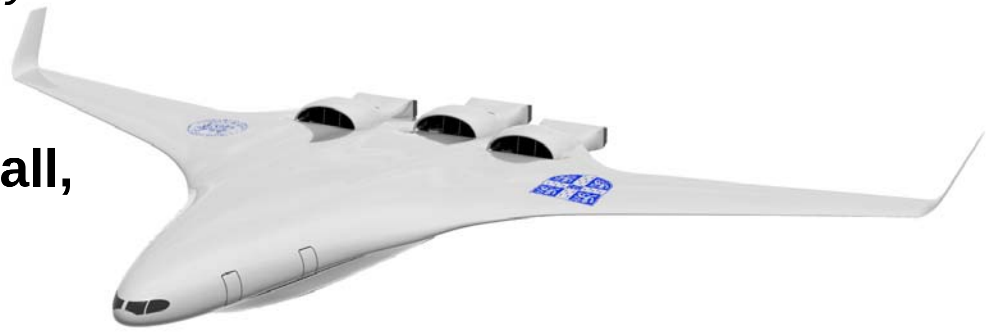
The Cambridge-MIT Institute

Silent Aircraft Initiative
...a new approach

Design Trade Considerations in Noise, Fuel Burn, and Technological Risk for Quiet Aircraft

James Hileman & Zoltan Spakovszky
Massachusetts Institute of Technology

Elena de la Rosa Blanco, Chez Hall, Tom Law, and Dan Crichton
Cambridge University



September 18, 2007

Presented at the 2007 SAE AeroTech Congress & Exhibition

Outline

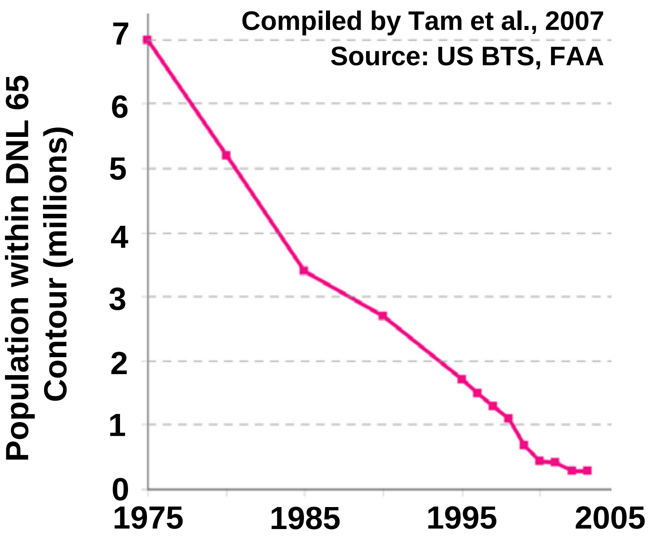
- Aviation and the Environment
- Aircraft Design Challenge

- The Silent Aircraft Initiative
- Design trades in noise and fuel burn
- Design trades in risk

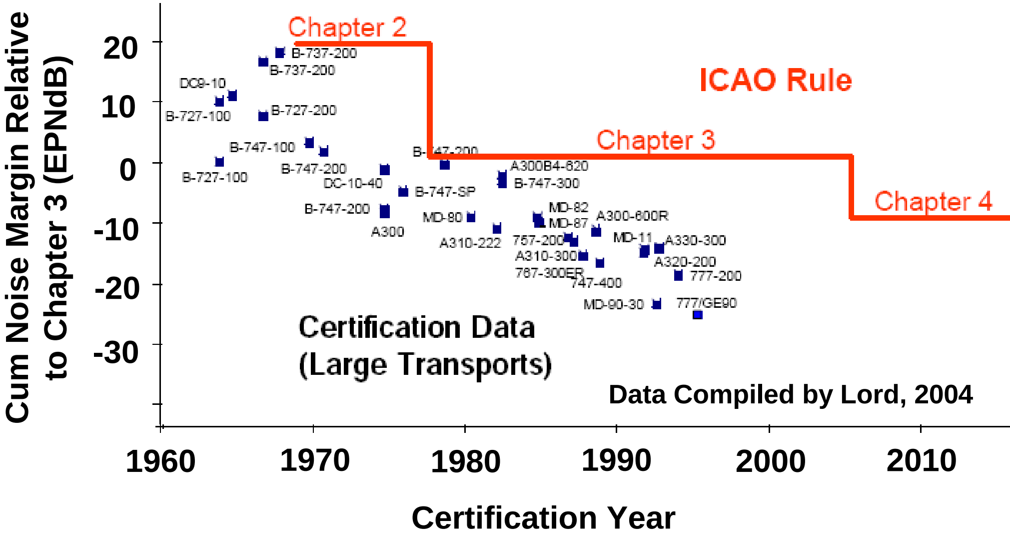
Historical Progress

Last 35 to 40 years…

- 6x growth in mobility
- Ticket prices cut in half
- 70% reduction in energy intensity
- NOx reduction through combustor technology improvements
- 95% reduction in people within US impacted by noise (55 DNL and 65 DNL)



Compiled by Tam et al., 2007
Source: US BTS, FAA

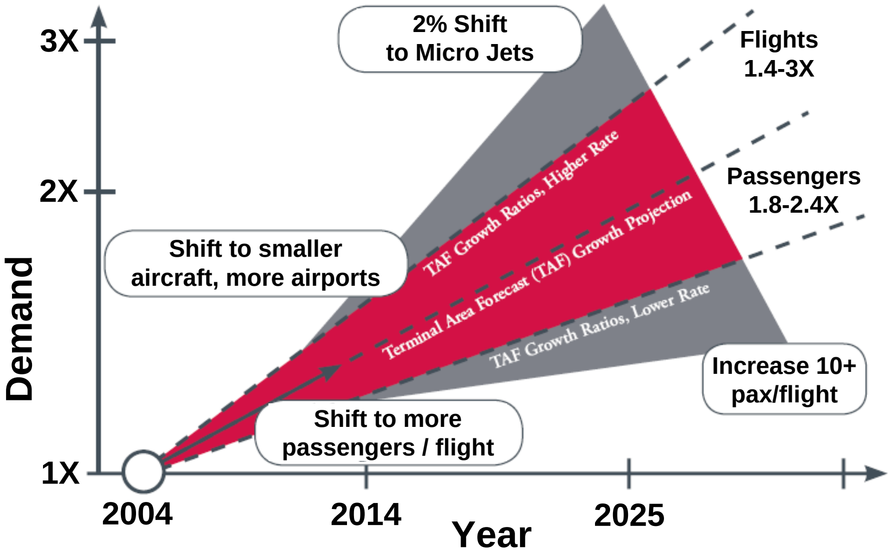


Certification Data (Large Transports)

Data Compiled by Lord, 2004

Constraints to Growth of Aviation

Demand for commercial aviation is growing …



Source: NextGen Integrated Plan, 2004

… as is the environmental footprint…

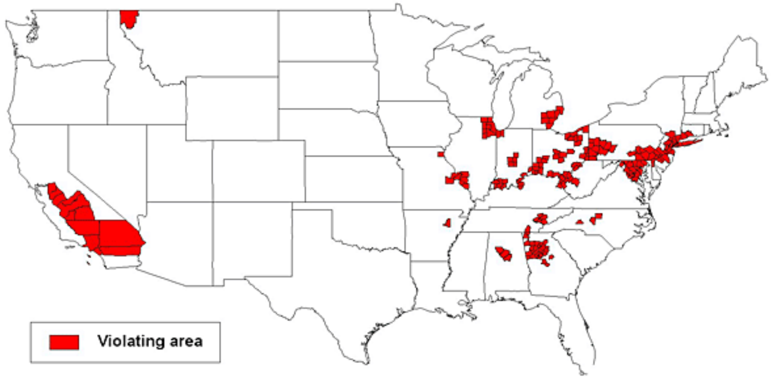
Preliminary Emissions for NextGen 2X Growth Scenario

HC	*+ 75%*
CO	*+ 70%*
NOx	*+ 90%*
SOx	*+ 85%*

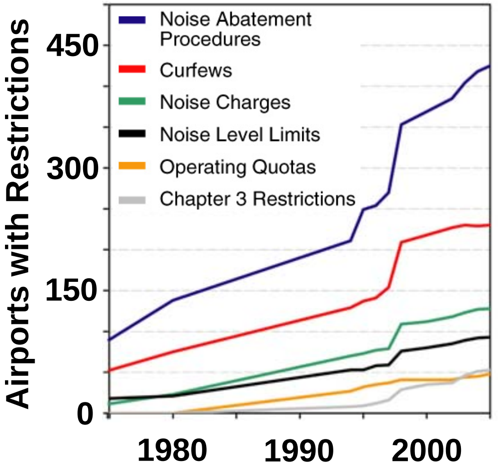
… and this is coupled with environmental capacity constraints.

Designated PM 2.5 Non-Attainment Areas as of 3-2007

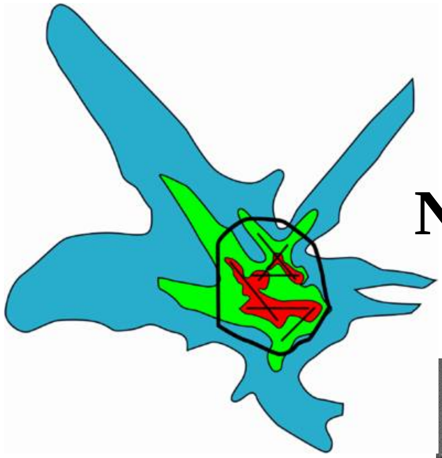
U.S. EPA data interpreted by A.S.L & Assoc. Helena, MT 3/2007



Compiled by Tam et al., 2007
from Boeing data 9/13/05

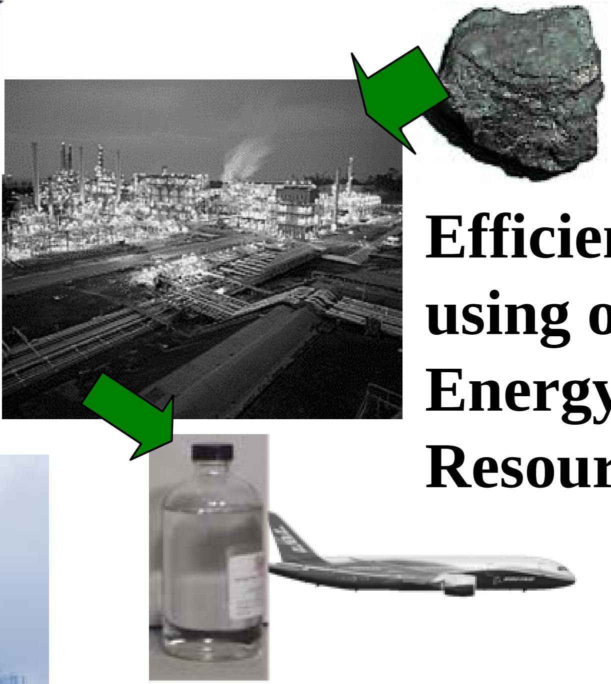


Environmental Challenges facing Aviation



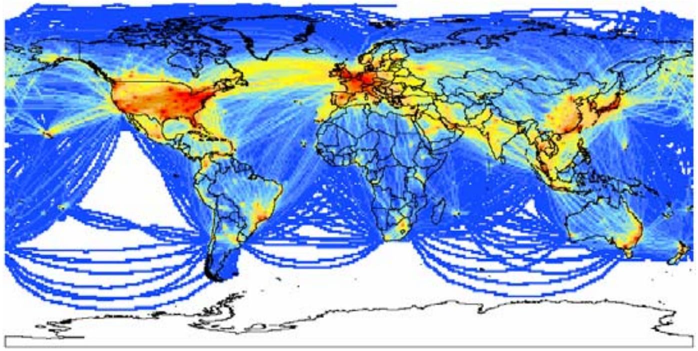
Reducing Community Noise Impacts

Improving Air Quality



Efficiently using our Energy Resources

Improving Water Quality



Addressing Global Climate Change

Aircraft Design Challenge

NextGen JPDO Environmental Goal:

Community noise and local air quality emissions that significantly impact human health and welfare **reduced in absolute terms while growing system capacity 2-3X.**

Aircraft design and environment:

- Environmental impacts typically considered separately:
  Noise -or- *Local Air Quality* -or- *Climate*
- *Aircraft Design* and *Operational Procedures* affect all three areas
- Poor decisions could have significant consequence:
  - High capital costs (e.g. $10B new airplane program)
  - Long time-scales (20-30 years)

Do you design for noise, emissions, fuel use, or direct operating cost?

Silent Aircraft Initiative (SAI)*

Goal: design a credible, functionally silent aircraft.

Procedure: start with a ‘clean sheet of paper’ to create a viable, conceptual aircraft with ***noise as the primary design variable***. To be viable, aircraft design ***must be fuel efficient*** else noise problem becomes fuel use / pollution problem.

Team: 30+ members involving academia (MIT, Cambridge University), government, and industry partners (Boeing, Rolls Royce, and others).

Funding: Three year project funded by U.K. government, completed September 2006.

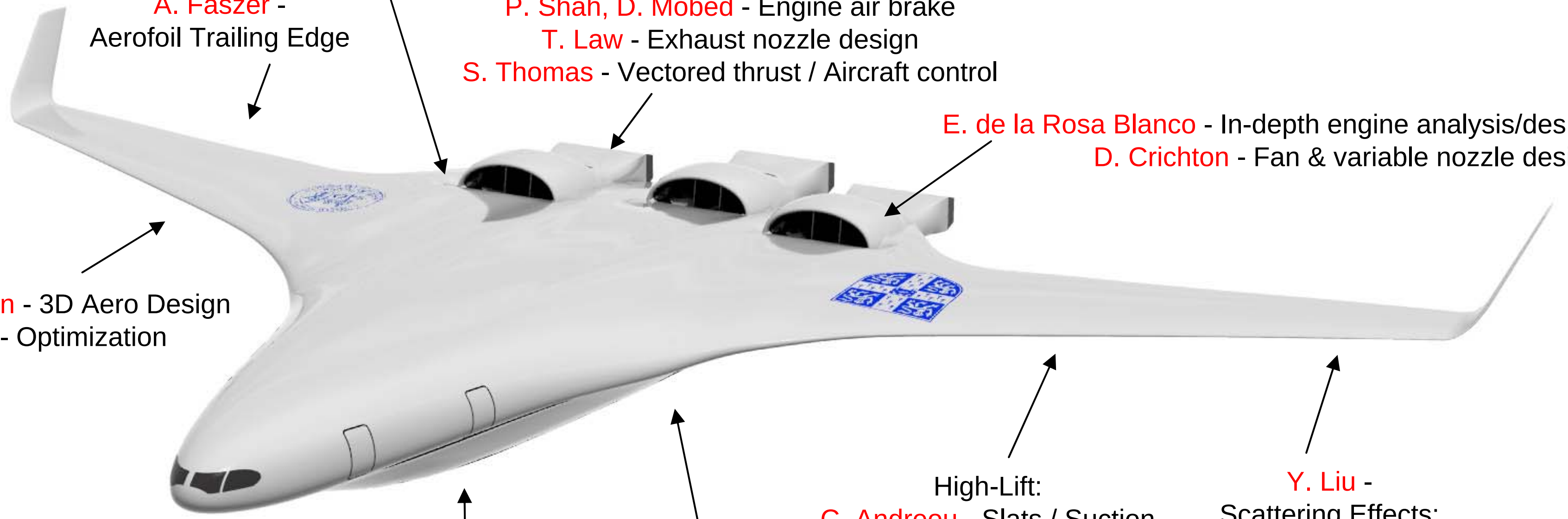
* “Silent” in the context of this research does not refer to the absence of acoustic sources; instead, it implies the aircraft is no louder than the ambient noise outside an urban airport.

The Cambridge-MIT Institute

CUED/MIT Silent Aircraft Team ~ 35 Researchers

Faculty: A. Dowling, E. Greitzer, H Babinsky, P. Belobaba, J.-P. Clarke, M. Drela, C. Hall, W. Graham , T. Hynes, K. Polenske, Z. Spakovszky, I. Waitz, K. Willcox, L. Xu

R. Tam - Economics
T. Reynolds - Operations



V. Madani - Inlet design
A. Plas - Effect of boundary layer ingestion on fuel burn
M. Sargeant - Inlet/airframe integration / 3D Airframe CFD

A. Faszer - Aerofoil Trailing Edge

P. Shah, D. Mobed - Engine air brake
T. Law - Exhaust nozzle design
S. Thomas - Vectored thrust / Aircraft control

E. de la Rosa Blanco - In-depth engine analysis/design
D. Crichton - Fan & variable nozzle design

J. Hileman - 3D Aero Design
A. Jones - Optimization

High-Lift:
C. Andreou - Slats / Suction
A. Townsend - L.E. Rot Cylinder

Y. Liu - Scattering Effects: Surface finish

A. Quayle - Undercarriage

A. Agarwal – Acoustic Shielding

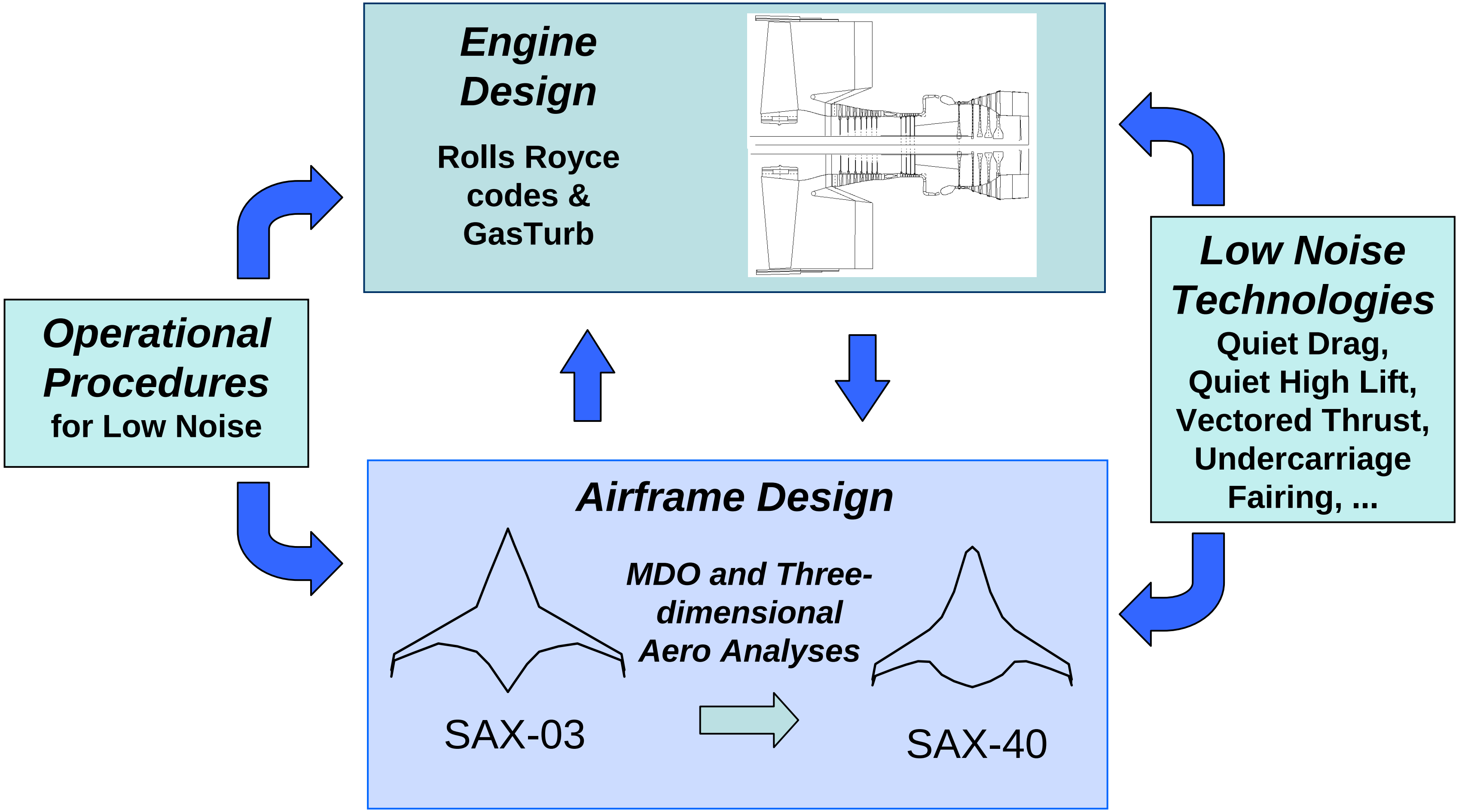
H.-C. Shin - Acoustic Measurements & Phased Array Design

Former Members:
A. Diedrich - SAX10 planform
P. Freuler - Inlet Design
D. Tan - Noise propagation modeling
G. Theis – Economics
N. Sizov – Operations
R. Morimoto - Economics
C. Hope – Economics
K. Sakaliyski – Drag Rudders / Spoilers
P. Collins - KIC Manager

Chief Engineers: J. Hileman and Z. Spakovszky

Design Reviews Provided by Boeing and Rolls Royce

Silent Aircraft eXperimental (SAX) Design Framework



Engine Design

Rolls Royce codes & GasTurb

Operational Procedures
for Low Noise

Low Noise Technologies
Quiet Drag, Quiet High Lift, Vectored Thrust, Undercarriage Fairing, ...

Airframe Design

MDO and Three-dimensional Aero Analyses

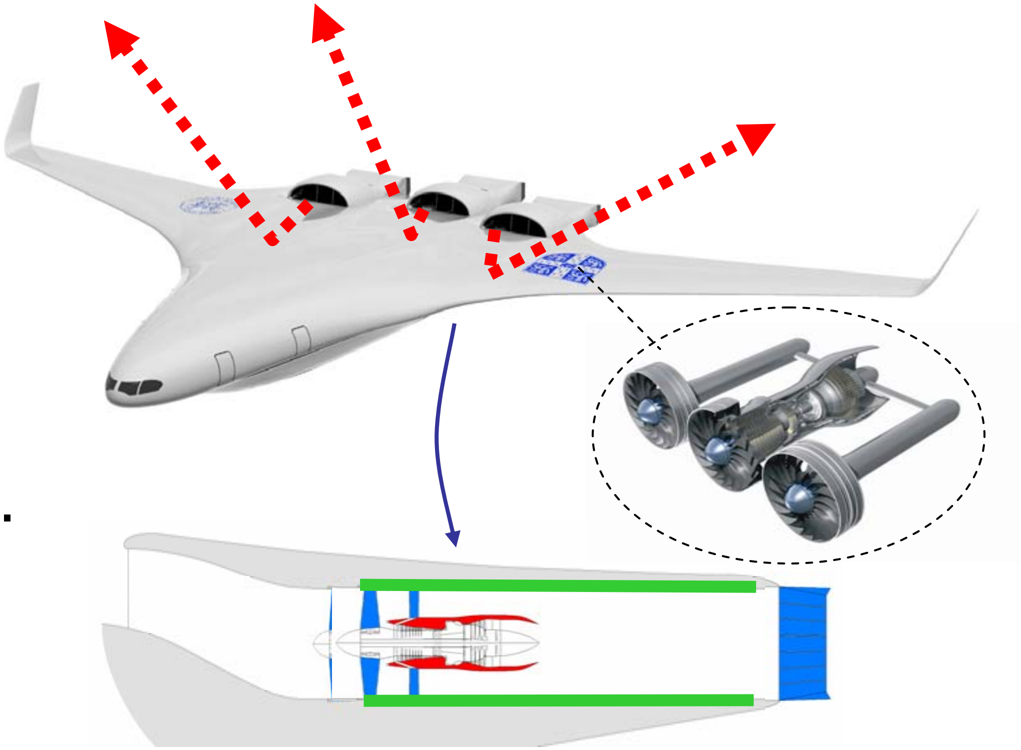
SAX-03

SAX-40

Engine Noise Reduction through Airframe Design

To dramatically reduce engine noise:

1. Ample room for high bypass ratio engines.
2. Shielding of forward radiating engine noise.
3. Extensive exhaust liners.



Aircraft illustration by M. Sargeant & S. Thomas
Engine illustration by S. Cross

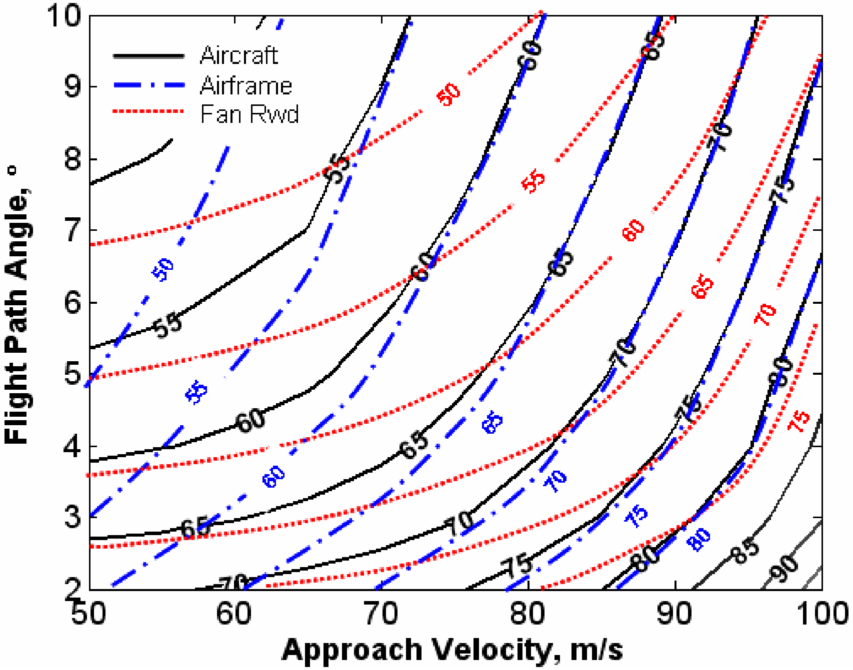
A single airframe can provide all three,

but also need low-noise airframe design.

Aerodynamic Design for Low Noise - I

- Flaps and slats eliminated from design, still have airfoil and faired undercarriage noise.
- Undercarriage noise proportional to u^6 / r^2
- Noise floor set by scattering of turbulent structures at trailing edges, noise proportional to u^5 / r^2
- Trim flight path angles < 4°

SAX-40 Approach Noise



Need airframe design compatible with slow and steep approach profiles

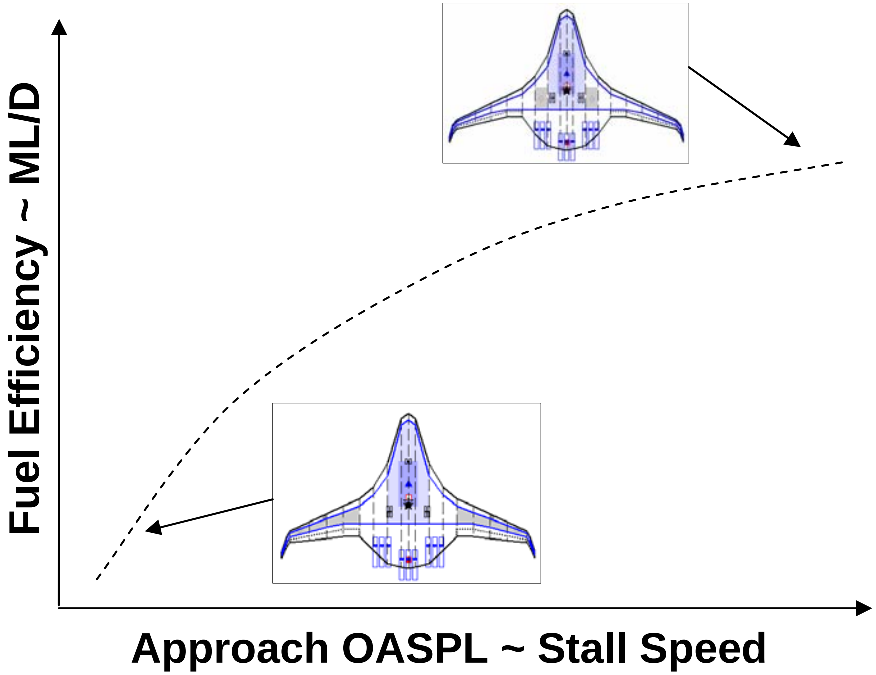
Aerodynamic Design for Low Noise - II

Airframe noise ~ $b\,U^n / r^2$

Design for *low approach speed with large wing area,* $U = \sqrt{W / (\tfrac{1}{2}\rho C_L S)}$

Flight speed on approach (i.e., 1.23 x stall speed) is directly related to cruise performance.

Airframe design philosophy: *minimize penalty in cruise L/D for low approach speed through advanced centerbody design and outer wing optimization.*



Aeroacoustic problem is now an aerodynamics problem. Still difficult, but now it's doable.

Aircraft Aerodynamics Overview

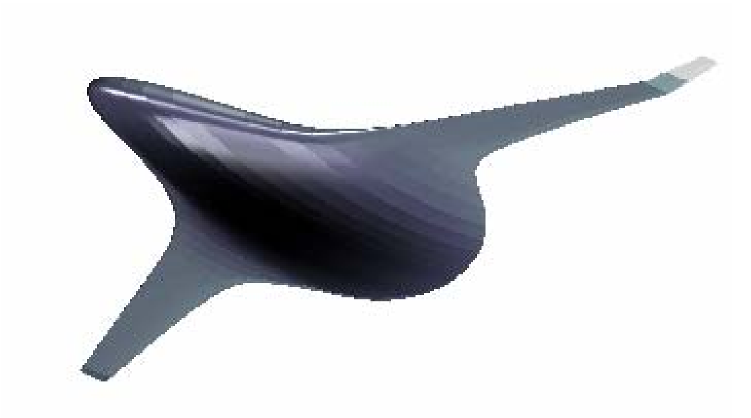
Primary challenge in blended-wing-body aircraft design is balancing the aerodynamic forces without a tail.

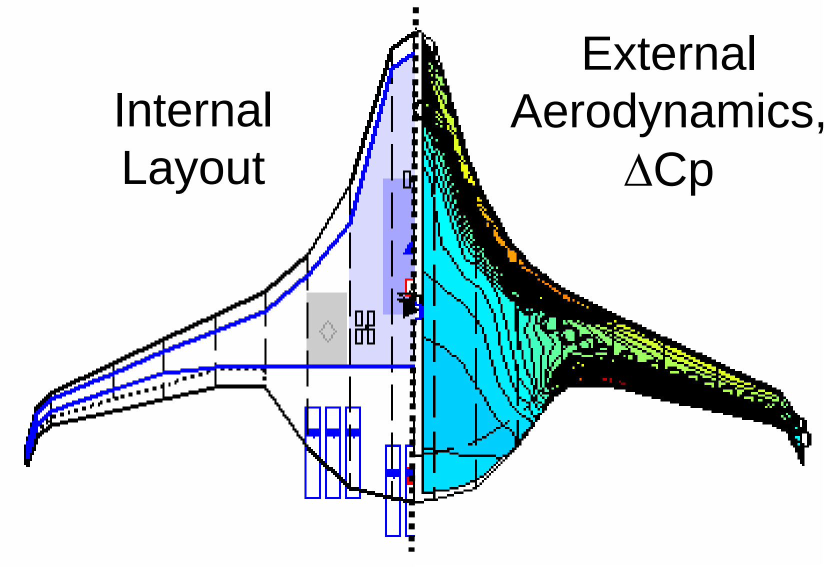
3D airframe must be designed to provide lift that is balanced about CG.

Leading edge camber provides canard-like impact to provide balanced lift without destabilizing effect.

Achieved elliptic lift distribution while trimmed.

Aircraft	ML/D
SAX-40 Airframe	**20.1**
Liebeck 2004, BWB	17 to 18
Boeing 777	15.5
Qin et al. 2004, BWB	13.4



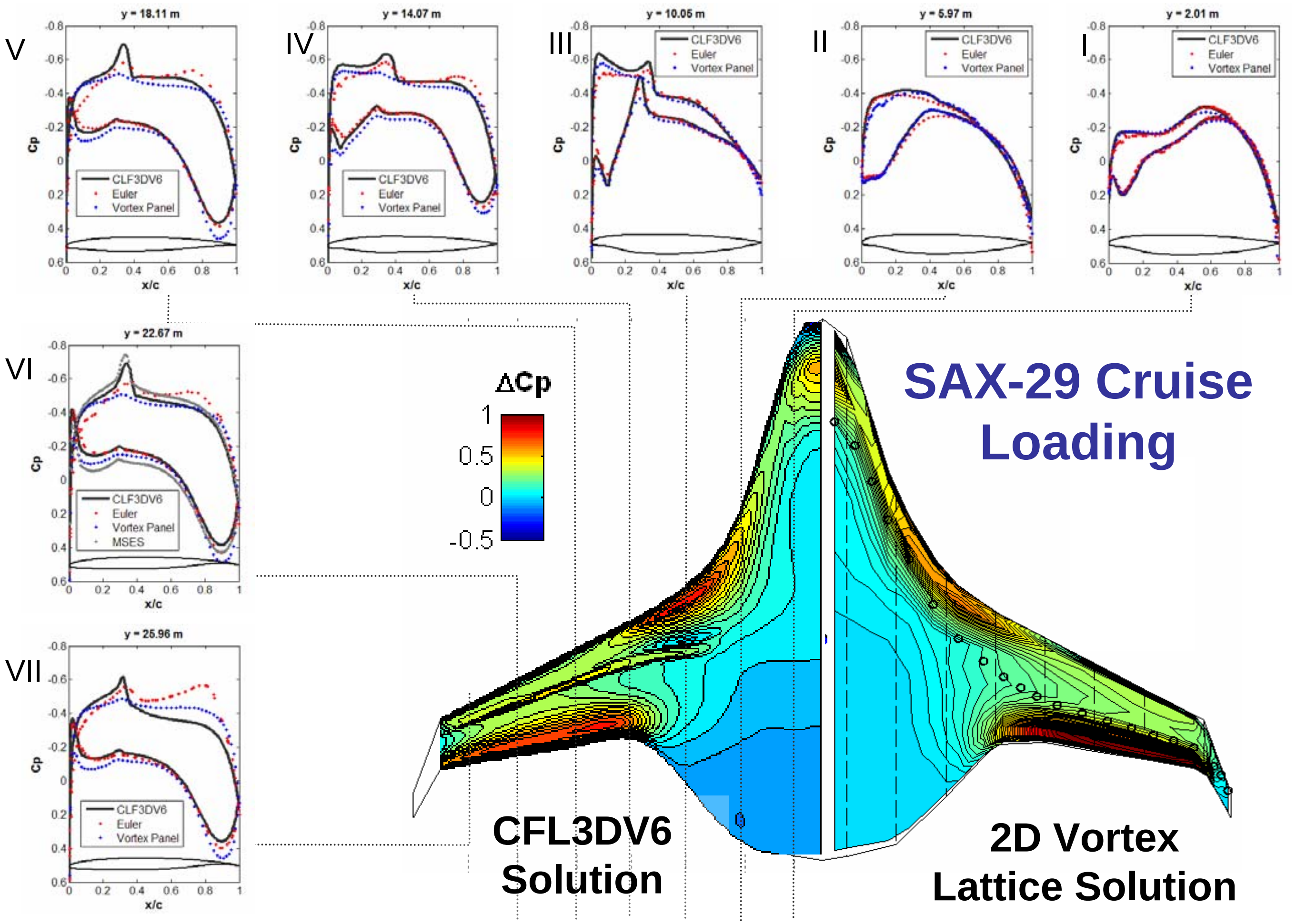


Validation of 3D Design Methodology / Aerodynamics

Outcome:

- Design framework adequately models three-dimensional centerbody flow.
- Aerodynamic shaping of centerbody provides lift to trim aircraft and improves L/D.

AIAA 2007-0453



SAX-29 Cruise Loading

CFL3DV6 Solution

2D Vortex Lattice Solution

Sensitivity of Performance to Drag Coefficient

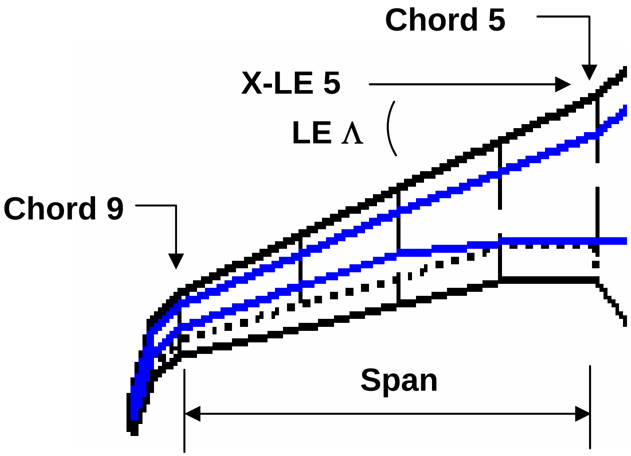
SAX-40 airframe analyzed with increasing C_D.

Range decreased to maintain MTOW.

C_D	ML/D	Range, nm	Fuel burn, pax*nm/gal
+0.0000	20.1	5,000	124
+0.0005	18.9	4,650	116
+0.0010	17.9	4,350	109
+0.0015	16.9	4,100	103

Adding 5 counts of drag has similar impact to adding 10,000 lbs of weight.

Outer Wing Optimization

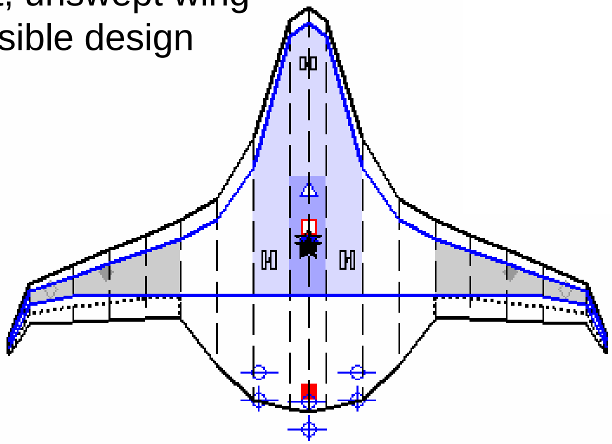


Optimization Overview

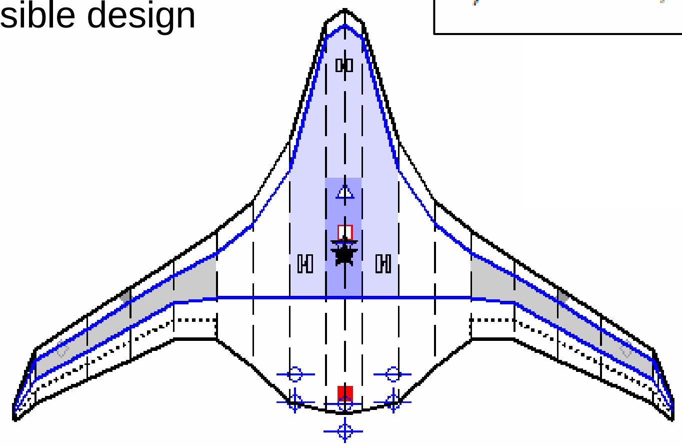
- Centerbody and airfoil profiles “frozen.”
- Design created through mulit-objective optimization on fuel burn and noise.

Criteria:
1) CBN AoA < 3. degrees
2) LE dCp < 1.0
3) (S.M.) (M.A.C.) > 25 in
4) Elevator - Spar > 0.1 m
5) Decreasing sweep w/ increasing span
6) MTOW < 346,000 lb

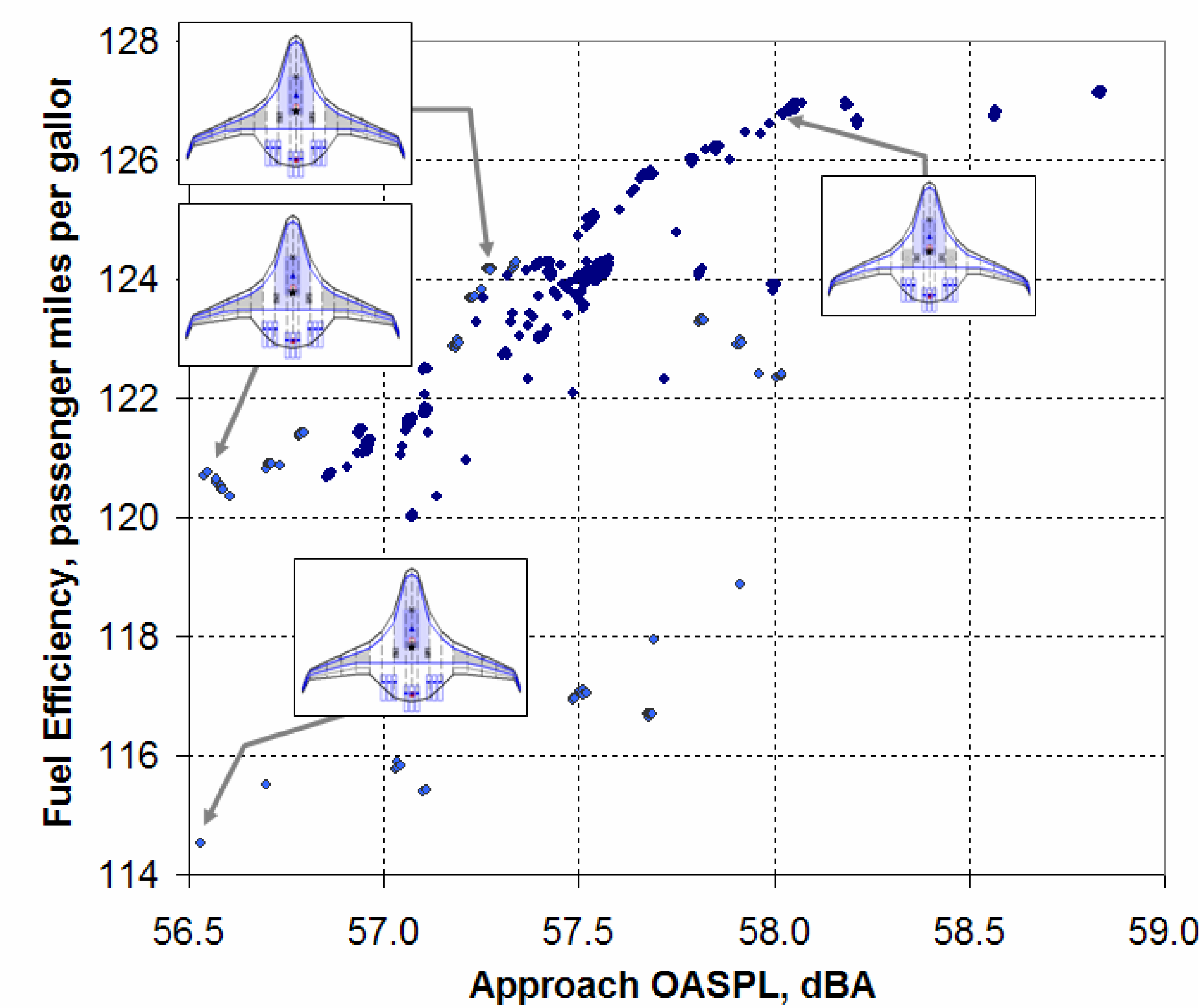
Short, unswept wing
Infeasible design



Long, highly swept wing
Infeasible design



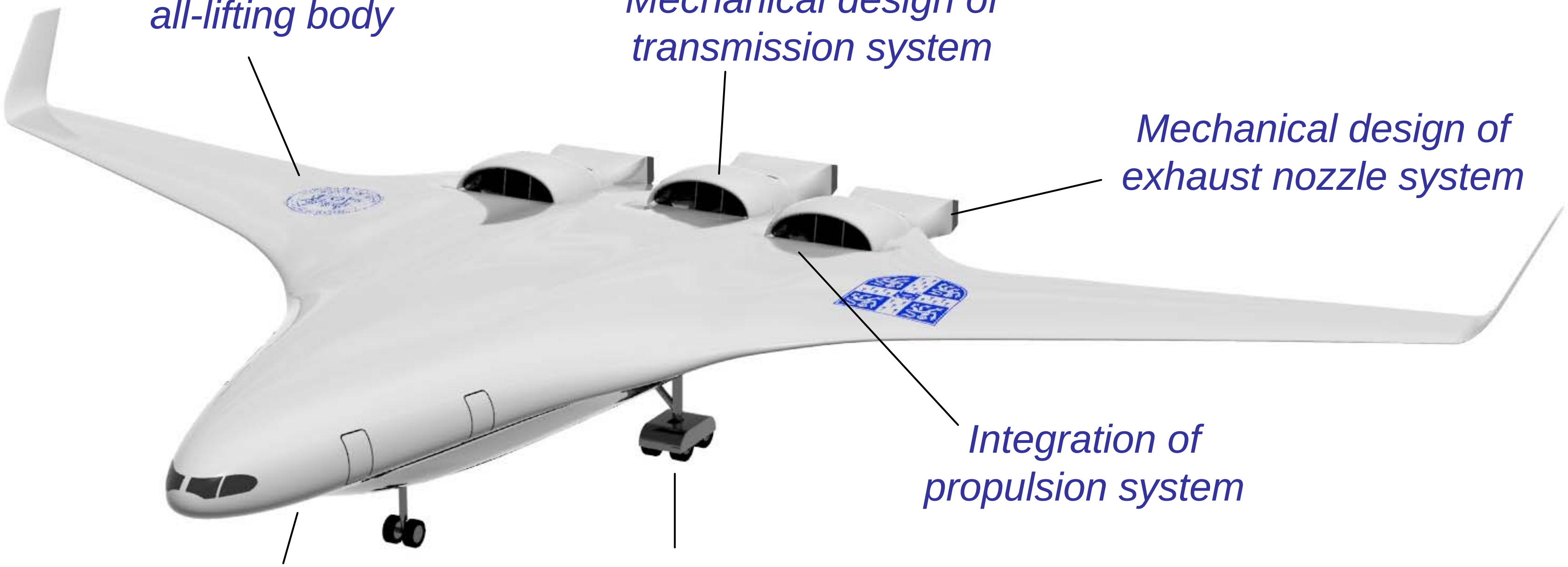
Wing Optimization Design Space - Fuel Burn / Noise



Wing details are critical to fuel efficiency and noise.

Wing area and wing sweep determine both stall speed and cruise performance.

Risk Assessment



Structural integrity of all-lifting body

Mechanical design of transmission system

Mechanical design of exhaust nozzle system

Integration of propulsion system

Pressure vessel for unconventional airframe

Implementation of fairings

Many technical challenges must be overcome before such a design concept could become a reality

Risk Assessment

Have considerable risk with propulsion system and airframe design.

Are these risks justified?

Conducted independent analyses:

1. Assessed technology contributions to noise and fuel burn, Mountains Chart, ISABE Paper 2007-1142.
2. Alternative, lower risk podded aircraft design.
3. Sensitivity studies.

Technology Assessment

Technology	Change* in Fuel Burn per Passenger-Mile (%)	Change* in Engine Noise (dBA)
2005 Technology	0	0
2025 Materials and Design	-15.0	-2.2
Variable Area Nozzle	-0.4	-4.9
Optimised Departure	0.0	-6.4
All-Lifting-Body Airframe	-17.0	-6.0
Engine Embedding	+3.4	-4.9
Boundary Layer Ingestion Distributed Propulsion	-9.3	-3.0

* Changes given incrementally, i.e. relative to previously listed technological step.

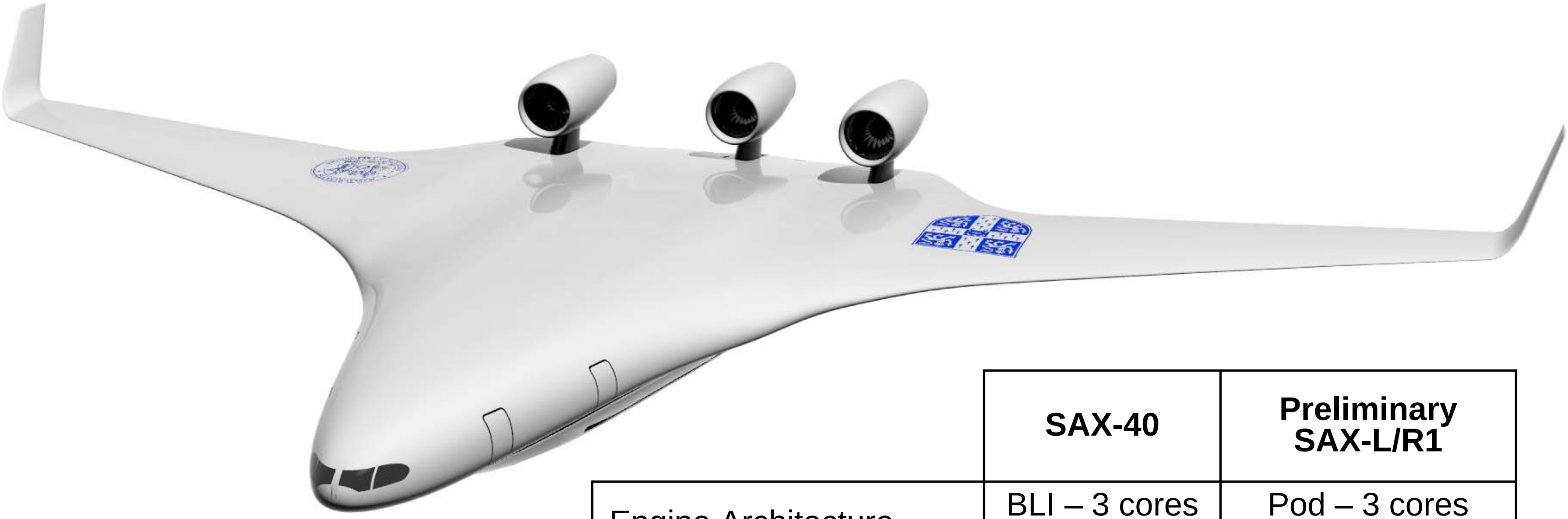
Risk Mitigation Plan

- The all-lifting wing airframe leads to lower noise as well as delivering a large fuel burn reduction.

- Embedded, distributed propulsion combined with boundary layer ingestion enables lower fuel burn as well as lower noise, but the technology is high risk.

- A lower risk design should have:
  - All-lifting wing airframe.
  - Podded UHBR engines with variable area exhaust nozzles.
  - Mixed exhaust with extensive acoustic liners.
  - Power managed take-off and displaced threshold.

Alternative Lower Risk Aircraft Design



Preliminary analysis of podded design

	SAX-40	Preliminary SAX-L/R1
Engine Architecture	BLI – 3 cores driving 9 fans	Pod – 3 cores driving 3 fans
Fuel burn, pax-miles per gal	124	113
Sideline / Flyover / Approach Noise, dBA	63 / 61 / 63	65 / 65 / ~70
Sideline / Flyover / Approach Noise, EPNdB	67 / 69 / 73	72 / 73 / ~80

Moderately louder than SAX-40 on take-off because of fan rearward noise.

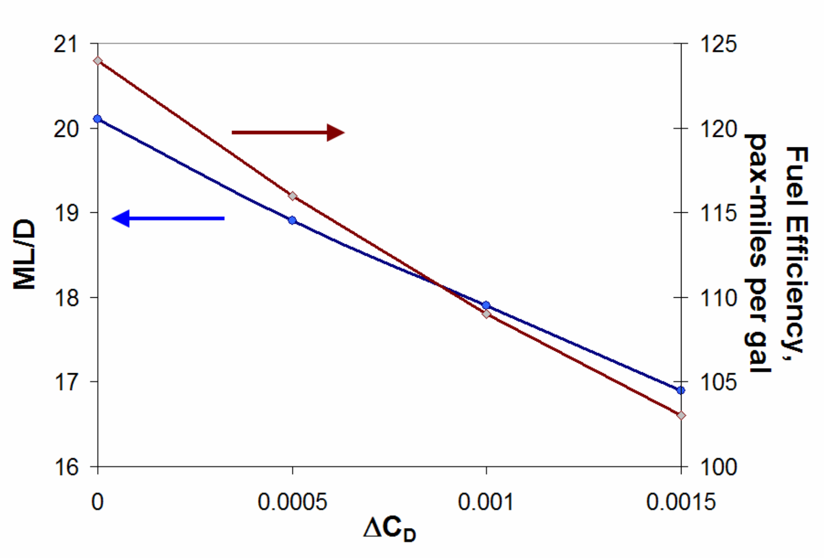
Cumulative 225 EPNdB, ~15 above SAX-40, but ~60 below Stage 4 requirement.

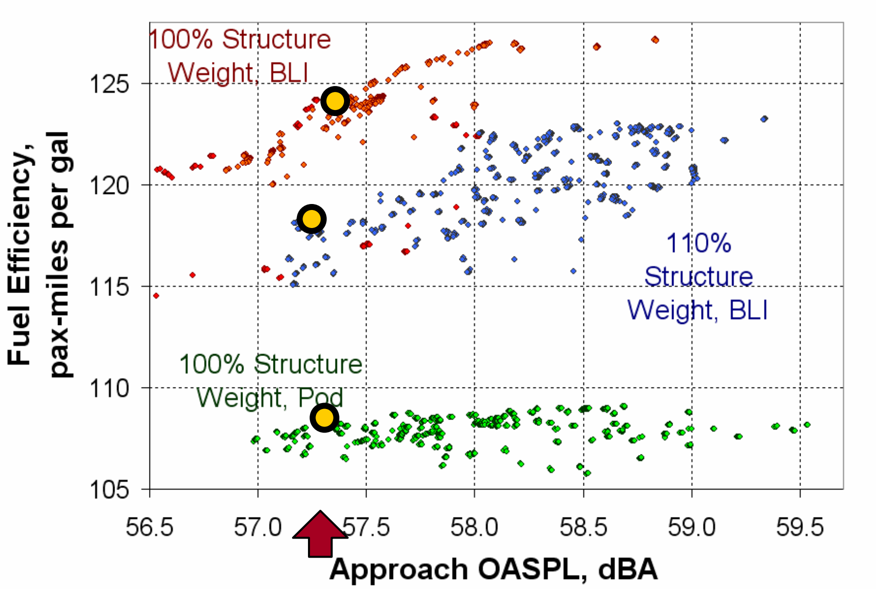
Sensitivity Studies

Analyzed multiple configurations to assess relative contributions of technological risks to noise and fuel efficiency:

- Engine embedding vs. podding (is propulsion system benefit worth risk?)
- Structural weight (impact of higher weight)
- Aerodynamic efficiency (impact of reduced ML/D)

Could create a feasible design with increased structural weight, increased drag, or podded engine configuration, but would pay fuel burn penalty.





Summary

- Meeting aggressive NextGen goals of 2-3X growth by 2025 requires novel aircraft design and operations.
- SAX-40 optimized for ultra low noise with consideration of fuel use and acceptance of high-risk technologies.
- SAX-L/R1 designed for moderate risk with less stringent noise criteria.
- *In future, use different optimization function:*
  risk, cost, energy, climate, local air quality, and/or noise.

For additional information:
http://silentaircraft.org