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

Presentation to ICAO's Noise
Technology Independent Expert Panel
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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 BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-71 dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)	-33%	-50%	-60%

* 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

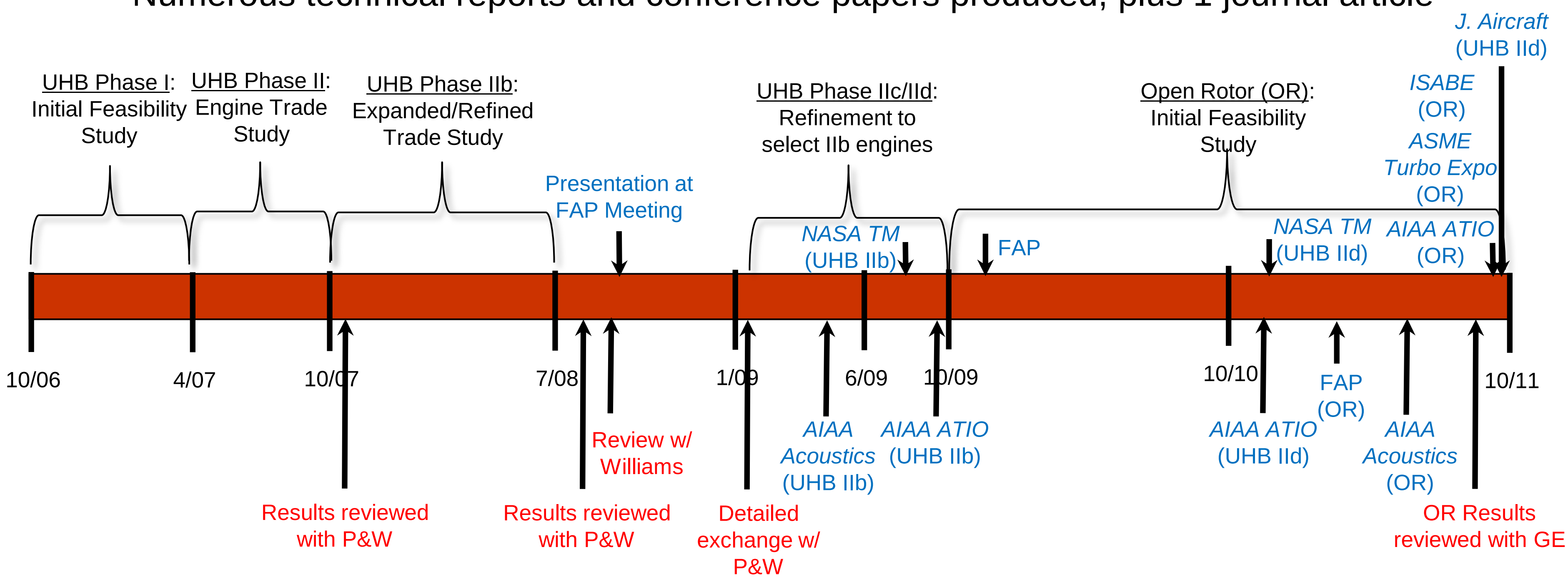
‡ CO_2 emission benefits dependent on life-cycle CO_{2e} per MJ for fuel and/or energy source used

SFW Approach

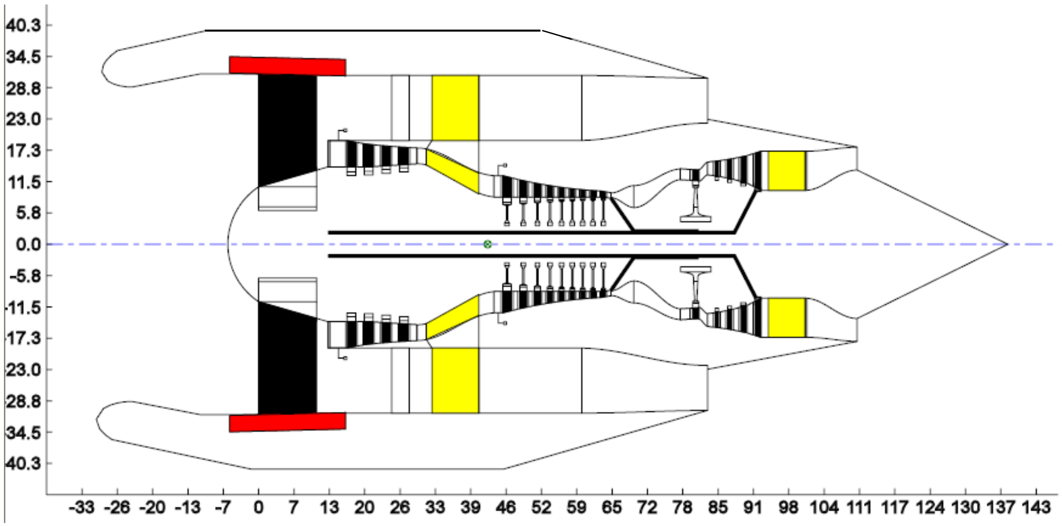
- Conduct Discipline-based Foundational Research
- Investigate Advanced Multi-Discipline Based Concepts and Technologies
- Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools and Processes
- Enable Major Changes in Engine Cycle/Airframe Configurations

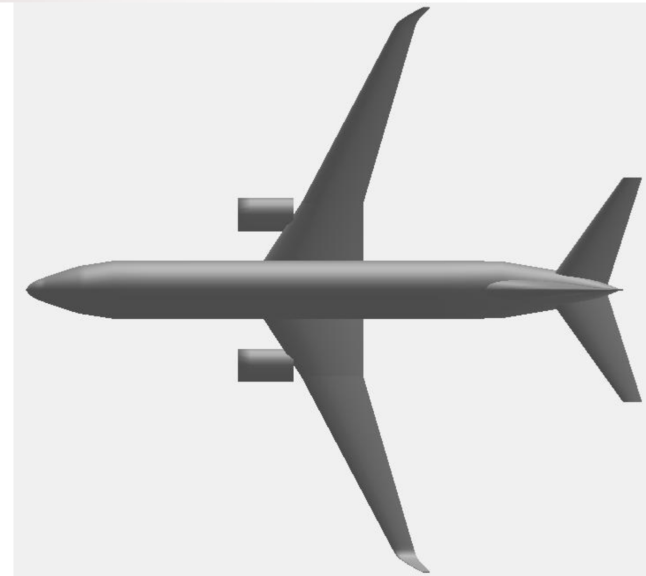
Historical Look at SFW Propulsion Studies

- 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



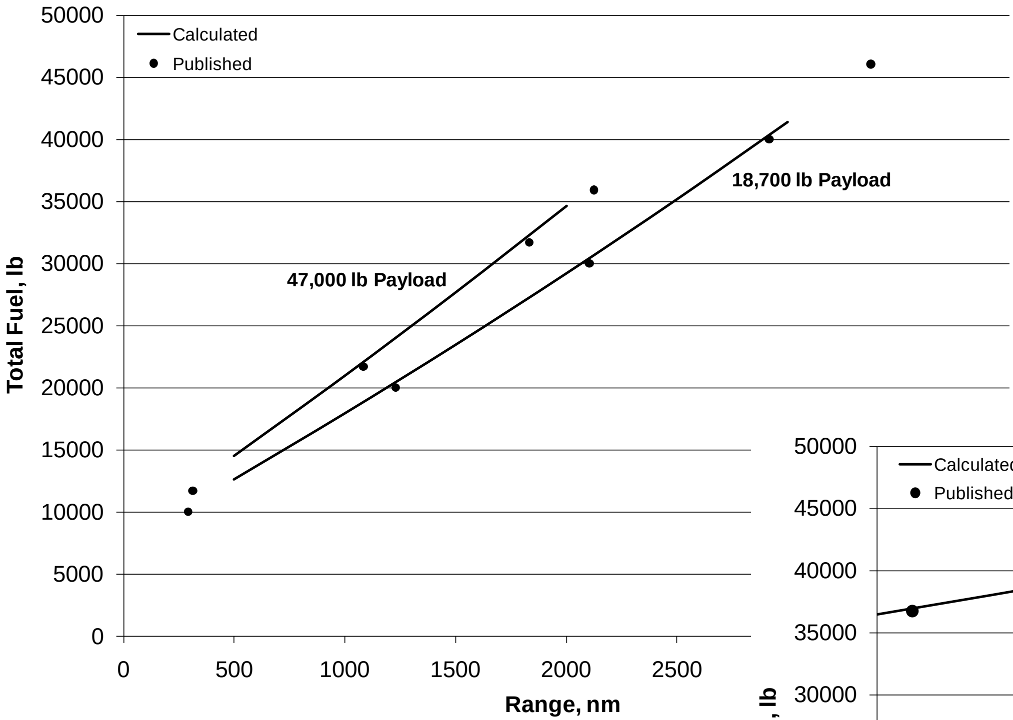
Baseline Vehicle Model

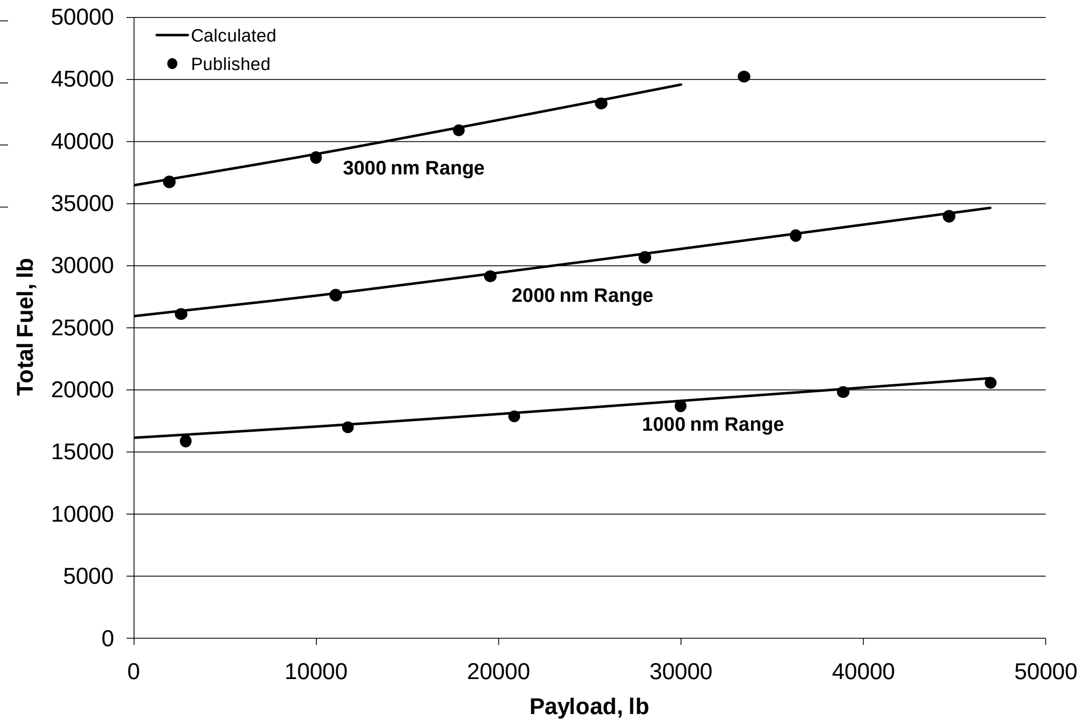




- Model of CFM56-7B type engine developed at Glenn Research Center using the Numerical Propulsion Simulation System (NPSS)
- Baseline 737-800 w/winglets airframe model developed in NASA's FLOPS (Flight Optimization System) software
  - Publicly available geometry, weight data; proprietary low speed and 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





Advanced Turbofan Trade Study

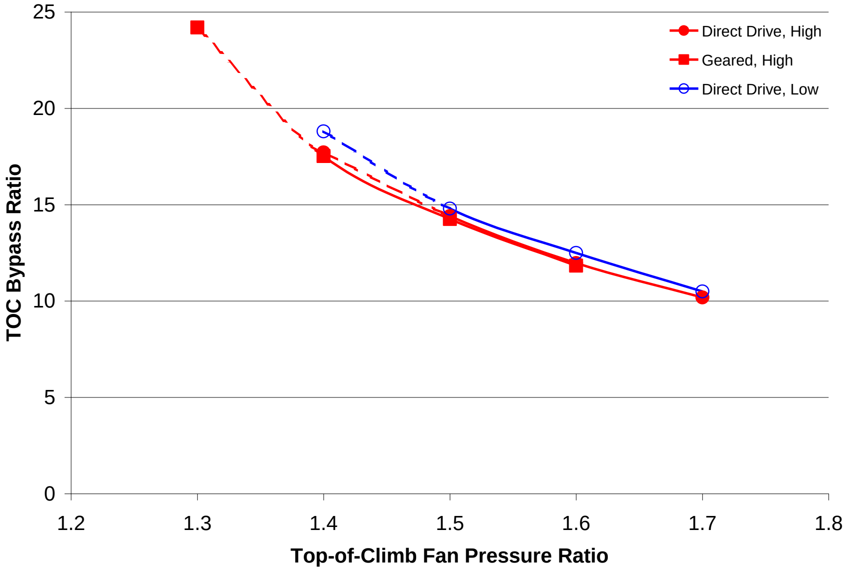
- 12 different turbofan engines developed with NPSS and WATE using consistent technology assumptions and ground rules (not all combinations result in practical designs)
  - Engine Aero Design Point: Overall Pressure Ratio=42; M=0.80; 35,000ft
  - Fan Pressure Ratio varied (FPR= 1.3 to 1.7); bypass ratio 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 NO_X 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

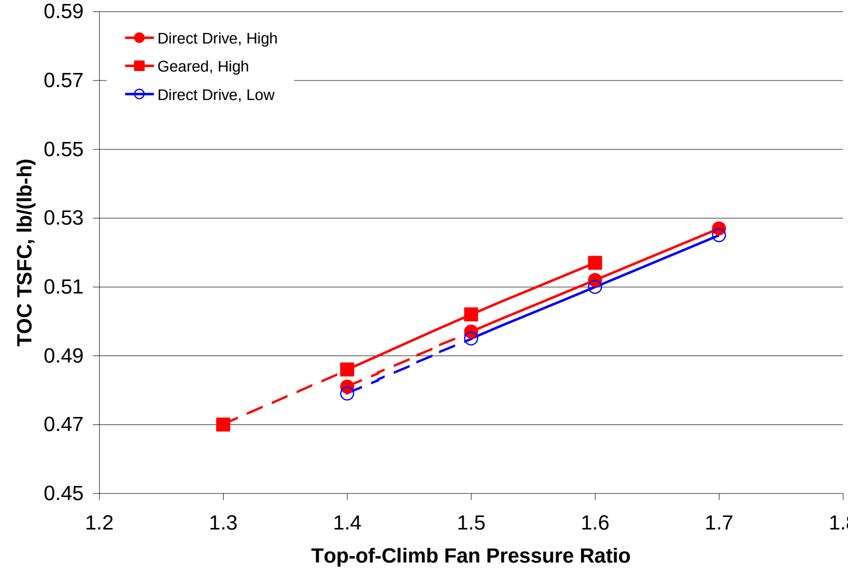
Engine Trade Space

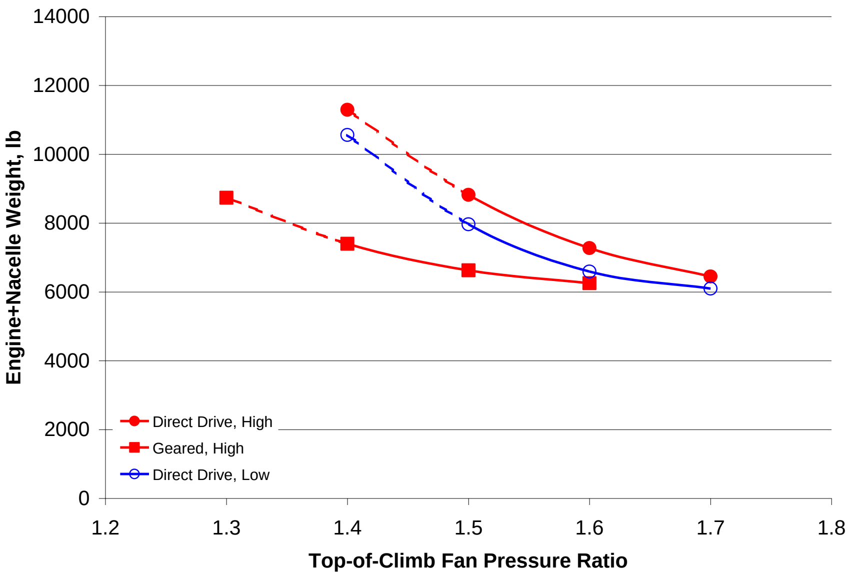
Engine	Fan Drive	Fan Nozzle	ADP	FPR	OPR	LPC PR	HPC PR
Lo_dd_fpr1.4_VAN*	Direct	Variable	M0.80/35kft	1.4	42	1.69	17.7
Lo_dd_fpr1.5_fixed	Direct	Fixed	M0.80/35kft	1.5	42	1.58	17.7
Lo_dd_fpr1.6_fixed	Direct	Fixed	M0.80/35kft	1.6	42	1.48	17.7
Lo_dd_fpr1.7_fixed	Direct	Fixed	M0.80/35kft	1.7	42	1.39	17.7
Hi_dd_fpr1.4_VAN*	Direct	Variable	M0.80/35kft	1.4	42	2.50	12.0
Hi_dd_fpr1.5_fixed	Direct	Fixed	M0.80/35kft	1.5	42	2.33	12.0
Hi_dd_fpr1.6_fixed	Direct	Fixed	M0.80/35kft	1.6	42	2.19	12.0
Hi_dd_fpr1.7_fixed	Direct	Fixed	M0.80/35kft	1.7	42	2.06	12.0
Hi_g_fpr1.3_VAN*	Geared	Variable	M0.80/35kft	1.3	42	2.69	12.0
Hi_g_fpr1.4_VAN	Geared	Variable	M0.80/35kft	1.4	42	2.50	12.0
Hi_g_fpr1.5_fixed	Geared	Fixed	M0.80/35kft	1.5	42	2.33	12.0
Hi_g_fpr1.6_fixed	Geared	Fixed	M0.80/35kft	1.6	42	2.19	12.0

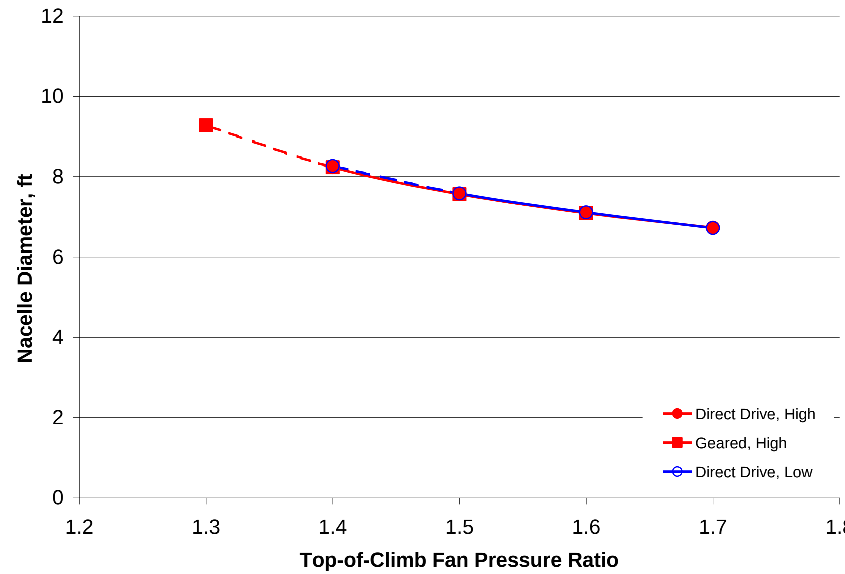
*Design ground rules lead to impractical designs for these cases

Engine Characteristics

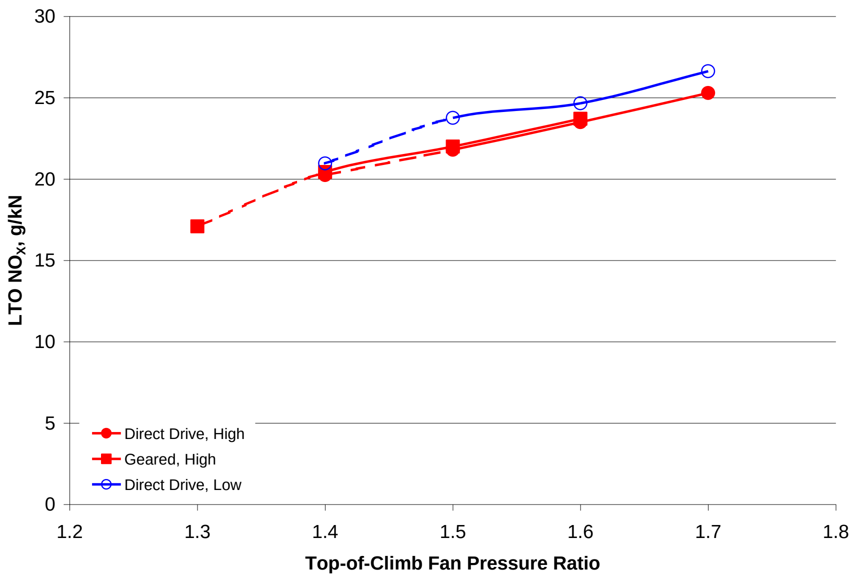


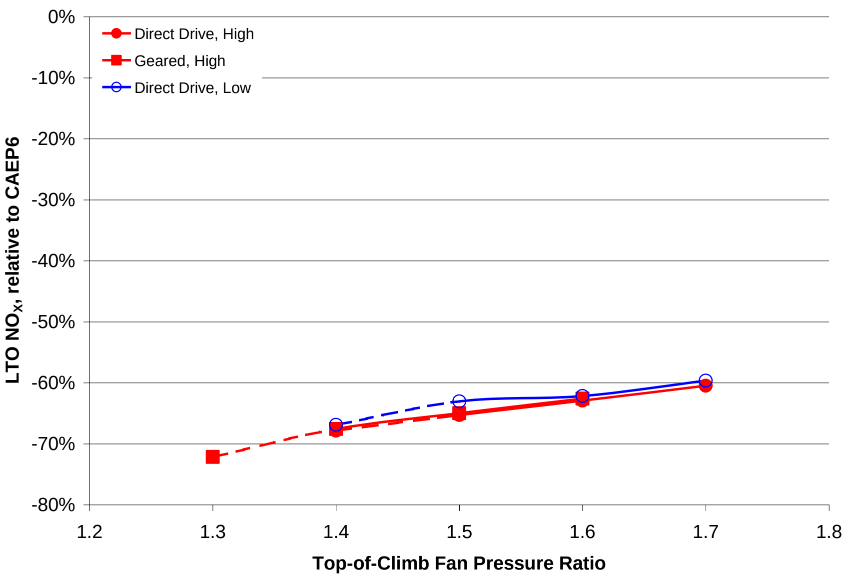






Engine Characteristics (2)



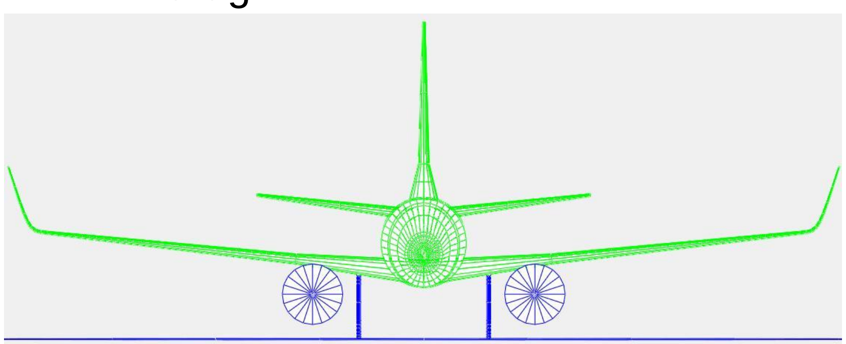


Advanced Airframe Assumptions

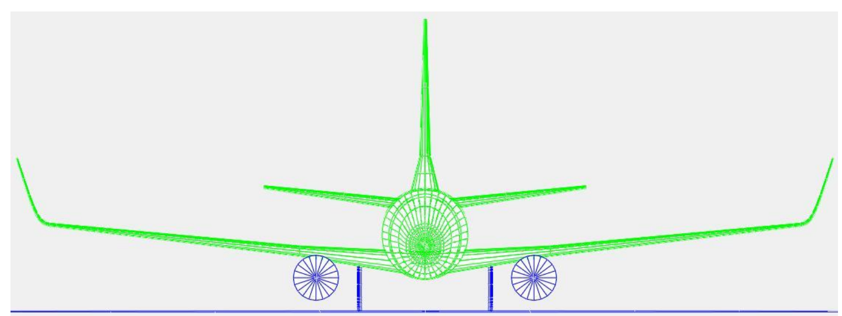
- Structures:
  - composite materials for wing, fuselage, and tails (15% structural weight benefit assumed)
- Aerodynamics:
  - 1% reduction in drag for trailing edge variable camber and drag clean-up
- Subsystems:
  - 5000 psi hydraulic pressure
- Design range @ 32,400 lb payload increased from 3060 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



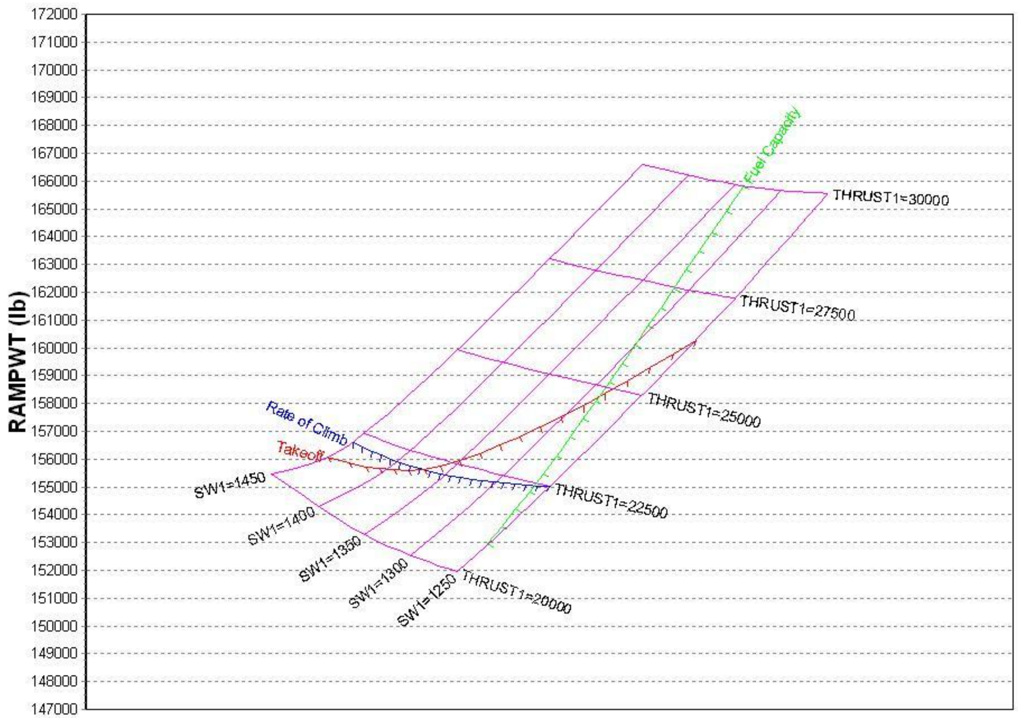
Example FPR=1.4 Configuration



Example FPR=1.7 Configuration

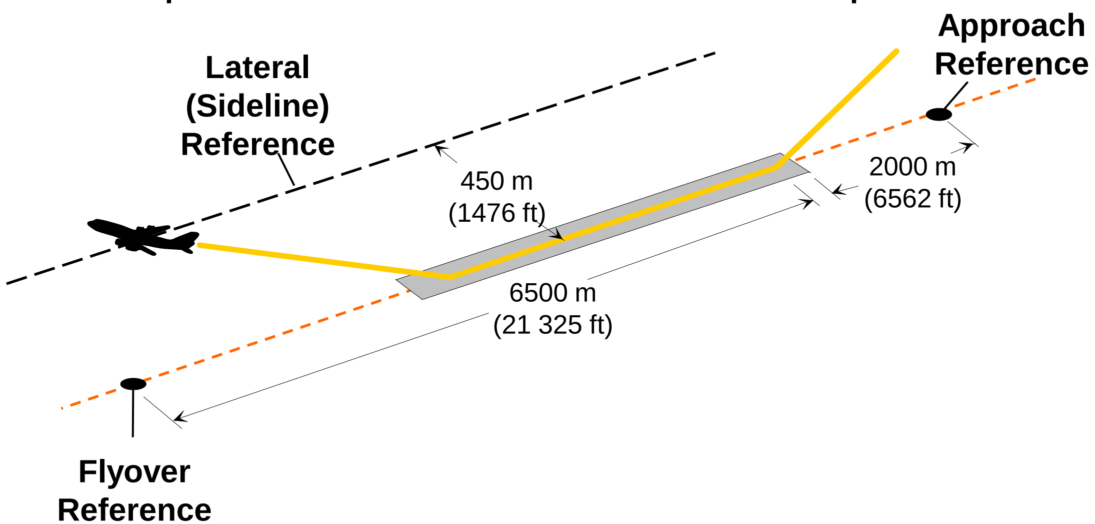
Aircraft Sizing

- 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

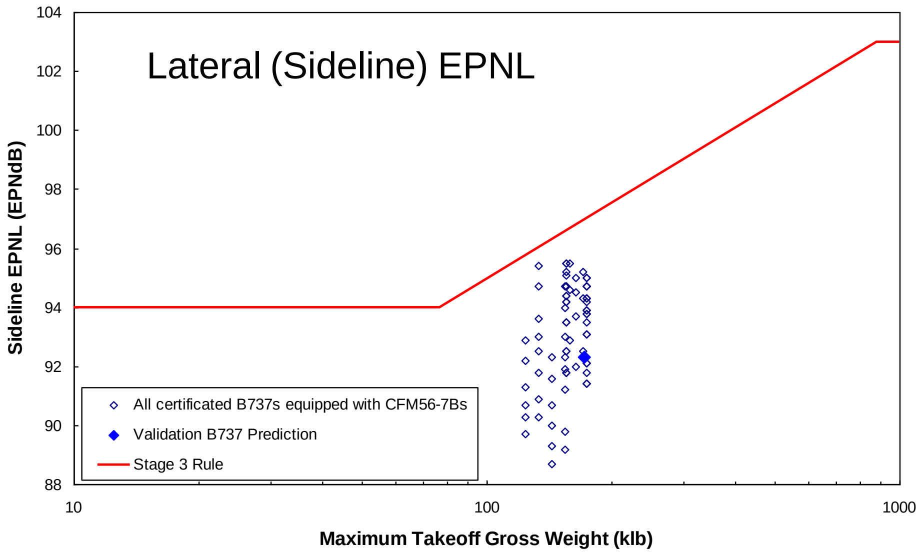
- Noise predictions performed using ANOPP
  - Source noise modules fed data from NPSS and WATE models
  - Propagation modeling includes spherical spreading, atmospheric attenuation, ground effects, reflections, and lateral attenuation
- Trajectory simulation done using SAE AIR-1845 INM empirical procedures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

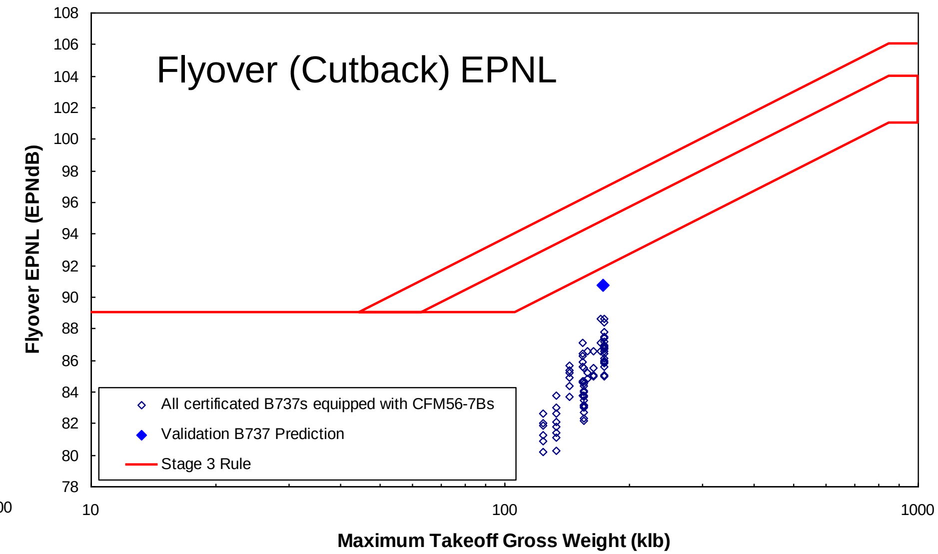


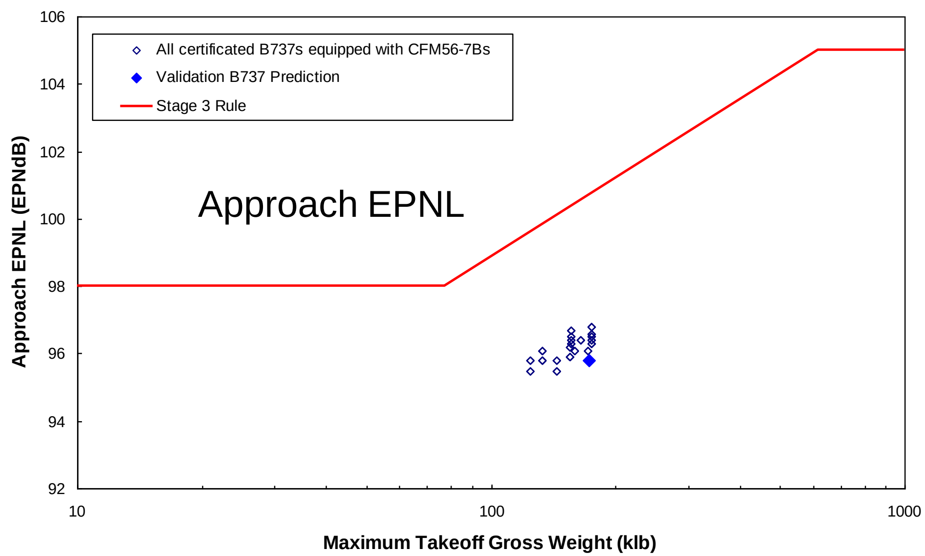
- Noise analysis validated by comparison to 737-800 certification data

Noise Analysis Validation

Comparison of predicted noise to published 737NG/CFM56-7B certification data



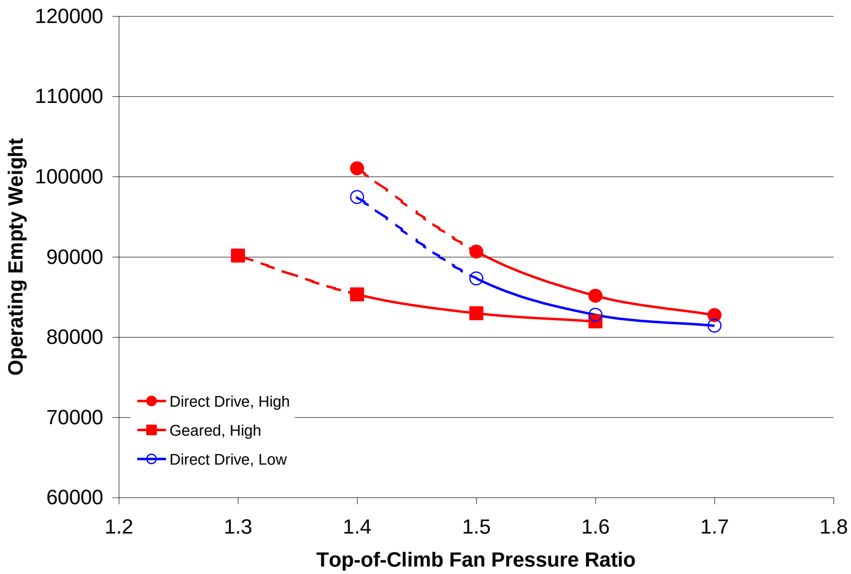


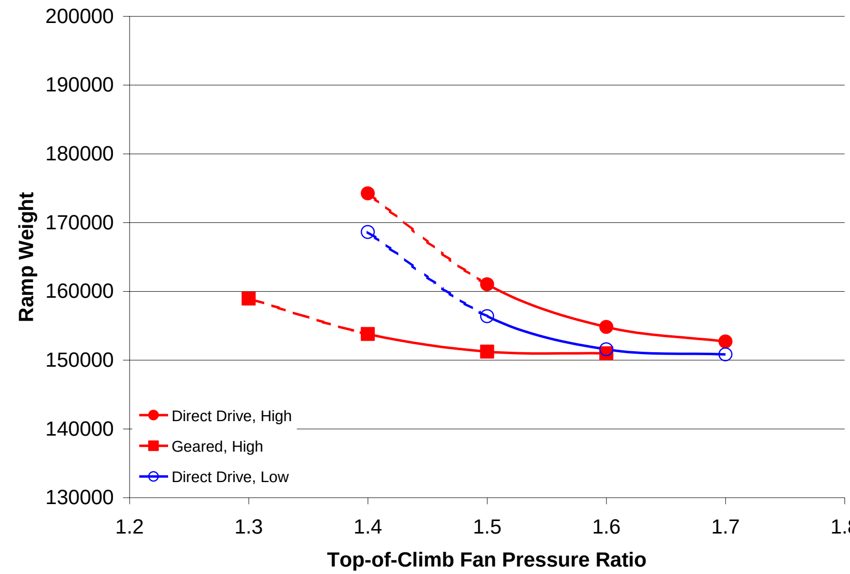


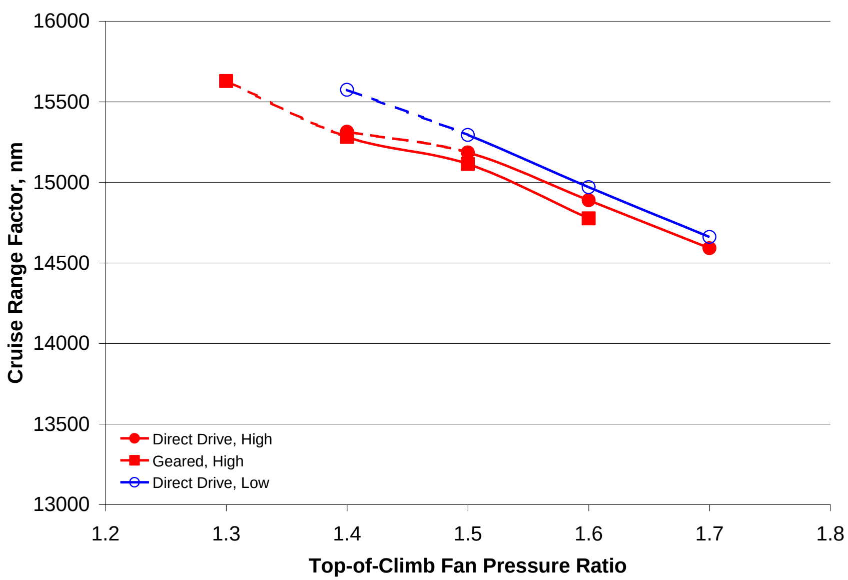
ASAT Noise Reduction Technology

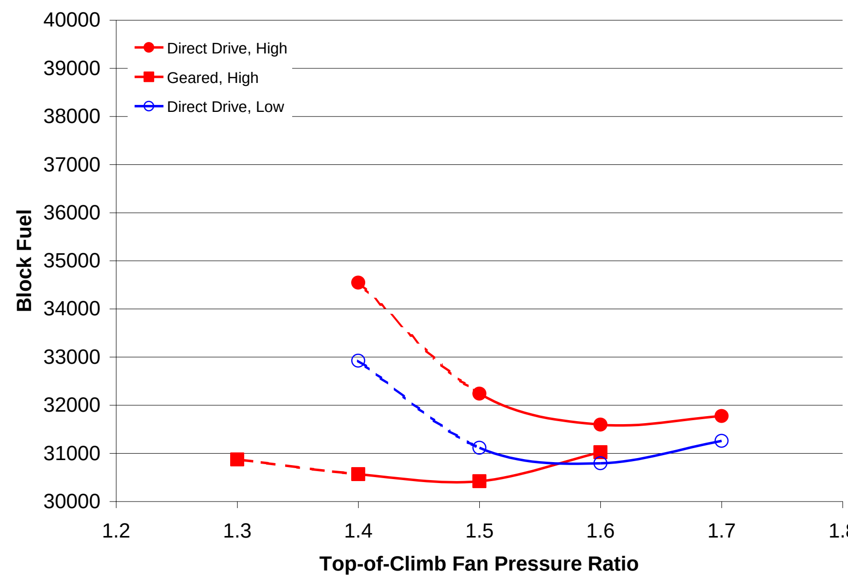
- Core nozzle chevrons assumed on all systems, bypass nozzle chevrons on fixed nozzles only (potential conflict with variable area bypass nozzles)
  - Benefit analytically modeled using 2004 Stone jet prediction methods in ANOPP
- Conventional 2DOF acoustic liner
- Soft vane and over-the-rotor liner 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

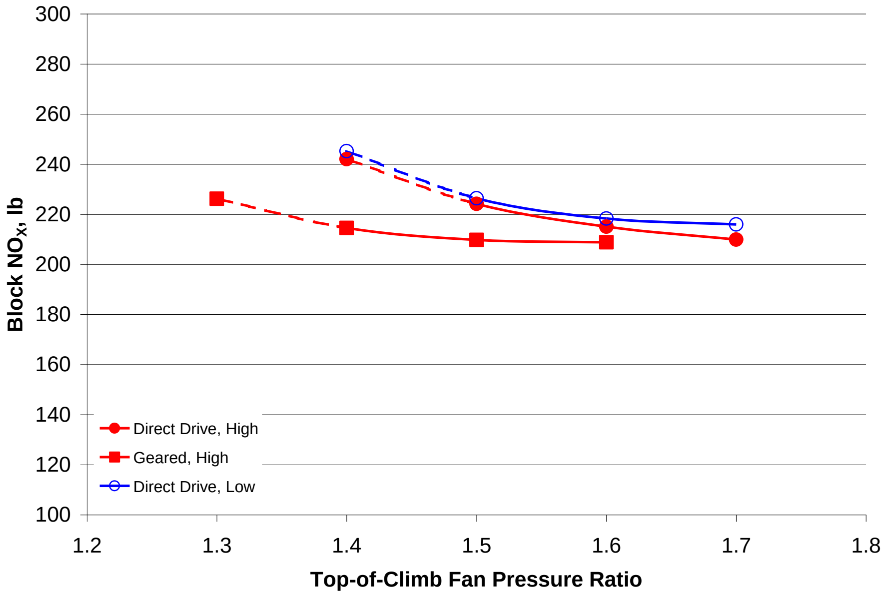


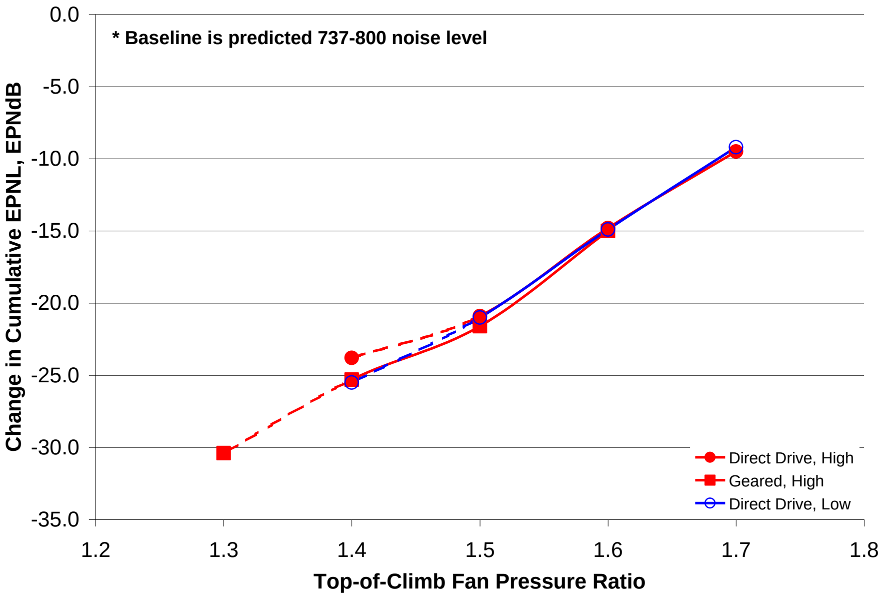




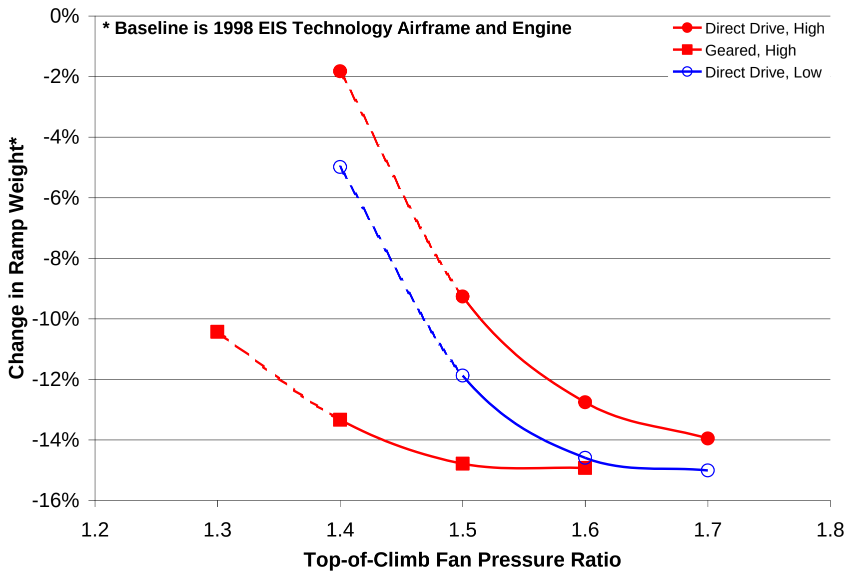


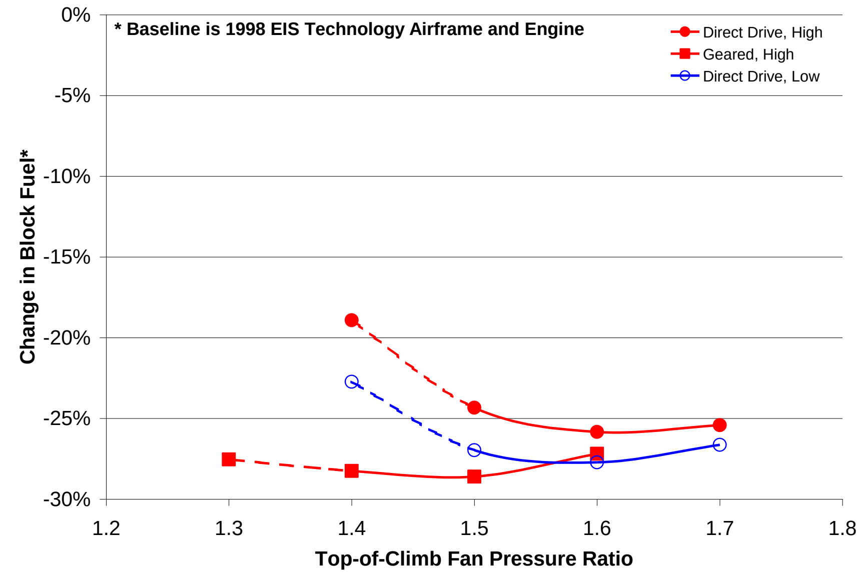
Aircraft Characteristics (2)

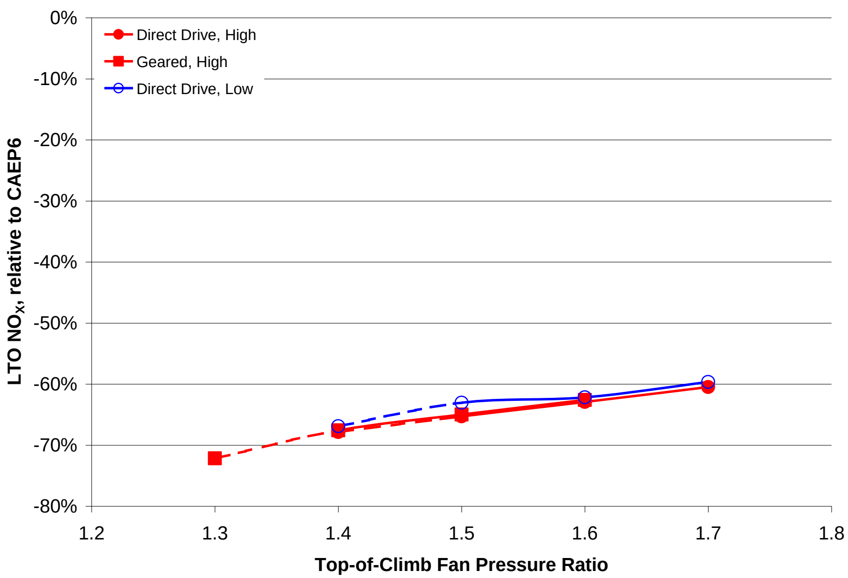


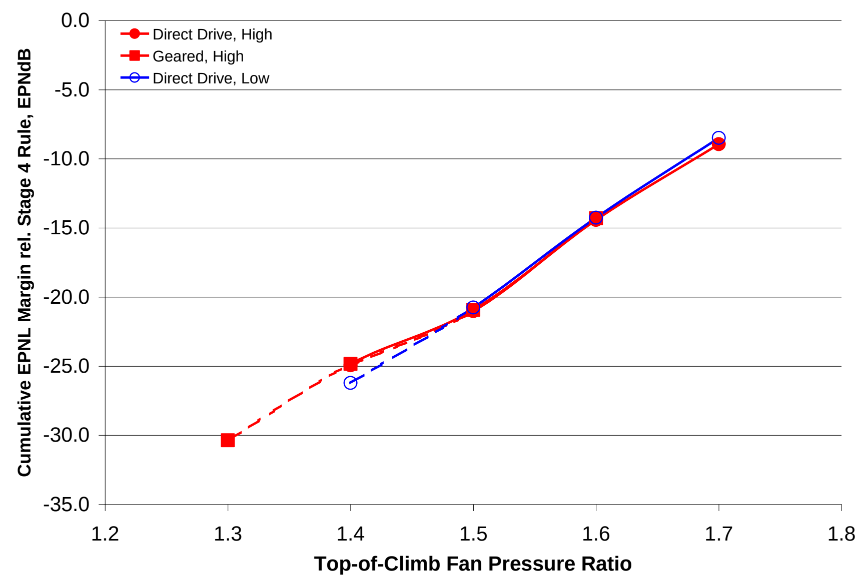


Overall Benefits









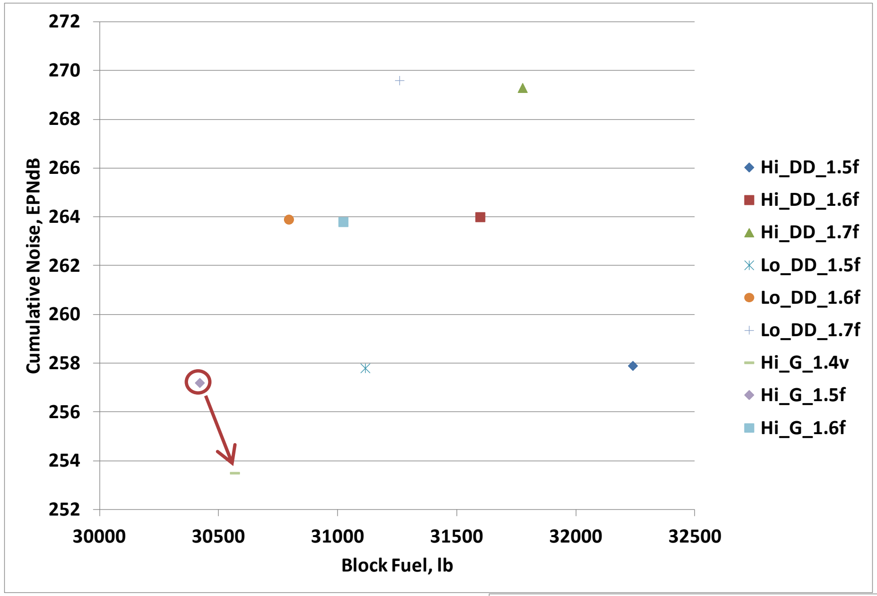
Trade-off Analysis

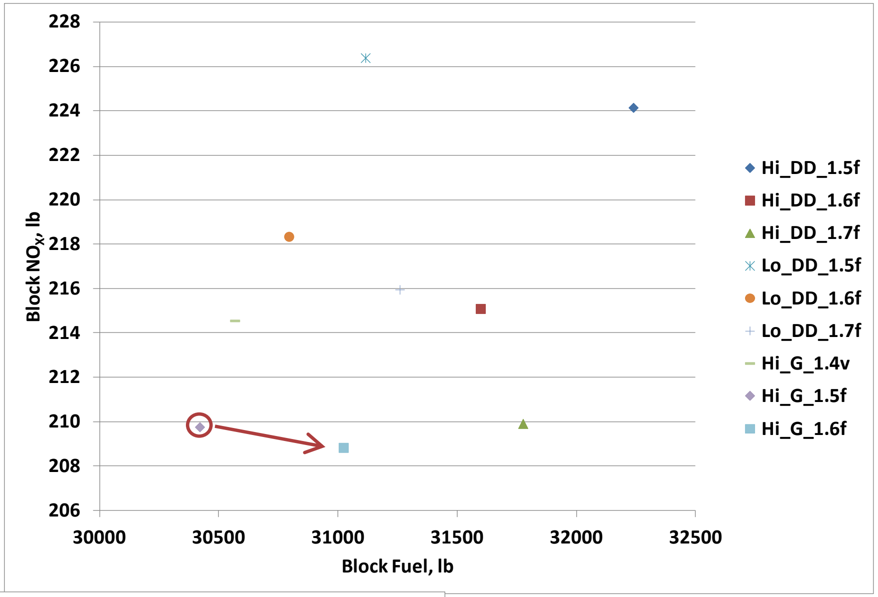
	Ramp Weight	Block Fuel	Block NO_X	LTO NO_X	Cum. EPNdB (Stage 4 Margin*)
High, Geared, FPR=1.4	**+2.0 %**	**+0.5%**	**+2.7%**	**Minimum**	**Minimum (25-29 cum.)**
High, Geared, FPR=1.5	**+0.3%**	**Minimum**	**+0.5%**	**+0.5%**	**+3.7 (21-25 cum.)**
Low, Direct, FPR=1.5	+3.7%	+2.3%	+8.4%	+10.6%	+4.3 (21-25 cum.)
High, Direct, FPR=1.5	+6.8%	+6.0%	+7.3%	+4.8%	+4.4 (21-25 cum.)
High, Geared, FPR=1.6	**+0.1%**	**+2.0%**	**Minimum**	**+6.9%**	**+10.3 (14-18 cum.)**
Low, Direct, FPR=1.6	+0.5%	+1.2%	+4.5%	+11.5%	+10.4 (14-18 cum.)
High, Direct, FPR=1.6	+2.6%	+3.9%	+3.0%	+6.9%	+10.5 (14-18 cum.)
Low, Direct, FPR=1.7	**Minimum**	**+2.8%**	**+3.4%**	**+18.9%**	**+16.1 (9-13 cum.)**
High, Direct, FPR=1.7	+1.2%	+4.5%	+0.5%	+12.7%	+15.8 (9-13 cum.)

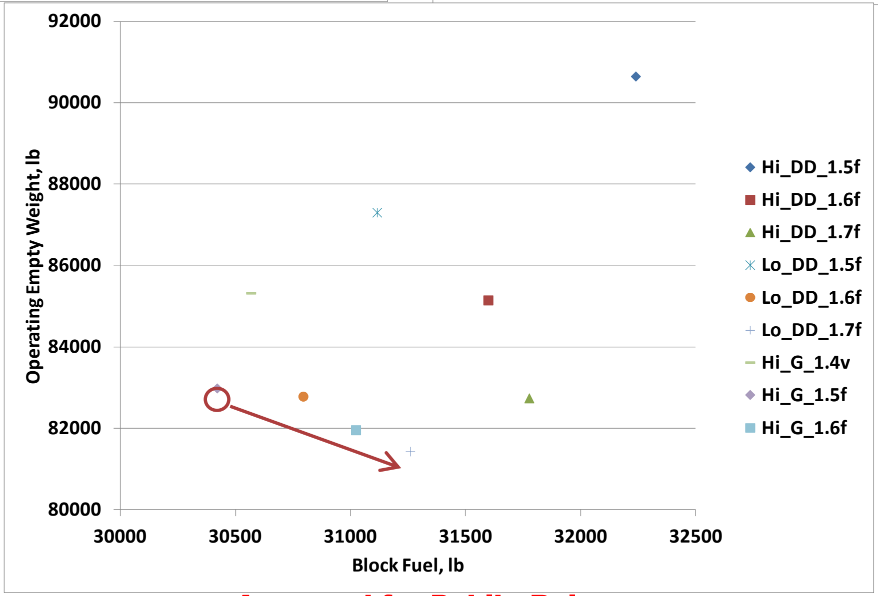
Good “balanced” performance across all metrics

* Range represents uncertainty associated with possible overprediction of flyover noise

Trade-off Analysis (Cont.)







Summary

- SFW project has been performing aircraft system studies to evaluated 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_X minimized with high FPR
  - LTO NO_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 **29%** reduction in fuel burn
  - Up to **25 EPNdB** cum. noise reduction (**25-29* EPNdB** cum. margin to Stage 4)
  - Up to **67%** below CAEP6 for LTO NO_X

* Range represents uncertainty associated with possible overprediction of flyover noise

NASA