cargo payload
- Improved empty weight fraction

<table>
<thead>
<tr>
<th>Class</th>
<th>PAX</th>
<th>Revenue Cargo(m²)</th>
<th>Range (nm)</th>
<th>Fuel Burn (kJ/kg-km)</th>
<th>OEW/MTOW</th>
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<tbody>
<tr>
<td>H1</td>
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<td>-</td>
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<td>4.41</td>
<td>61.5</td>
<td>20.7</td>
</tr>
<tr>
<td>H2</td>
<td>256</td>
<td>143</td>
<td>8,300</td>
<td>3.07</td>
<td>44.7</td>
<td>24.0</td>
</tr>
</tbody>
</table>
**H3 Performance**

Larger aircraft reduces impact of white space

- Cabin aisle height requirements
- Longitudinal static stability constraints
- Airport constraints
- Increased cargo payload
- Improved empty weight fraction

<table>
<thead>
<tr>
<th>Class</th>
<th>PAX</th>
<th>Revenue Cargo (m²)</th>
<th>Range (nm)</th>
<th>Fuel Burn (kJ/kg-km)</th>
<th>OEW/MTOW</th>
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</tr>
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<tr>
<td>H1</td>
<td>180</td>
<td>-</td>
<td>3,000</td>
<td>4.41</td>
<td>61.5</td>
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<td>H2</td>
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<td>143</td>
<td>8,300</td>
<td>3.07</td>
<td>44.7</td>
<td>24.0</td>
</tr>
<tr>
<td>H3</td>
<td>354</td>
<td>194</td>
<td>7,600</td>
<td>2.75</td>
<td>44.6</td>
<td>24.2</td>
</tr>
</tbody>
</table>
**Fuel Burn vs. Noise - Fundamentals**

- Examined tradeoff between noise and fuel burn
- Governing equations:
  - Airframe performance
    \[
    R = \frac{V}{SFC} \frac{L}{\lambda D} \ln \left( 1 + \frac{W_F}{OEW + W_R + W_P} \right)
    \]
    \(\lambda\) defined as ratio of net required thrust to total airframe drag
  - Airframe noise ~ stall speed
    \[
    U_{\text{stall}} = \sqrt{\frac{2 W}{\rho S C_{L_{\text{max}}}}}
    \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>High wing loading</td>
<td>Low empty weight fraction: Low fuel burn</td>
<td>High stall speed: High airframe noise</td>
</tr>
<tr>
<td>High wing sweep</td>
<td>High cruise L/D at M=0.83: Low fuel burn</td>
<td>Low (C_{L_{\text{max}}}), high stall speed: High airframe noise</td>
</tr>
<tr>
<td>High exhaust duct</td>
<td>Large noise attenuation: Low engine noise</td>
<td>High empty weight fraction: High fuel burn</td>
</tr>
<tr>
<td>(L_{\text{duct}}/D_{\text{fan}})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low takeoff FPR</td>
<td>Low takeoff engine noise</td>
<td>Takeoff field length constraint more difficult</td>
</tr>
</tbody>
</table>
Fuel Burn vs. Noise - HWB Comparison

- Multi-Objective Optimization resulted in H3.2x Pareto front
  - H3.2 had lowest fuel burn
  - H3.2Q had lowest stall speed
- Compared H3.2 and H3.2Q to Silent Aircraft, SAX-40
- Achieve lower noise with low approach speed, low takeoff FPR, long liners
- Penalty for low noise in terms of higher fuel burn due to OEW/MTOW or wetted area
- H3.2 airframe chosen over H3.2Q for final N+3 HWB design
- 25% fuel burn improvement chosen over 12 EPNdB noise reduction

<table>
<thead>
<tr>
<th>Parameter</th>
<th>H3.2</th>
<th>H3.2Q</th>
<th>SAX-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>OEW/MTOW</td>
<td>44%</td>
<td>45%</td>
<td>62%</td>
</tr>
<tr>
<td>Approach Speed (m/s)</td>
<td>80</td>
<td>69</td>
<td>60</td>
</tr>
<tr>
<td>Take Off FPR</td>
<td>1.39</td>
<td>1.31</td>
<td>1.19</td>
</tr>
<tr>
<td>Liner $L_{duct}/D_{fan}$</td>
<td>2</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Performance</td>
<td>H3.2</td>
<td>H3.2Q</td>
<td>SAX-40</td>
</tr>
<tr>
<td>Fuel Burn</td>
<td>2.75</td>
<td>3.45</td>
<td>5.90</td>
</tr>
<tr>
<td>Cum. Noise (EPNdB)</td>
<td>242</td>
<td>230</td>
<td>210</td>
</tr>
</tbody>
</table>
## H3.2 Performance

### Mission
- Payload: 354 PAX
- Range: 7600 nm

<table>
<thead>
<tr>
<th>Metric</th>
<th>777-200 LR Baseline</th>
<th>N+2 Goals % of Baseline</th>
<th>N+3 Goals % of Baseline</th>
<th>H3.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Burn (PFEI) (KJ/kg-km)</td>
<td>5.94</td>
<td>3.58 (40% Reduction)</td>
<td>1.79 (70% reduction)</td>
<td>2.75 (54% reduction)</td>
</tr>
<tr>
<td>Noise (EPNdB below Stage 4)</td>
<td>288</td>
<td>246 (-42 EPNdB)</td>
<td>217 (-71 EPNdB)</td>
<td>242 (-46 EPNdB Below Stage 4)</td>
</tr>
<tr>
<td>LTO Nox (g/kN) (% Below CAEP 6)</td>
<td>67.9</td>
<td>24.5 (75% below CAEP 6)</td>
<td>&gt;24.5 (75% below CAEP 6)</td>
<td>18.6 (81% below CAEP 6)</td>
</tr>
<tr>
<td>Field Length (ft)</td>
<td>10,000</td>
<td>4375 (50%)</td>
<td>metroplex</td>
<td>9000</td>
</tr>
</tbody>
</table>
H3.2 Take-off Noise

Technologies for reduced take off noise:

- High thrust and low jet velocity using variable area nozzle
- Acoustic liners for fan rearward and forward noise
- Airframe shielding for fan forward noise
- Faired undercarriage
H3.2 Approach Noise

Technologies for reduced approach noise:
- Elimination of flaps and slats.
- Fair ed undercarriage
- Deployable dropped leading edge
- Acoustic liners for fan rearward and forward noise
- Airframe shielding for fan forward noise
- Low engine idle thrust
H3.2 LTO NOx

Technologies for reduced LTO NOx:
- Improved engine cycle and ultra high bypass ratio engine
  - Lower TSFC
- Lean Direct Injection (LDI) Combustor

LTO NOx for H3.2 configuration is 18.6 g/kN and cruise NOx emissions 5.6 g/kg
(81% Reduction with respect to CAEP 6)
H3.2 Fuel Burn Results

PFEI for H3.2 configuration 2.75 kJ/kg-km
(54% Reduction with respect to baseline B777-200LR)
Contribution of Different Technologies to Fuel Burn

- HWB airframe configuration with podded engines provides greatest benefits
- Boundary layer ingestion with distributed propulsion system
- Advanced composite materials yielding 30% reduction in structural weight

<table>
<thead>
<tr>
<th>Technology</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>H3B - Configuration (Engines with BPR=13)</td>
<td>31.30%</td>
</tr>
<tr>
<td>Boundary Layer Ingestion (Engines with BPR=20)</td>
<td>9.52%</td>
</tr>
<tr>
<td>Airframe Advanced Materials and Processes</td>
<td>9.29%</td>
</tr>
<tr>
<td>Turbine Efficiency</td>
<td>1.34%</td>
</tr>
<tr>
<td>Tmetal Materials</td>
<td>1.25%</td>
</tr>
<tr>
<td>Compressor Efficiency</td>
<td>0.66%</td>
</tr>
<tr>
<td>Combustor Pressure Drop</td>
<td>0.44%</td>
</tr>
<tr>
<td>Turbine Stanton Number</td>
<td>0.06%</td>
</tr>
<tr>
<td>Cooling Effectiveness</td>
<td>0.06%</td>
</tr>
</tbody>
</table>

Total Contribution: 53.91%
H3.2 Climate Performance

- Climate metric of interest = $\Delta T$-yrs
  - Globally averaged, time-integrated surface temperature change
  - Normalized by productivity (payload*distance)
  - Used 800 year time-window to capture full CO$_2$ impact

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Payload (kg)</th>
<th>Distance (km)</th>
<th>$\Delta T$-years ($^\circ$K-yrs)</th>
<th>Normalized Climate Impact ($^\circ$K-yrs / (kg x km))</th>
</tr>
</thead>
<tbody>
<tr>
<td>B777-300ER</td>
<td>34785</td>
<td>11908</td>
<td>1.11E-07</td>
<td>2.69E-16</td>
</tr>
<tr>
<td>N+3 Goals</td>
<td>34785</td>
<td>11908</td>
<td>3.33E-08</td>
<td>8.04E-17</td>
</tr>
<tr>
<td>H3.2</td>
<td>60977</td>
<td>14075</td>
<td>5.85E-08</td>
<td>6.82E-17</td>
</tr>
</tbody>
</table>

- H3.2 $\rightarrow$ 75% climate improvement over baseline
- Benefit attributable to fuel burn savings
Challenges of HWB Aircraft Design

• Design efficient hybrid wing body aircraft with minimum “white space”

• To improve aircraft design, need to
  – Develop modular cabin design amenable to sensitivity analysis and optimization
  – Develop conceptual structural model based on first principles and analytical estimates (currently based on proprietary data)
  – Capture sufficient 3-D aerodynamics for centerbody optimization
  – Incorporate above features into revised version of HWBOpt to widen design space being explored
Concept and Technology Development
Risk Assessment (I)

Risk

The measure of uncertainty in advancing an aircraft concept capable of achieving NASA N+3 goals to TRL 4* by 2025.

Method to measure uncertainty: Expert Judgment (Delphi method**)

- Useful for new technologies
- Verification using technology trend extrapolation (when historical data was available)

Likelihood vs. Consequence Charts

- For each technology, analyzed:
  1. Likelihood = Risk of not achieving TRL 4 by 2025
  2. Consequence = Impact of each technology on final configuration

* TRL 4 = Component and/or breadboard validation in laboratory environment
Risk Assessment (II)

Delphi Method

- 18 experts from Academia, Industry, and Government
- Each technology reviewed by 2+ experts, who provided data on:
  1. Current state-of-the-art of different technologies
  2. Probability of these technologies achieving TRL 4+ by 2025
  3. Major technological barriers
  4. Technology development steps (maturation plans)

Trend Extrapolation

- Linear trends (used for short periods of time or minimal performance growth)
- Exponential trends (used for high-growth technologies)
- S-Curves (used for competing technologies or high saturation

\[ X = \frac{A}{1 + Be^{-ct}} \]
# D8.5 - Risks vs. Noise Reduction

<table>
<thead>
<tr>
<th>Consequence</th>
<th>Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

- **1. Step Approach Trajectory at 4 Degrees** (-3 dB)
- **2. Displaced Runway Threshold at Approach** (-3 dB)
- **3. Fair Undercarriage** (-2 dB)
- **4. Fan Efficiency** (-2 dB)
- **5. UH BPR Engines (High Efficiency Small Cores)** (-11 dB)
- **6. D8.1 - Configuration Only** (-40 dB)

The chart illustrates the risks vs. noise reduction for various technologies, with the x-axis representing the likelihood of not achieving TRL 4 by 2025 and the y-axis representing the consequences of the technology impact on the final configuration.
D8.5 - Risks vs. LTO NOx Reduction

1. Fan Efficiency (-0%)
2. Turbine Efficiency (-1%)
3. Compressor Efficiency (-1%)
4. Advanced Combustor Technology (-18%)
5. Ultra High BPR Engines (-16%)
6. D8.1 - Configuration Only (-52%)

Consequence (Impact of technology on final config.)

Likelihood (Risk of not achieving TRL 4 by 2025)
D8.5 - Risks vs. Fuel Burn Reduction

1. Compressor Efficiency (0%)
2. Advanced Engine Materials (-1%)
3. Fan Efficiency (-1%)
4. Turbine Efficiency (-1%)
5. Secondary Structures (-1%)
6. Turbine Cooling (-3%)
7. Airframe Design Load Reduction (-1%)
8. Natural Laminar Flow on Bottom Wings (-3%)
9. UH BPR Engines (High Efficiency Small Cores) (-4%)
10. Airframe Advanced Materials and Processes (-8%)
11. D8.1 - Configuration Only (-49%)

(Risk of not achieving TRL 4 by 2025)

(Consequence (Impact of technology on final config.))

170
H3 - Risks vs. Fuel Burn Reduction

1. Airframe Advanced Materials and Processes (-9%)
2. Boundary Layer Ingestion (BPR = 20) (-10%)
3. Turbine Cooling Technologies (-1%)
4. Turbine Efficiency (-1%)
5. Compressor Efficiency (-1%)
6. H3 - Configuration Only (BPR = 13) (-31%)
Summary of Results

1. We considered technological risk into the final design
2. Most of the technology choices are low risk
   - 95% of each N+3 goal is obtained with technologies with low risk
   - Configuration provides the highest gains for all N+3 goals
3. Small fraction of higher-risk technologies required to meet N+3 goals
N+3 Program Process

Adjust Technology selection, Configuration

Aircraft Development
- TASOPT, HWBOpt
- Configuration
- Integration
- Sizing
- Optimization

Evaluation Against Goals
- Noise
- LTO NOx
- Fuel burn
- Bal. field length
- Climate
- Risks

Acceptable?

Final Configuration

Technologies

Mission Scenario Requirements

NASA N+3 Goals

TMPs
Technology Maturation Plans

• From the discussions with experts, we obtained
  1. Current state of the art for each technology
  2. Technology risks
  3. Technology barriers and advancements to achieve N+3 goals
  4. Identified the development steps to advance each technology to TRL 4 by 2025

• We developed 14 technology roadmaps to mitigate the risks of each technology

• We will present 4 roadmaps, corresponding to the technologies that provide the highest gains on N+3 goals
## D8 Series Configuration

### Goal
Double bubble fuselage, lifting nose, pi-tail, flush-mounted aft engines, reduced cruise Mach number, and no slats

<table>
<thead>
<tr>
<th>PROPULSION SYSTEM</th>
<th>Development Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Perform detailed design / 3D viscous CFD analysis of D8 fuselage/engine OML at design and off design conditions</td>
</tr>
<tr>
<td>2</td>
<td>Perform detailed design / analysis of nacelle including thrust reverses, VAN, structural mounting, and pylon</td>
</tr>
<tr>
<td>3</td>
<td>Perform engine fan design and analysis under vertically stratified inlet distortion conditions</td>
</tr>
<tr>
<td>4</td>
<td>Conduct low speed wind tunnel testing</td>
</tr>
<tr>
<td>5</td>
<td>Conduct high speed wind tunnel testing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AIRFRAME INTEGRATION</th>
<th>Development Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Perform detailed design / analysis of primary structures</td>
</tr>
<tr>
<td>2</td>
<td>Conduct tests for subscale structural concept verification</td>
</tr>
<tr>
<td>3</td>
<td>Conduct structural ground tests of large-scale primary structures</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>AIRCRAFT</th>
<th>Development Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Perform sub-scale aircraft flight tests</td>
</tr>
<tr>
<td>2</td>
<td>Conduct high fidelity noise analysis</td>
</tr>
</tbody>
</table>

### Timeline
- 2010
- 2015
- 2020
- 2025
**H3 Series Configuration**

**Goal**  Develop HWB that allows for tail-less all lifting body with improved aerodynamic performance and low structural weight with acceptable manufacturability.

<table>
<thead>
<tr>
<th>Development Steps</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Develop conceptual structural weight model</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Develop rapid 3D inviscid centerbody aero optimization</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Develop full mission static control models</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Develop 3D viscous aerodynamic CFD solution</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Establish detailed 3D design model</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Conduct low speed wind tunnel testing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 Conduct high speed wind tunnel testing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Manufacture sub-component and centerbody sections</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 Perform ground tests of large-scale structures</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 Conduct sub-scale aircraft flight test (X48B flight test for H3.2 design)</td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>
Ultra High Bypass Ratio Engines

Goal

BPR of 20 for D8.5 and for H3.2

Current State

BPR of 13 for a geared turbofan, BPR of 10 for a direct drive turbofan

<table>
<thead>
<tr>
<th>Development Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIGH EFFICIENCY SMALL CORES</td>
</tr>
<tr>
<td>1 Perform computational and experimental studies to mitigate the efficiency drop associated to small axial compressors and turbines (technology roadmaps included under “Small axial compressor with high efficiency” and “Small axial turbine with high efficiency”)</td>
</tr>
<tr>
<td>2 Improve design and behavior prediction of seals</td>
</tr>
<tr>
<td>3 Develop manufacturing techniques for small HPC blades with the required tolerances</td>
</tr>
</tbody>
</table>

BEVEL GEARS FOR AIRBORNE TRANSMISSION SYSTEMS

| 1 Develop reliable high power bevel gears for high rotational speed applications |
BPR Historical Trend Graph

Historical Data Source:
OPR Historical Trend Graph

Sources:
**Airframe Advanced Materials and Processes**

**Goal**
New materials and processes with unit strength of $\sigma/\rho \approx 2$ over aluminum.

**Current State**
Aluminum. AS4 and IM7 (military) and T800 (civil) carbon fibers are also used on aircraft; M65J and T1000 are the current state of the art carbon fibers. Airbus Next Generation Composite Wing (NGCW) is developing a resin system; MIT NESCT carbon nanotube program developing short CNTs.

<table>
<thead>
<tr>
<th>Development Steps</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Develop stabilized materials and processes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Improve producibility: increase ability to fabricate large amount of short carbon nanotubes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Assess mechanical properties of new materials</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Analyze predictability of structural performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Improve supportability, reparable, maintainability, and reliability</td>
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</tr>
</tbody>
</table>
Reprise and Closing
**Narrative of Team Accomplishments**

- Established documented scenario and aircraft requirements
- Created two conceptual aircraft: D (double-bubble) Series and H (Hybrid Wing Body) Series
  - D Series for domestic size meets fuel burn, LTO NOx, and balanced field length N+3 goals, provides significant step change in noise
  - H Series for international size meets LTO NOx and balanced field length goals
  - D Series aircraft configuration with current levels of technology can provide major benefits
- First-principles methodology developed to simultaneously optimize airframe, engine, and operations
- Generated risk assessment and technology roadmaps for configurations and enabling technologies
Two Scenario-Driven N+3 Aircraft

Double-Bubble (D series): modified tube and wing with lifting body

Baseline: B737-800
Domestic size

Hybrid Wing Body (H series)

Baseline: B777-200LR
International size

Fuel burn (PFEI) (kJ/kg-km)

Field length

Noise

LTO NOx

100% of N+3 goal

100% of N+3 goal
D and H Series Fuel Burn for Different Missions

- D Series has better performance than H Series for missions examined
- H Series performance improves at international size

Note: M = 0.83
D Series Configuration is a Key Innovation

- D8 configuration
- Airframe materials/processes
- High bypass ratio engines
- T metal engine material and advanced cooling processes
- Natural laminar flow on bottom wing
- Engine component efficiencies
- Airframe load reduction
- Secondary structures weight
- Advanced engine materials
- Approach operations
- Fair ed undercarriage
- LDI combustor

% Fuel burn reduction relative to baseline
% LTO NOx reduction relative to CAEP6

Balanced Field Length for all designs = 5000 feet

- Blue: Fuel burn
- Green: Noise
- Orange: LTO NOx

EPNdb Noise reduction relative to Stage 4
Leveraged University-Industry Collaboration

- University perspective, skills
  - Impartial look at concepts, analysis, conclusions
  - Educating the next generation of engineers
- Industry perspectives, skills
  - Aircraft, engine design and development procedures
  - In-depth product knowledge
- Collaboration and teaming
  - Assessment of fundamental limits on aircraft and engine performance
  - Seamless teaming within organizations AND between organizations
- Program driven by ideas and technical discussion
  ⇒ many changes in “legacy” beliefs