Quantification of the Aerodynamic Benefit of Boundary Layer Ingestion

A University-Industry-NASA Collaboration

Technology Lead:	Alejandra Uranga	auranga@usc.edu
Chief Engineer:	Mark Drela	drela@mit.edu
Principal Investigator:	Edward Greitzer	greitzer@mit.edu

Green Aviation Technical Interchange Meeting
NASA Langley Research Center

March 29 – 31, 2016

Message

- Closer integration of propulsion system and airframe provides new opportunities to increase fuel efficiency of commercial aircraft
  - Boundary layer ingestion (BLI)
  - Novel configurations
  - System optimization (airframe, engine, operations)
- Flow power and dissipation provide useful metrics for integrated configurations
- Aerodynamic merit of BLI demonstrated in back-to-back comparison of BLI vs non-BLI: 8–10% power reduction at cruise

Outline

1. Introduction
2. Boundary Layer Ingestion (BLI)
3. Aerodynamic BLI Benefit
4. System-Level Benefits
5. Summary and Conclusions

MIT N+3 Project

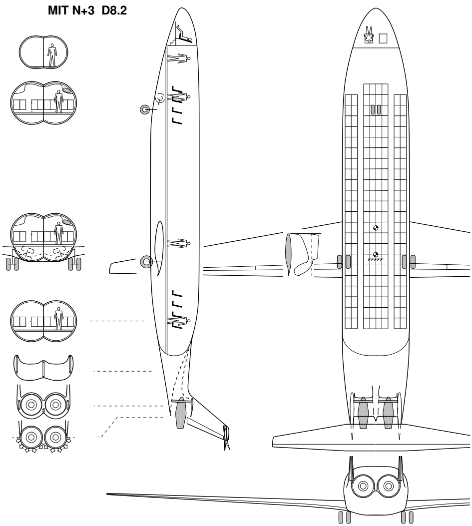
Aircraft and Technology Concepts for an N+3 Subsonic Transport

- Phase 1 (2008 – 2010): development of *double-bubble* D8 aircraft
- Phase 2 (2010 – 2015): benefit of airframe-engine integration

  30+ people including 2 faculty, 3 staff, 9 grads, 13 undergrads

- Phase 3 (2015 – present): performance vs. speed, transonic OML

The D8 Aircraft Concept



- B737-800/A320 class
- 180 PAX, 3,000 nm range
- Double-bubble lifting fuselage with pi-tail
- Two aft, flush-mounted engines ingest ∼40% of fuselage BL
- Cruise Mach 0.72

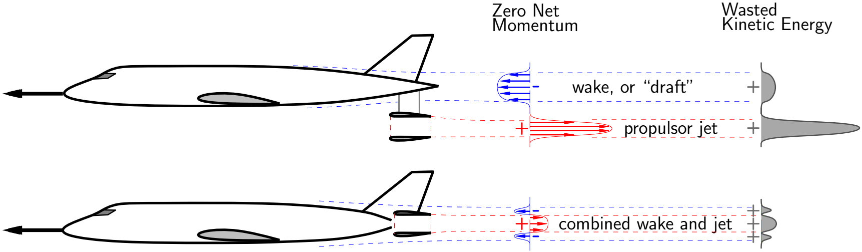
−36% fuel with current tech

−65% fuel with advanced tech (2025-2035)

No "magic bullet"

E. Greitzer et al. 2010, NASA CR 2010-216794
A. Uranga et al. 2014, AIAA 2014-0906

Boundary Layer Ingestion (BLI)



- BLI reduces wasted KE in combined jet+wake (mixing losses)

- Ambiguous decomposition into drag (airframe) and thrust (propulsion)

$\Rightarrow$ consider power balance instead of force accounting

M. Drela 2009, AIAA Journal 47(7)

BLI Benefit

BLI benefit (aerodynamic)

Savings in power required for given net stream-wise force with BLI engines relative to non-BLI engines

Power metric

Mechanical flow power transmitted to the flow by the propulsors

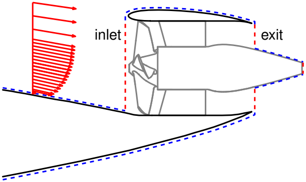
$$P_K \equiv \oiint (p_t - p_{t_\infty}) \mathbf{V} \cdot \hat{n} \, dS = \dot{m} \, \frac{\overline{\Delta p_t}}{\rho}$$

- Independent of propulsor characteristics
- Surrogate for fuel burn: $\dot{m}_{\text{fuel}} = \dfrac{P_K}{h_{\text{fuel}} \, \eta_{th} \, \eta_f}$

Obtaining P_K

Direct Measurement: Integrating propulsor inlet and outlet flows

$$P_K = \iint_{\text{exit}} (p_t - p_{t_\infty}) \mathbf{V} \cdot \hat{n}\, dS - \iint_{\text{inlet}} (p_t - p_{t_\infty}) \mathbf{V} \cdot \hat{n}\, dS$$

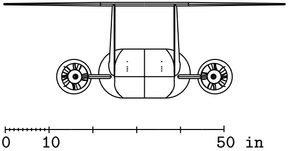


Indirect Measurement: Use *electrical power* to motor, P_E

$$P_K = \underbrace{\eta_f}_{\text{fan efficiency}} \times \underbrace{\underbrace{\eta_m}_{\text{motor efficiency}} \times P_E}_{\text{shaft power}}$$

Numerical Simulations: Use CFD to predict flow on full airframe with engine model, from which force and power can be extracted by integration

Non-BLI (Podded) Configuration



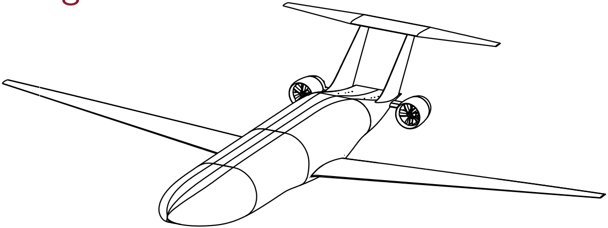
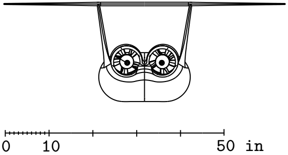


Photo NASA/George Homich

BLI (Integrated) Configuration



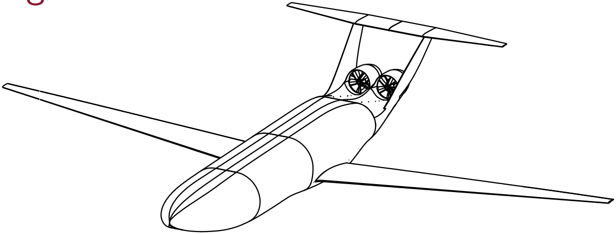
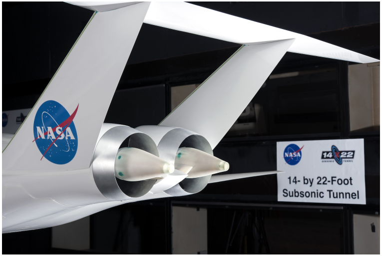


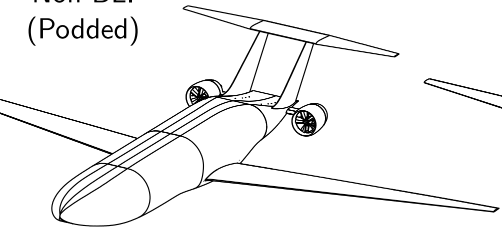
Photo NASA/George Homich

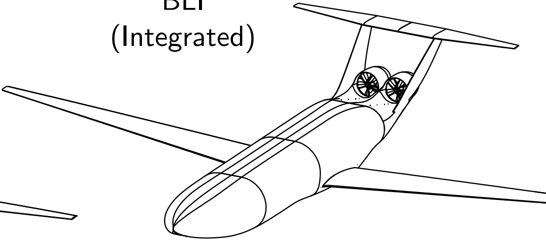
BLI (Integrated) Configuration



Photos NASA/George Homich

Back-to-Back Comparison





BLI Benefit: $\text{Power Ratio} \equiv \dfrac{\text{power required with BLI}}{\text{power required without BLI}} = \dfrac{P_K}{P'_K}$

Propulsive Efficiency:

$$\eta_p \equiv \frac{\text{net propulsive power to vehicle}}{\text{power added to flow}} \equiv \frac{P_K - \Phi_{\text{jet}}}{P_K}$$

Experiments

NASA LaRC 14×22 tunnel (2 entries)

- 1:11 powered model, 13.4 ft (4 m) span

$$V_\infty = 70\,\text{mph}, \quad Re_c = 570\text{k}, \quad M_\infty = 0.09$$
$$84\,\text{mph} \qquad 680\text{k} \qquad 0.11$$

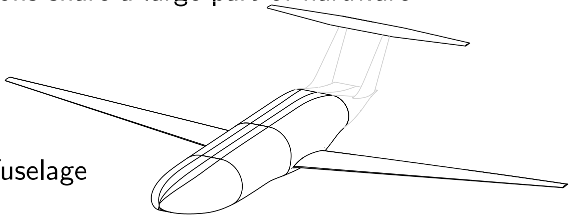
- Non-BLI and BLI configurations

MIT 1×1 tunnel

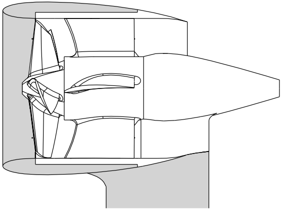
- Turbomachinery characterization

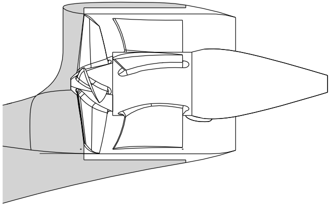
Experiments

Non-BLI and BLI configurations share a large part of hardware



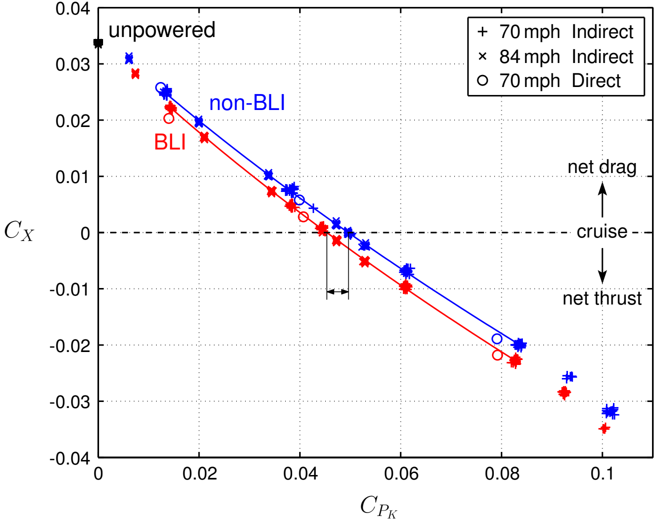
- Common wings
- Common front 80% of fuselage
- Common propulsor units plug into interchangeable tails
  (fan stage, motor, center-body, housing, nozzle, electronics)





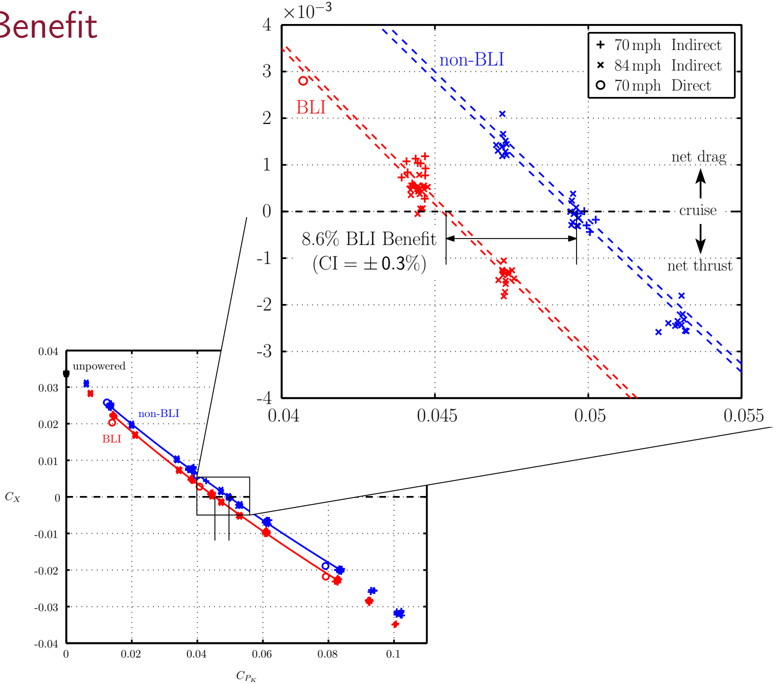
Outline

BLI Benefit: Less Power to Produce Given Force



Data taken at 70 mph and 84 mph during both 2013 and 2014 NASA Langley entries; 12–17 repeat runs at each condition

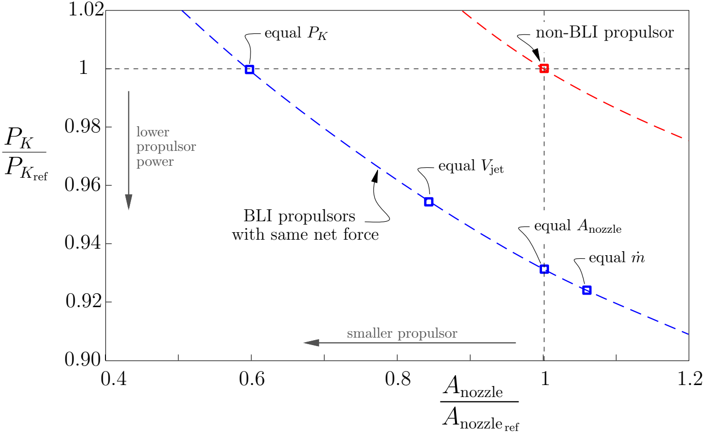
BLI Benefit



$\times 10^{-3}$
4
3
2
1
0
-1
-2
-3
-4
0.04
0.045
0.05
0.055
non-BLI
BLI
70 mph Indirect
84 mph Indirect
70 mph Direct
net drag
cruise
net thrust
8.6% BLI Benefit
(CI = ± 0.3%)
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
0
0.02
0.04
0.06
0.08
0.1
unpowered
non-BLI
BLI
C_X
C_{P_K}

Bases for Comparison

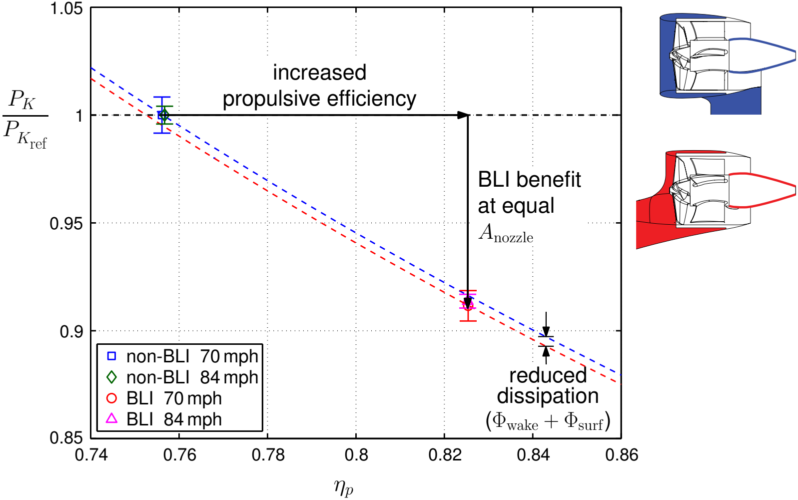
Given a non-BLI propulsor with some jet velocity, mass flow, nozzle area, how do you choose an "equivalent" BLI propulsor for comparison?



BLI Benefit and Propulsive Efficiency

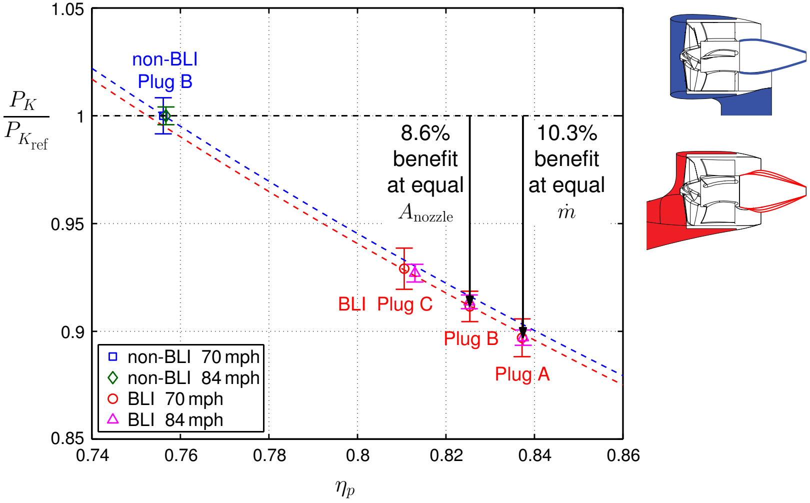
Benefit primarily due to higher propulsive efficiency

Additional 1% gain from reduced body dissipation



BLI Benefit: Not Unique

Vary propulsive efficiency by changing nozzle area



Outline

System Impact of BLI

BLI benefits

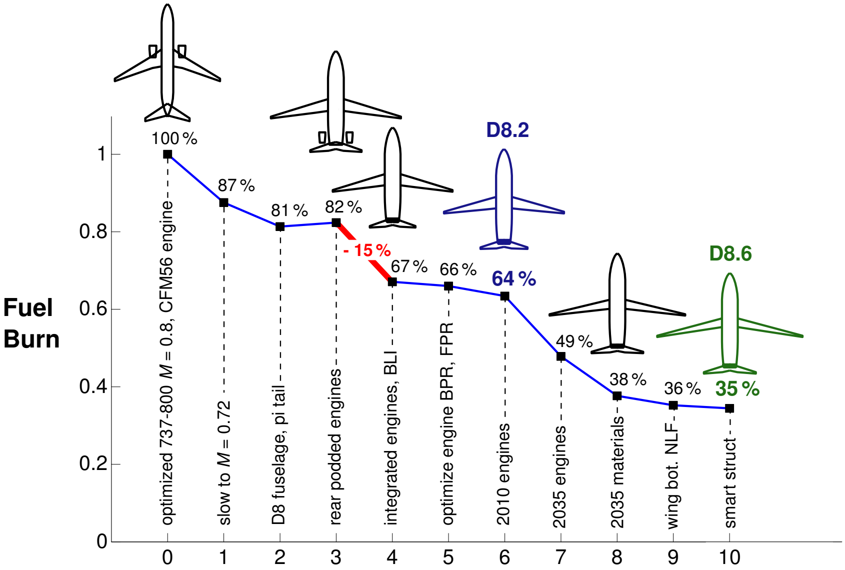
- *Aerodynamic* (direct) benefits
  - Reduced jet and wake dissipation
  - Reduced nacelle wetted area
- *System-level* (secondary) benefits
  - Reduced engine weight
  - Reduced nacelle weight
  - Reduced vertical tail size
  - Compounding from reduced overall weight

"Morphing" sequence: B737-800 $\mapsto$ D8

- Features of D8 introduced one at a time
- Sequence of conceptual aircraft designs, optimized at each step (TASOPT)

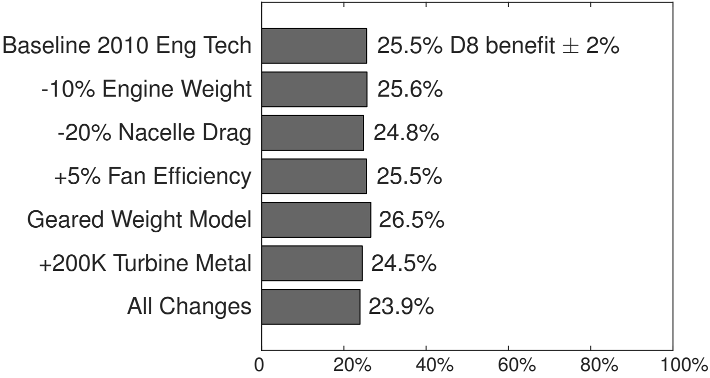
E. Greitzer et al. 2010, NASA CR 2010-216794
M. Drela 2011, AIAA 2011-3970
A. Uranga et al. 2014, AIAA 2014-0906

Morphing Sequence: B737-800 $\mapsto$ D8.2 $\mapsto$ D8.6



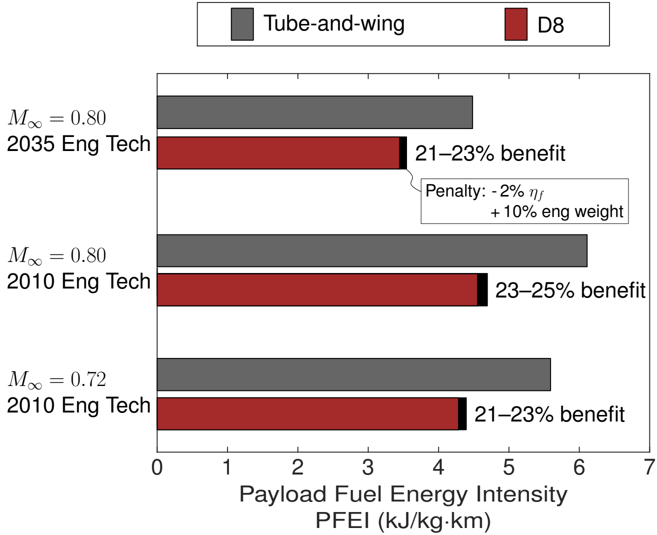
Sensitivities to Conceptual Models (Preliminary Phase 3)

- Assessing uncertainty on TASOPT's conceptual predictions
  - Mission: 180 PAX, 3 000 nm, Mach 0.80 cruise
  - Compare overall (system-level) benefit of the D8 relative to a conventional tube-and-wing aircraft *with same technology, speed, etc.*
  - Introduce changes in engine models, and re-assess D8's benefit

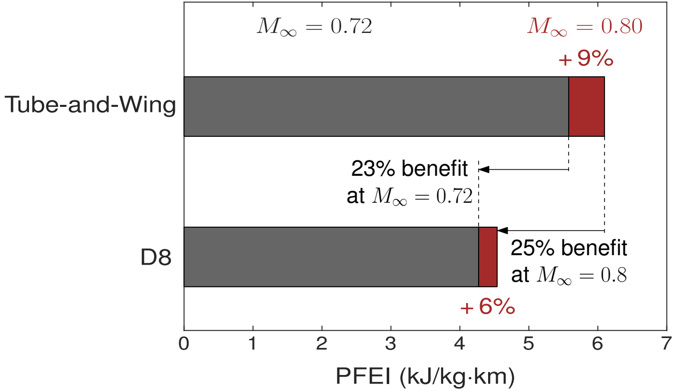


Relative Benefit of D8 (Preliminary, Phase 3)

Benefit of the D8 relative to conventional tube-and-wing configuration is insensitive to changes in engine models



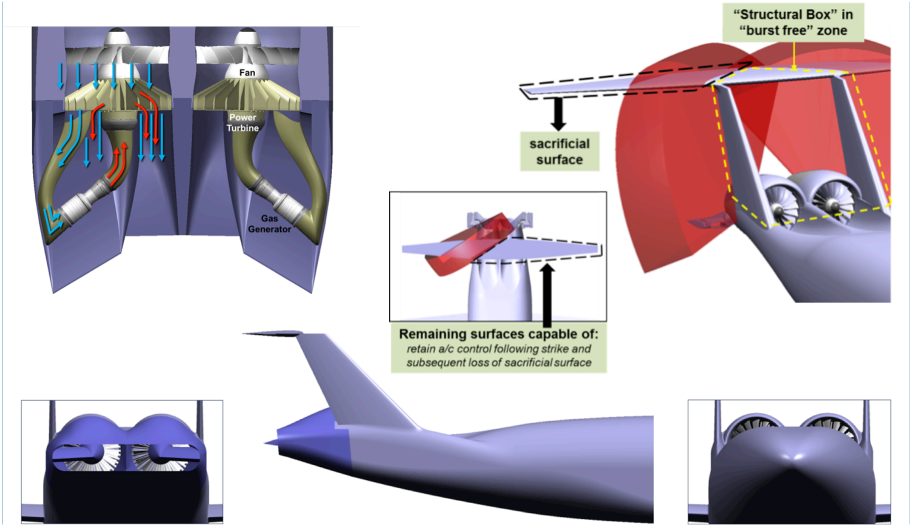
Effect of Cruise Speed (Preliminary, Phase 3)



- Cost of flying faster is significant
- Cost for D8 is smaller than for tube-and-wing
  - Larger nacelles in tube-and-wing aircraft cause higher penalties (weight, drag) from larger engines

High-Efficiency, High-OPR, Small Cores

Pratt & Whitney – Lord et al., AIAA 2015-0071



Outline

Summary

- BLI has potential for large fuel reduction for transport aircraft
- Carried out first back-to-back comparison of BLI vs non-BLI
- Demonstrated aerodynamic merit of BLI for realistic configuration

  8.6% at equal nozzle area $\pm$1.8% at 95% confidence

  10.3% at equal mass flow
- Proof-of-concept of BLI for fuel reduction of commercial transports
- System-level benefit of BLI estimated to be above 20%

A View of the Future?

- There have been 50+ years of developing non-BLI systems we now need to learn to use BLI
- Opened up new possibilities for advanced transport aircraft
- Identified new class of important research problems
  - Aircraft configuration and airframes
  - Propulsion system and integration
  - Component technologies

Acknowledgments

- Funding from NASA under Cooperative Agreements NNX08AW63A, NNX11AB35A, NNX15AM91A
- Team members at MIT, Aurora, Pratt & Whitney, NASA
- NASA Project management
- Staff at NASA Langley 14×22 Foot Subsonic Wind Tunnel
- N. Cumpsty, Y. Dong, A. Epstein, E. Gallagher, A. Murphy, J. Sabnis, G. Tillman, H. Youngren

Contact Information:

Alejandra Uranga, Ph.D.
Assistant Professor and Provost Fellow
Aerospace & Mechanical Engineering
University of Southern California

Email: auranga@usc.edu
Phone: (213) 821-0846