NASA’s Turbofan Engine Concept Study for a Next-Generation Single-Aisle Transport

Presentation to ICAO’s Noise Technology Independent Expert Panel
January 25, 2012

National Aeronautics and Space Administration
U.S.A.
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Presentation Outline

• Introduction
• Baseline Vehicle
• Engine Modeling
• Airframe Modeling
• Noise Modeling
• Results and Trade-off Analysis
• Summary
### NASA Subsonic Transport System Level Metrics

#### ...technology for dramatically improving noise, emissions, & performance

#### TECHNOLOGY GENERATIONS

(Technology Readiness Level = 4-6)

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Noise (cum margin rel. to Stage 4)</td>
<td>-32 dB</td>
<td>-42 dB</td>
<td>-71 dB</td>
</tr>
<tr>
<td>LTO NOx Emissions (rel. to CAEP 6)</td>
<td>-60%</td>
<td>-75%</td>
<td>-80%</td>
</tr>
<tr>
<td>Cruise NOx Emissions (rel. to 2005 best in class)</td>
<td>-55%</td>
<td>-70%</td>
<td>-80%</td>
</tr>
<tr>
<td>Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)</td>
<td>-33%</td>
<td>-50%</td>
<td>-60%</td>
</tr>
</tbody>
</table>

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* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines.

** ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

† CO₂ emission benefits dependent on life-cycle CO₂e per MJ for fuel and/or energy source used.

### SFW Approach

- Conduct Discipline-based Foundational Research
- Investigate Advanced Multi-Discipline Based Concepts and Technologies
- Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools and Processes
- Enable Major Changes in Engine Cycle/Airframe Configurations
Historical Look at SFW Propulsion Studies

- SFW has been conducting an on-going engine trade study to assess propulsion options for advanced single-aisle (737/A320 class) aircraft
  - Multi-year, Multi-phase effort
  - Initial focus on ultra-high bypass ratio (UHB) turbofan concepts, followed by investigation of open-rotor engine architectures
  - Multiple interactions with industry over the years to obtain feedback
  - Numerous technical reports and conference papers produced, plus 1 journal article

10/06 4/07 10/07 7/08 1/09 6/09 10/09 10/10 10/11

Results reviewed with P&W

Presentation at FAP Meeting

Review w/ Williams

Detailed exchange w/ P&W

NASA TM (UHB IIb)

FAP

NASA TM (UHB IId)

AIAA ATIO (OR)

AIAA ATIO (UHB IIb)

AIAA Acoustics (UHB IId)

AIAA Acoustics (UHB IIb)

Approved for Public Release
Baseline Vehicle Model

- Model of CFM56-7B type engine developed at Glenn Research Center using the Numerical Propulsion Simulation System (NPSS)
- Baseline 737-800 w/winglets airframe model developed in NASA’s FLOPS (Flight Optimization System) software
  - Publicly available geometry, weight data; proprietary low speed and cruise aerodynamic data
  - Minor calibrations performed to match available data
- Overall mission performance modeled with FLOPS
  - minor calibration of fuel consumption performed to match published range capability
- 737 model resized to assumed N+1 vehicle mission to provide a 1998 technology baseline vehicle
737-800 Fuel Consumption Validation

- **18,700 lb Payload**
- **47,000 lb Payload**

- **1000 nm Range**
- **2000 nm Range**
- **3000 nm Range**

Graph showing the relationship between Total Fuel, lb and Range, nm for different Payload, lb scenarios.
Advanced Turbofan Trade Study

• 12 different turbofan engines developed with NPSS and WATE using consistent technology assumptions and ground rules (not all combinations result in practical designs)
  – Engine Aero Design Point: Overall Pressure Ratio=42; M=0.80; 35,000ft
  – Fan Pressure Ratio varied (FPR= 1.3 to 1.7); bypass ratio set by jet velocity ratio at ADP
  – Fan drive approach varied (direct or geared); gearbox efficiency of 0.99
  – Fan exit nozzle type varied (fixed or variable area); surge margin target of 20%
  – Low spool compression work varied (“high” or “low”)

• 2015-2020 entry-into-service assumed for technology projections
  – Advanced Materials: polymer matrix composites, Titanium aluminide, Titanium metal matrix composite, 5th generation nickel-based alloys
  – Turbine inlet (T4) & turbine rotor inlet (T41) temperatures increased over current technology
  – Advanced Low NOX combustor (using NASA in-house Emission Index correlation representative of Lean Direct Injection architecture)

• Engines designed to meet same thrust requirements at Aero Design Point (top-of-climb) & rolling takeoff (M=0.25, SL)

• Engines applied to a common advanced single-aisle transport (“ASAT”) airframe

• Sensitivity of efficiency, emissions, and noise to engine design assessed
# Engine Trade Space

<table>
<thead>
<tr>
<th>Engine</th>
<th>Fan Drive</th>
<th>Fan Nozzle</th>
<th>ADP</th>
<th>FPR</th>
<th>OPR</th>
<th>LPC PR</th>
<th>HPC PR</th>
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<tr>
<td>Lo_dd_fpr1.4_VAN*</td>
<td>Direct</td>
<td>Variable</td>
<td>M0.80/35kft</td>
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<td>42</td>
<td>1.69</td>
<td>17.7</td>
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<td>Fixed</td>
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<td>42</td>
<td>1.39</td>
<td>17.7</td>
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<td>1.4</td>
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<td>2.50</td>
<td>12.0</td>
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<tr>
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<td>Fixed</td>
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<td>1.5</td>
<td>42</td>
<td>2.33</td>
<td>12.0</td>
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<td>Fixed</td>
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<td>2.19</td>
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<td>2.06</td>
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<td>2.69</td>
<td>12.0</td>
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<td>12.0</td>
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<td>Fixed</td>
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<td>42</td>
<td>2.19</td>
<td>12.0</td>
</tr>
</tbody>
</table>

*Design ground rules lead to impractical designs for these cases*
Engine Characteristics

- Top-of-Climb Fan Pressure Ratio
- TOC Bypass Ratio
- TOC TSFC, lb/(lb-h)
- Engine+Nacelle Weight, lb
- Nacelle Diameter, ft

Graphs showing the relationship between Top-of-Climb Fan Pressure Ratio and other engine characteristics for different drive types (Direct Drive, High; Geared, High; Direct Drive, Low).
Engine Characteristics (2)

![Graph 1](image1.png)

![Graph 2](image2.png)
Advanced Airframe Assumptions

- **Structures:**
  - composite materials for wing, fuselage, and tails (15% structural weight benefit assumed)

- **Aerodynamics:**
  - 1% reduction in drag for trailing edge variable camber and drag clean-up

- **Subsystems:**
  - 5000 psi hydraulic pressure

- **Design range @ 32,400 lb payload** increased from 3060 nm to 3250 nm

- **Cruise Mach number** increased to 0.8
  - Wing sweep adjusted to reflect changes in cruise Mach from 737
Engine-Airframe Integration

- Relative span-wise and chord-wise location of engine unchanged from 737-800
- Nacelle drag assumed proportional to nacelle size (wetted area)
- Approximate calculation of required landing gear length
  - Minimum nacelle clearance (18 inches)
  - No nacelle impact in case of nose gear collapse
- Approximate sizing of vertical tail
  - Minimum tail volume (based on 737-800)
  - Maximum tail loading during one engine out
  - Handbook method for windmilling drag, 737-800 data used for engine out control drag

Example FPR=1.4 Configuration

Example FPR=1.7 Configuration
Aircraft Sizing

- Aircraft weight, thrust, and wing area sized with FLOPS analysis
  - design mission: 3250 nm @ 32,400 lb payload
  - 7000 ft takeoff field length constraint
  - 300 fpm rate-of-climb constraint at M=0.80; 35,000 ft

- Basic geometric parameters (e.g., fuselage length, wing aspect ratio, wing taper ratio, etc.) unchanged from 737-800
Noise Analysis Methodology

- Noise predictions performed using ANOPP
  - Source noise modules fed data from NPSS and WATE models
  - Propagation modeling includes spherical spreading, atmospheric attenuation, ground effects, reflections, and lateral attenuation
- Trajectory simulation done using SAE AIR-1845 INM empirical procedures for a 737-800 and FLOPS for advanced vehicles
- Noise predictions performed for noise certification points

- Noise analysis validated by comparison to 737-800 certification data
Noise Analysis Validation

Comparison of predicted noise to published 737NG/CFM56-7B certification data
ASAT Noise Reduction Technology

• Core nozzle chevrons assumed on all systems, bypass nozzle chevrons on fixed nozzles only (potential conflict with variable area bypass nozzles)
  – Benefit analytically modeled using 2004 Stone jet prediction methods in ANOPP

• Conventional 2DOF acoustic liner

• Soft vane and over-the-rotor liner technologies applied to all systems
  – Additional acoustic treatment in areas not currently treated
  – ANOPP HDNFAN is insensitive to this feature; system-level 4 dB reduction applied
  – Benefits are additive, and assumed constant across frequency, direction, and throttle setting

• Advanced airframe noise reduction technologies
  – Innovative slat cove designs, flap porous tips, landing gear fairings
  – 4 dB reduction in slat/flap noise; 3 dB reduction in gear noise
Aircraft Characteristics (2)

* Baseline is predicted 737-800 noise level
Overall Benefits

![Graph showing Overall Benefits](image1)

- **Baseline is 1998 EIS Technology Airframe and Engine**

- **Change in Ramp Weight**
  - Direct Drive, High
  - Geared, High
  - Direct Drive, Low

- **Change in Block Fuel**
  - Baseline is 1998 EIS Technology Airframe and Engine
  - Direct Drive, High
  - Geared, High
  - Direct Drive, Low

- **LTO NOx, relative to CAEP6**
  - Direct Drive, High
  - Geared, High
  - Direct Drive, Low

- **Cumulative EPWL Margin, Stage 4 Rule, EPNdB**
  - Direct Drive, High
  - Geared, High
  - Direct Drive, Low
# Trade-off Analysis

<table>
<thead>
<tr>
<th>High, Geared, FPR=1.4</th>
<th>Ramp Weight</th>
<th>Block Fuel</th>
<th>Block NO\textsubscript{X}</th>
<th>LTO NO\textsubscript{X}</th>
<th>Cum. EPNdB (Stage 4 Margin\textsuperscript{*})</th>
</tr>
</thead>
<tbody>
<tr>
<td>+2.0 %</td>
<td>+0.5%</td>
<td>+2.7%</td>
<td>Minimum</td>
<td>Minimum</td>
<td>Minimum (25-29 cum.)</td>
</tr>
<tr>
<td>High, Geared, FPR=1.5</td>
<td>+0.3%</td>
<td>Minimum</td>
<td>+0.5%</td>
<td>+0.5%</td>
<td>+3.7 (21-25 cum.)</td>
</tr>
<tr>
<td>Low, Direct, FPR=1.5</td>
<td>+3.7%</td>
<td>+2.3%</td>
<td>+8.4%</td>
<td>+10.6%</td>
<td>+4.3 (21-25 cum.)</td>
</tr>
<tr>
<td>High, Direct, FPR=1.5</td>
<td>+6.8%</td>
<td>+6.0%</td>
<td>+7.3%</td>
<td>+4.8%</td>
<td>+4.4 (21-25 cum.)</td>
</tr>
<tr>
<td>High, Geared, FPR=1.6</td>
<td>+0.1%</td>
<td>+2.0%</td>
<td>Minimum</td>
<td>+6.9%</td>
<td>+10.3 (14-18 cum.)</td>
</tr>
<tr>
<td>Low, Direct, FPR=1.6</td>
<td>+0.5%</td>
<td>+1.2%</td>
<td>+4.5%</td>
<td>+11.5%</td>
<td>+10.4 (14-18 cum.)</td>
</tr>
<tr>
<td>High, Direct, FPR=1.6</td>
<td>+2.6%</td>
<td>+3.9%</td>
<td>+3.0%</td>
<td>+6.9%</td>
<td>+10.5 (14-18 cum.)</td>
</tr>
<tr>
<td>Low, Direct, FPR=1.7</td>
<td>Minimum</td>
<td>+2.8%</td>
<td>+3.4%</td>
<td>+18.9%</td>
<td>+16.1 (9-13 cum.)</td>
</tr>
<tr>
<td>High, Direct, FPR=1.7</td>
<td>+1.2%</td>
<td>+4.5%</td>
<td>+0.5%</td>
<td>+12.7%</td>
<td>+15.8 (9-13 cum.)</td>
</tr>
</tbody>
</table>

* Range represents uncertainty associated with possible overprediction of flyover noise

Good “balanced” performance across all metrics.
Trade-off Analysis (Cont.)
Summary

• SFW project has been performing aircraft system studies to evaluate advanced propulsion concepts for 2015-2020 advanced single-aisle transports

• For advanced turbofans, optimum fan pressure ratio depends on metric of interest
  – Empty/Ramp weight minimized with high FPR
  – Block fuel minimized with FPR ~1.5
  – Block NO\textsubscript{X} minimized with high FPR
  – LTO NO\textsubscript{X} and noise minimized with FPR low as possible

• With current models and assumptions
  – Fan pressure ratio with best compromise among all objectives seems to be ~1.5
  – Geared fan approach is preferred for fan pressure ratios at and below 1.5
  – A direct drive, FPR=1.6 engine can provide similar fuel burn to the geared FPR=1.5 engine, but has higher noise

• Relative to 1998 EIS technology, “practical” study configurations demonstrate
  – Up to \textbf{29\%} reduction in fuel burn
  – Up to \textbf{25 EPNdB} cum. noise reduction (\textbf{25-29* EPNdB} cum. margin to Stage 4)
  – Up to \textbf{67\%} below CAEP6 for LTO NO\textsubscript{X}

* Range represents uncertainty associated with possible overprediction of flyover noise