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Transonic Truss-Braced Wing Maturation

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NASA Advanced Air Transport Technology (AATT) Project

Vision

Enable Aircraft with Dramatically Improved Energy Efficiency, Environmental Compatibility, and Economic Impact for the Nation

Mission

Explore and develop viable game-changing concepts, technologies, and tools to improve vehicle and propulsion system energy efficiency and environmental compatibility

Scope

Subsonic fixed-wing commercial transport aircraft

Evolution of Subsonic Transports

NASA System-Level Metrics

v2016.1

TECHNOLOGY BENEFITS	TECHNOLOGY GENERATIONS (Technology Readiness Level = 5-6)		
	Near Term 2015-2025	Mid Term 2025-2035	Far Term beyond 2035
Noise (cum below Stage 4)	22 - 32 dB	32 - 42 dB	42 - 52 dB
LTO NOx Emissions (below CAEP 6)	70 - 75%	80%	> 80%
Cruise NOx Emissions (rel. to 2005 best in class)	65 - 70%	80%	> 80%
Aircraft Fuel/Energy Consumption (rel. to 2005 best in class)	40 - 50%	50 - 60%	60 - 80%

NASA Aeronautics Strategic Thrusts

Safe, Efficient Growth in Global Operations

- Achieve safe, scalable, routine, high-tempo airspace access for all users

Innovation in Commercial Supersonic Aircraft

- Achieve practical, affordable commercial supersonic air transport

Ultra-Efficient Subsonic Transports

- Realize revolutionary improvements in economics and environmental performance for subsonic transports with opportunities to transition to alternative propulsion and energy

Safe, Quiet, and Affordable Vertical Lift Air Vehicles

- Realize extensive use of vertical lift vehicles for transportation and services including new missions and markets

In-Time System-Wide Safety Assurance

- Predict, detect and mitigate emerging safety risks throughout aviation systems and operations

Assured Autonomy for Aviation Transformation

- Safely implement autonomy in aviation applications

Strategic Thrust 3: Subsonic Strategy

Advanced Air Vehicles Program (AAVP) & Integrated Aviation Systems Program (IASP) shall develop an initial integrated plan of technology development, ground demonstrations and flight validation of subsonic technologies

Four Key Subsonic Transport Technologies

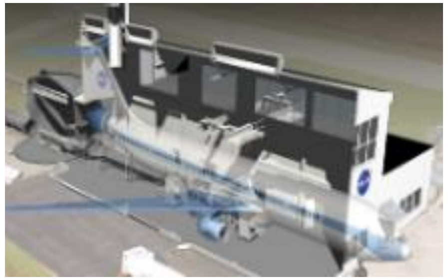
Create new "S" curve for the next 50 years of subsonic transports

Electrified Aircraft Propulsion
- Improved efficiency/emissions
- Mild hybrid systems promising for early 2030s

Small Core Gas Turbine
- Increased gas turbine efficiency
- Facilitates airframe integration – conventional or EAP

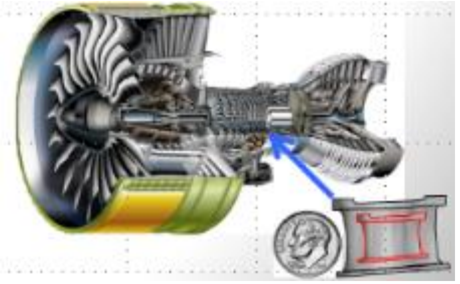
Transonic Truss-Braced Wing
- Increased aerodynamic and structural efficiency
- Propulsion system integration and high rate production

High Rate Composite Manufacturing
- Critical to US competitiveness via reduced delivery time
- Reduced time/cost to market with increased performance



Electrified Aircraft Propulsion

synergistic



Small Core Gas Turbine

Transonic Truss-Braced Wing

synergistic

High Rate Composites

Advance key technologies to TRL 6 by 2025-28 to create early 2030s market opportunities for US industry

TTBW Context in Advanced Air Transport Technology Project

Goals Metrics (N+3)	Noise Stage 42 – 52 dB cum	Emissions (LTO) CAEP6 – 80%	Emissions (cruise) 2005 best – 80%	Energy Consumption 2005 best – 60-80%

Goal-Driven Advanced Concepts (N+3)

Technology Theme 2: Higher Aspect Ratio Optimal Wing

Future wings will be of higher aspect ratio, lighter, more flexible, and have varying degrees of laminar flow to reduce drag and improve performance

Technical Challenge 2.1 Higher Aspect Ratio Optimal Wing

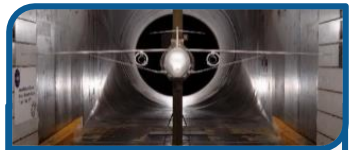
Enable a 1.5-2X increase in the wing aspect ratio with safe structures and flight control (TRL 3)

Program Timeline & Key Test Campaigns

- TTBW has been in continuous development since 2008

Non-linear Aeroelastics Test
NASA LaRC TDT (2013)
- Verify vehicle aeroelastic modes and nonlinear behavior

High-Speed Test (M=0.745)
NASA Ames 11' (2016)
- First high-speed TTBW aero performance test

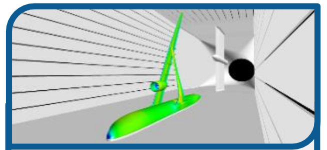


High-Speed Test #2 (M=0.745)
NASA Ames 11' (2018)
- Build on previous transonic test experience

High-Speed Test #3 (M=0.80)
NASA Ames 11' (2019)
- Increase design cruise speed to M=0.80

High-Lift Test
NASA LaRC 14x22 (2019)
- First low-speed (high-lift) TTBW test

High-Lift Test #2
NASA LaRC 14x22 (2021)
- 2nd low-speed (high-lift) test – IGE and icing investigations



Transonic Buffet (M=0.80)
NASA Ames 11' (2022)
- Investigation of transonic buffet onset

2008 - 2014	2015	2016	2017	2018	2019	2020	2021	2022

Phase I/II (2008-2014)
- *Conceptual Design Studies*

Phase III (2014-2016)
- *M=0.745 High-Speed Design*

Phase IV (2016-2020)
- *M=0.80 Design, High-Lift System Design*

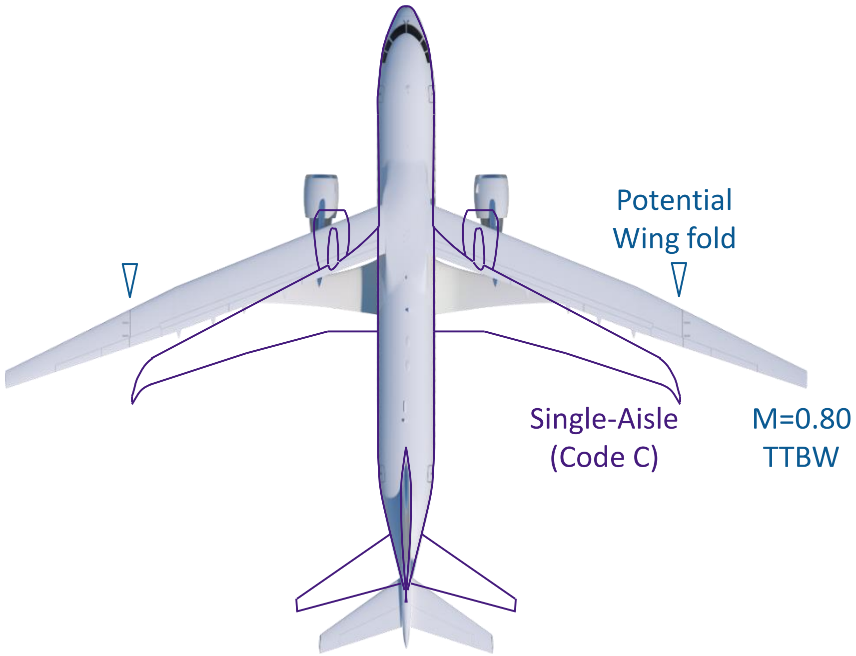
Phase V (2020-2022)
- *High-Speed buffet, ground effects, icing*

Future Development

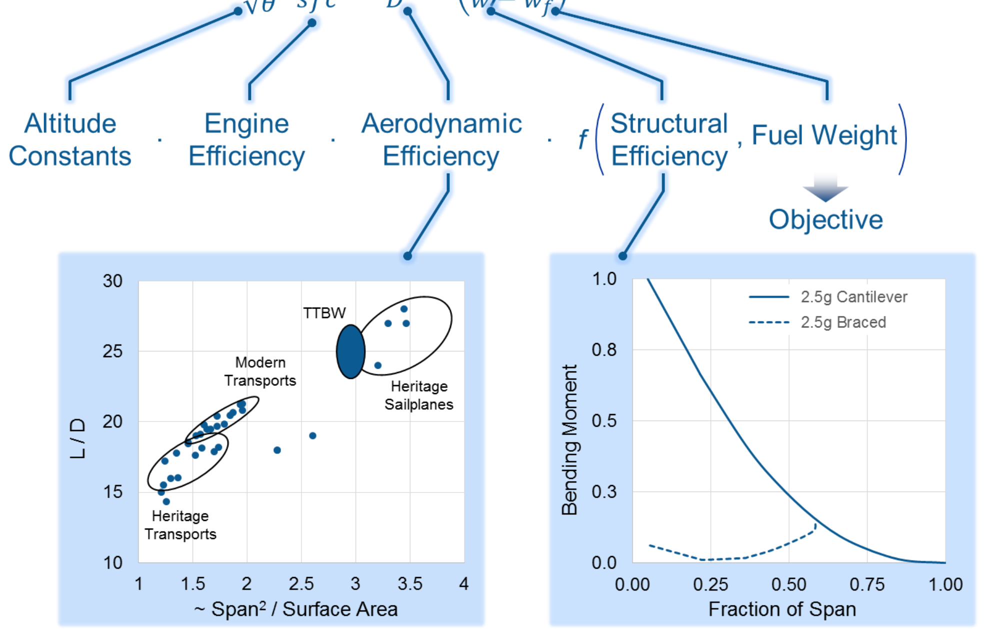
NASA committed to enabling industry adoption of TTBW technology

Potential Benefits of TTBW Technology

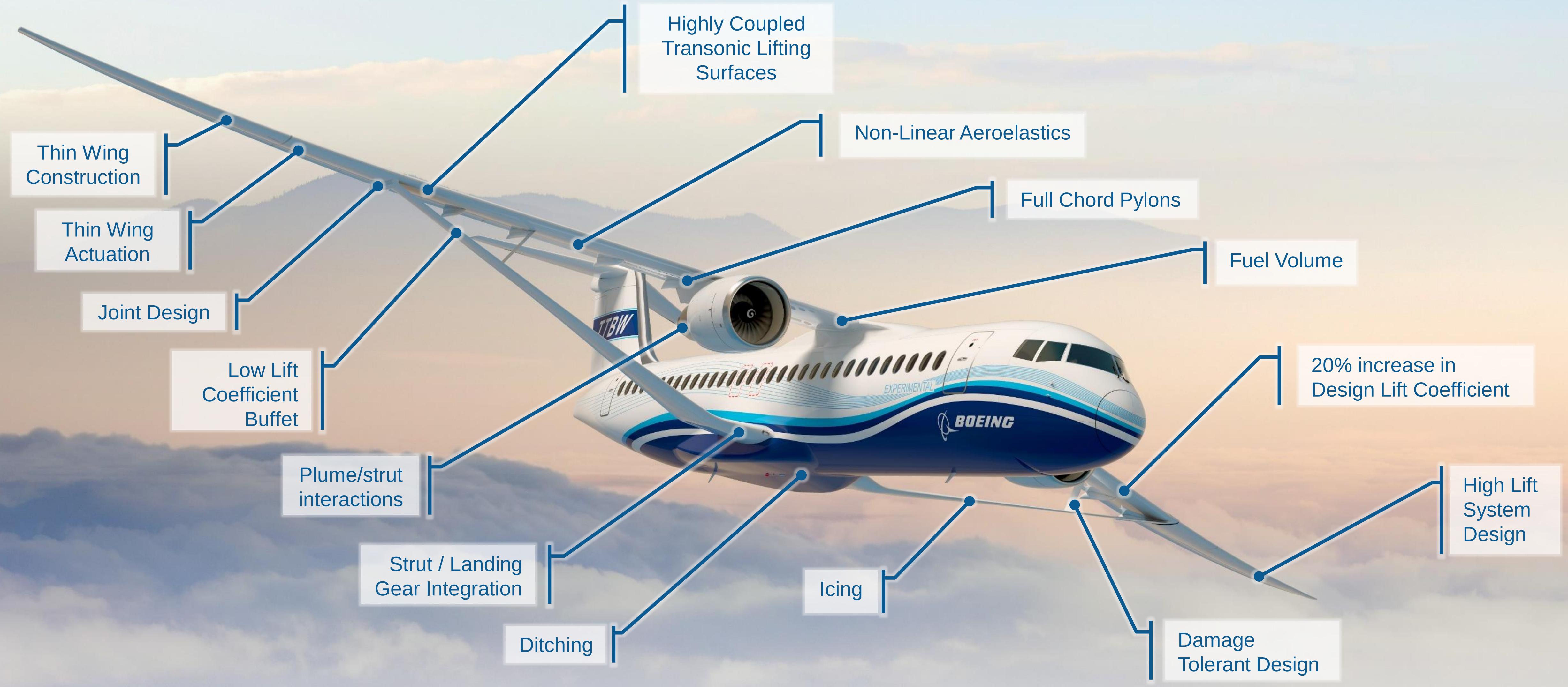
- Dramatic increase in wing aspect ratio – significant decrease in vehicle induced drag
- Wing structural efficiency via strut-bracing – decrease in wing root bending moments
- Potential for simplified major structural attachments – pin joints



$$Range = \frac{a_o}{\sqrt{\theta}} \cdot \frac{1}{sfc} \cdot M \frac{L}{D} \cdot \ln\left(\frac{w}{w - w_f}\right)$$



TTBW Development Challenges



Aero and structural characteristics significantly outside existing databases

SUGAR Phase IV

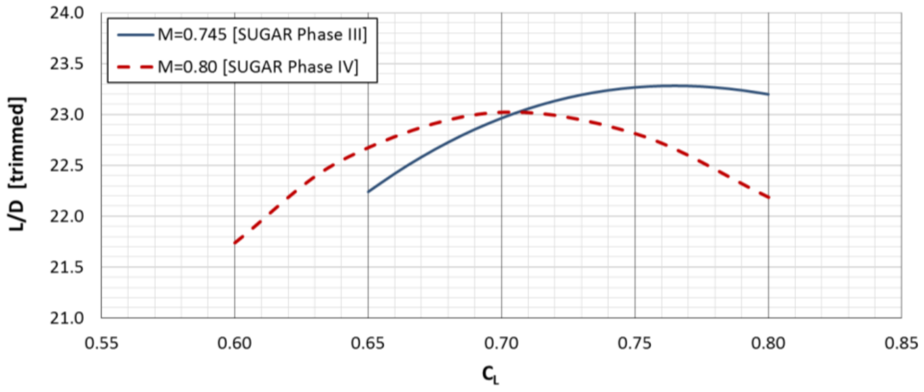
SUGAR Phase IV

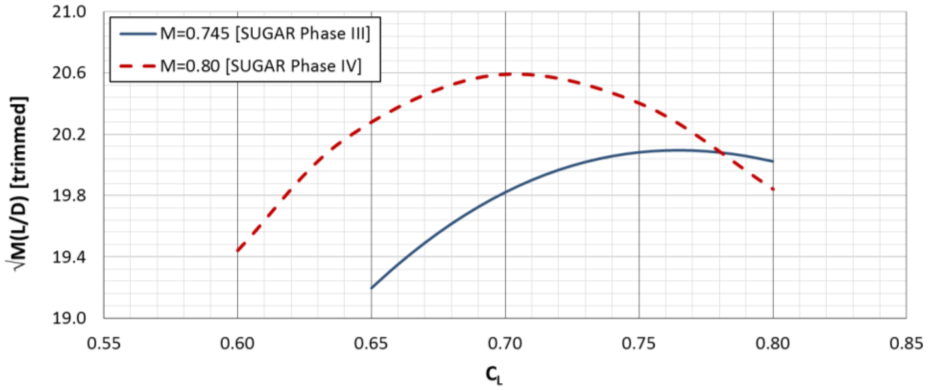
- **Primary objectives:**

  1) Design a TTBW configuration that can operate efficiently at a cruise Mach = 0.80, and validate the high-speed aerodynamic performance of this vehicle in a transonic wind tunnel test.
  2) Develop a high-lift system for the TTBW vehicle, and validate the low-speed aerodynamic performance in a low-speed wind tunnel test.
  3) Develop and compare an advanced tube-and-wing configuration of equivalent technology level to meet the same mission requirements as the TTBW vision vehicle.
  4) Identify remaining technical challenges associated with application of TTBW technology to modern commercial aircraft, and develop a roadmap for the continued systematic reduction in risk.

High-Speed Design

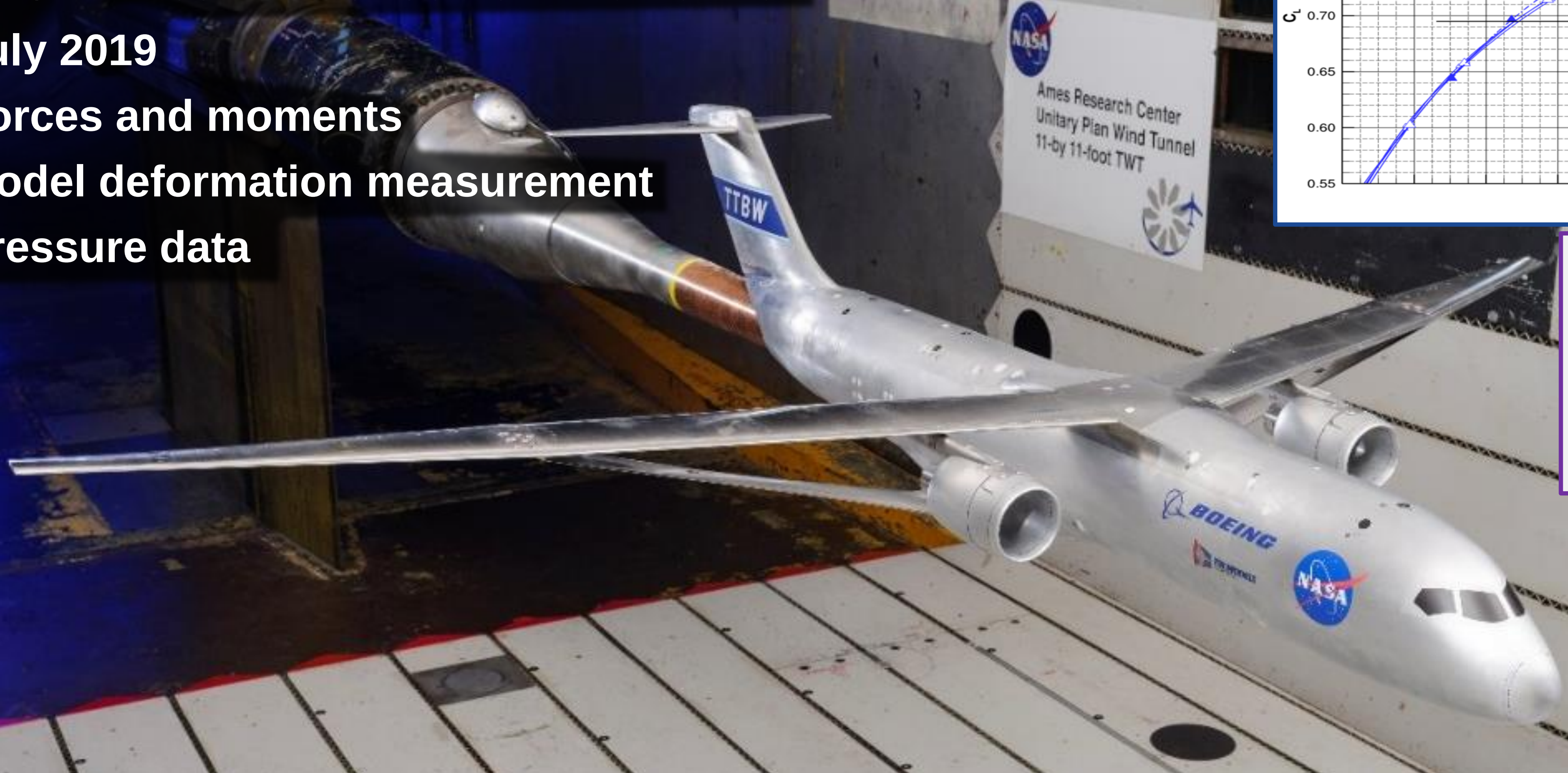
- **Final results obtained using NASA RANS code OVERFLOW (structured, overset grids, SARC turbulence model)**
- **Results at flight Re (turbulent, trimmed) show an L/D of ~23 at the design C_L = 0.695**
- **Considering higher cruise Mach of Phase IV design shows improved aerodynamic efficiency as compared to Phase III**
  - Phase III design would most likely benefit from configuration changes and optimization methods applied in Phase IV
- **Additional aerodynamic performance improvement possible when incorporating laminar flow**

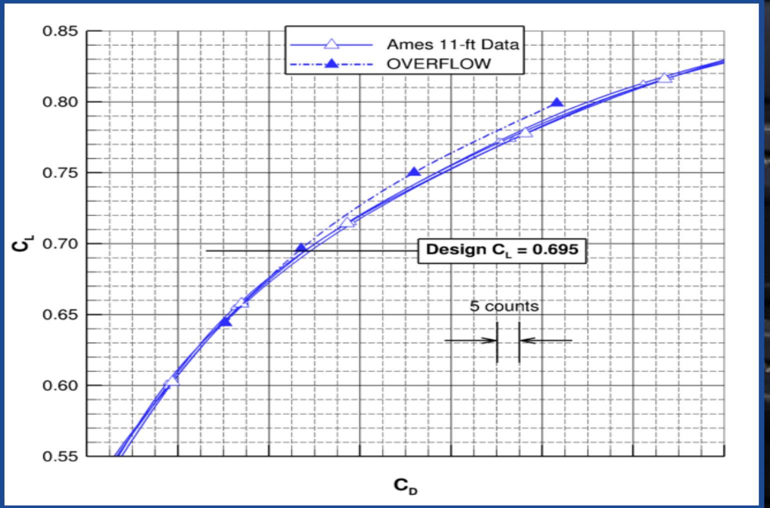




M=0.80 TTBW High-Speed Test

- NASA Ames 11’ Transonic Wind Tunnel
- July 2019
- Forces and moments
- Model deformation measurement
- Pressure data





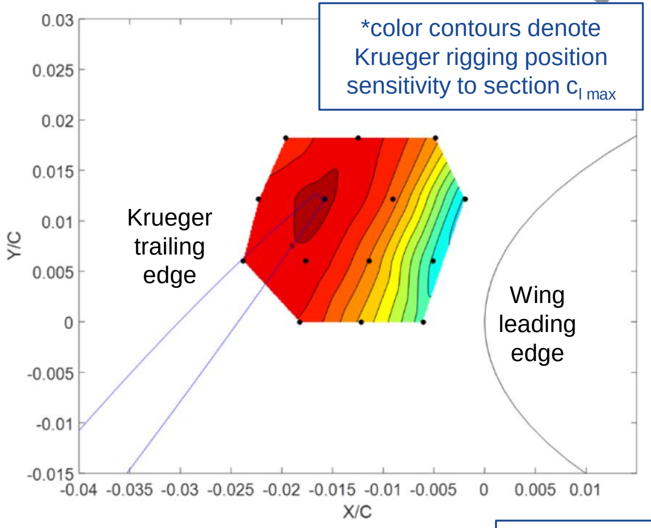
At cruise lift coefficient wind tunnel data and pre-test CFD predictions agree within 2cts drag

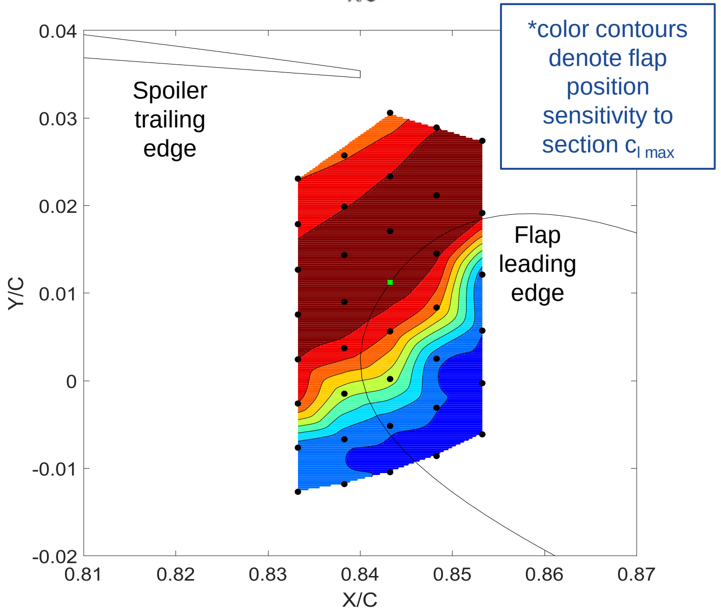
TTBW configuration well-suited for efficient operation at M=0.80

*** Projected 9% reduction in fuel burn for 3500nm SUGAR mission profile ***

High-Lift System Design

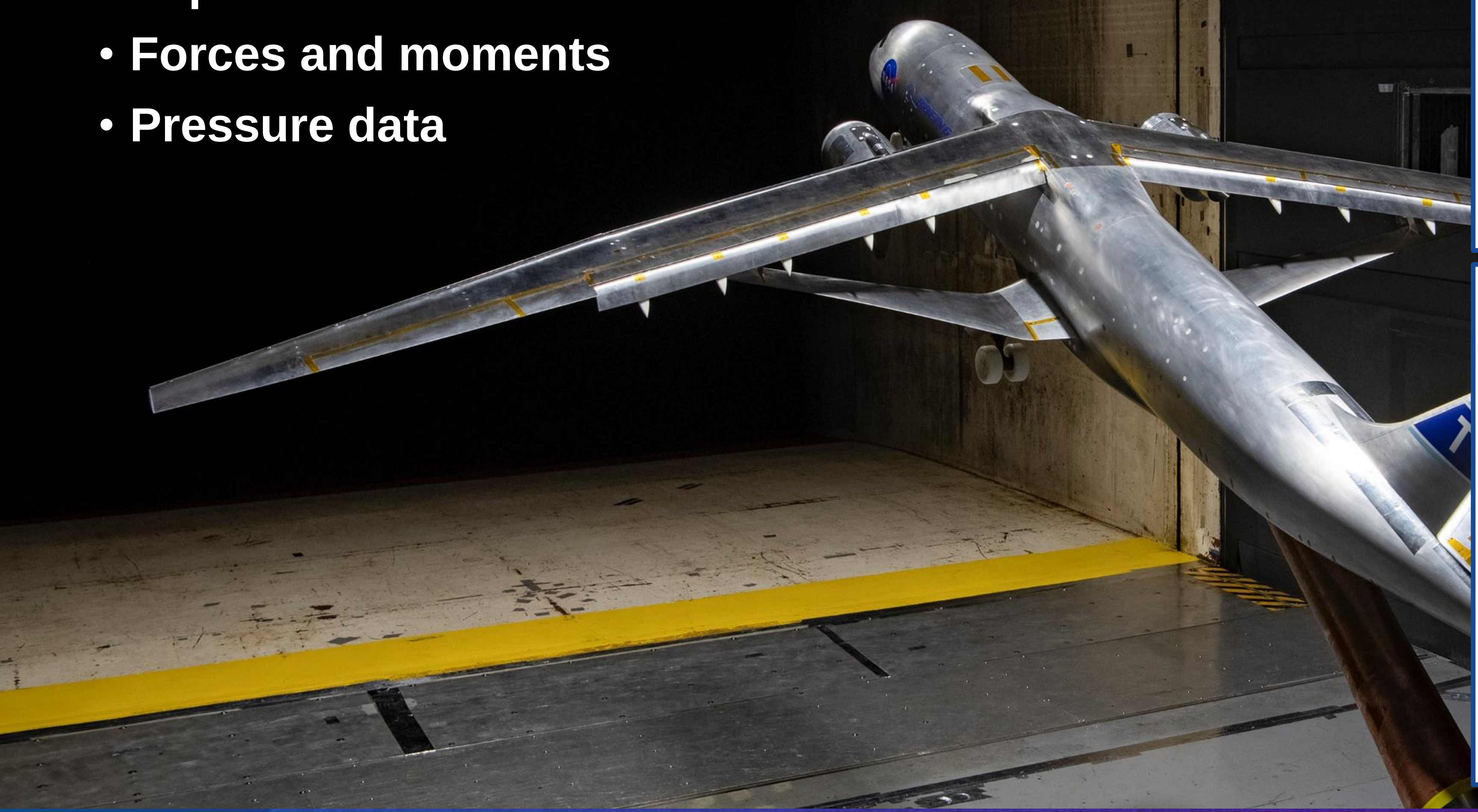
- **Phase IV work is first detailed design of a high-lift system for a TTBW**
- **2D investigations of different leading edge concepts**
  - Krueger, slat, drooped and morphing leading edge concepts considered
  - Both fixed and variable camber Krueger considered due to laminar flow compatibility
    - Variable Camber Krueger (VCK) selected
- **Single-slotted Fowler flap used for all configurations**
- **Candidate control surface planforms studied prior to application of high-lift concept to 3D design**
- **Implementation of high-lift system to 3D design indicated the necessity for differential rigging of leading edge device on the outboard wing panel**
- **At flight Re, the strut was shown to have minimal effect on vehicle high-lift performance – stall limited by wing high-lift system**

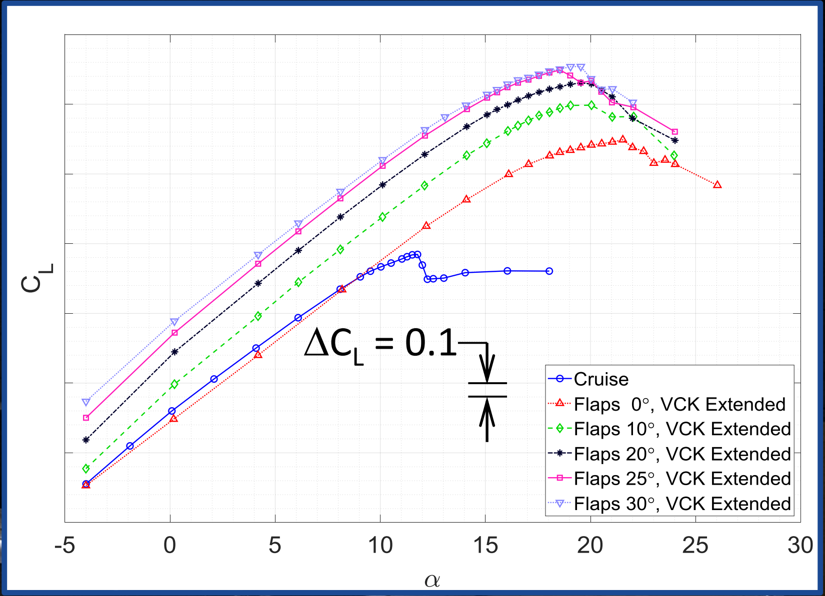


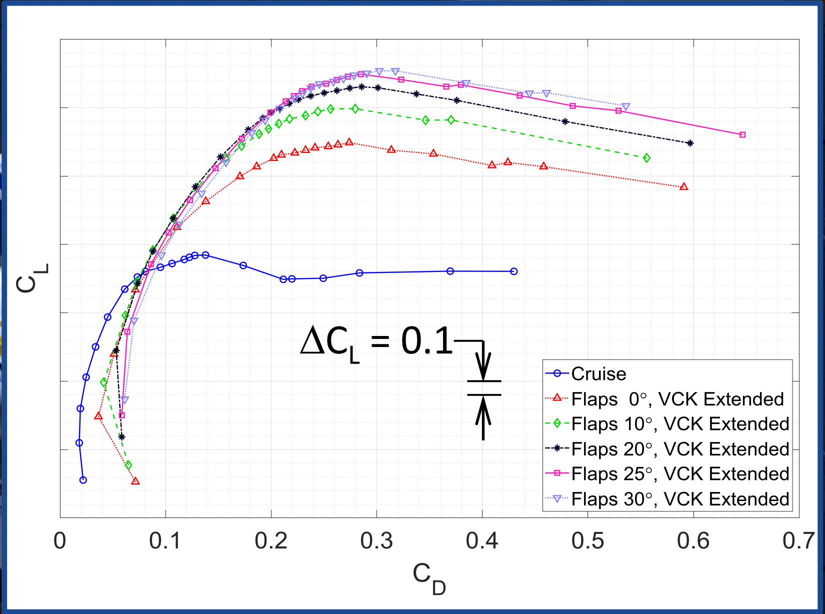


Low-Speed Wind Tunnel Test

- NASA Langley 14- by 22-Foot Subsonic Tunnel
- September 2019
- Forces and moments
- Pressure data





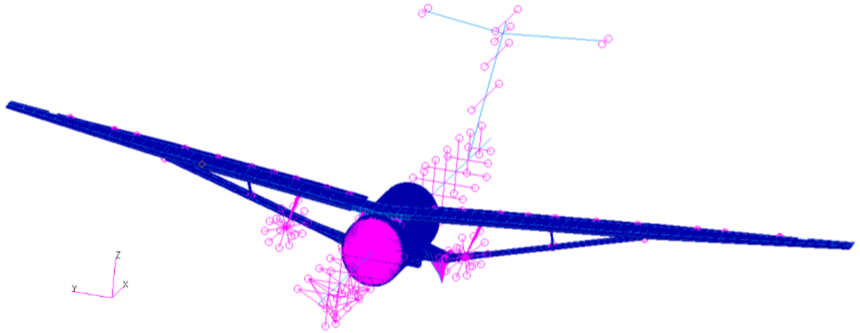


High-Lift performance achieved pretest targets

Structural Design and Analysis

- **Development of global finite element Model (FEM) and conceptual study of joint structural concepts**

- **FEM Development and Update**
  - Updated loads and airframe structural sizing
  - Weight estimation
  - Aeroelastic Analysis and Flutter assessment
    - » Wing, strut, and jury sized for critical maneuver and gust loads; weights close to earlier Mach 0.745 analyses
    - » Strut reduces shear and bending loads on inboard wing
    - » Healthy flutter margins up through Mach 0.85
    - » Flutter analysis at dive speed (Mach 0.92) requires higher fidelity method



Updated Integrated Vehicle Finite Element Model

Doublet Lattice Aerodynamic Model with Refined Mesh

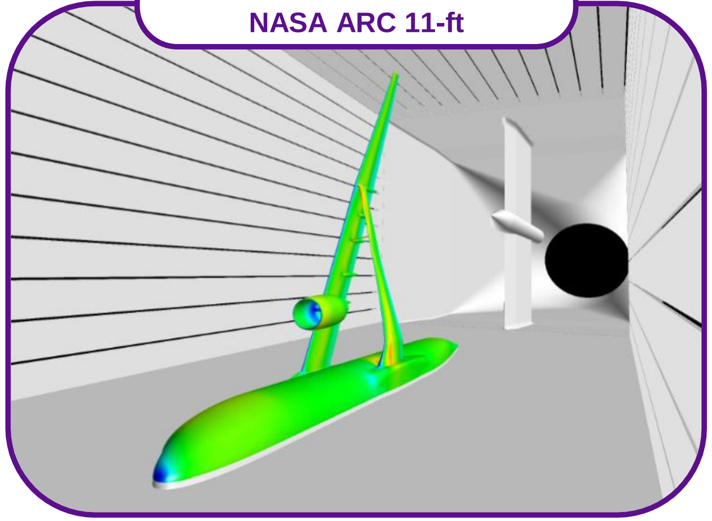
SUGAR Phase V

SUGAR Phase V

- **Continue to reduce risk on TTBW configuration**
  - Period of performance: October 2020 – April 2022
- **Objectives**
  - Low-speed test entry #2 into NASA LaRC 14- by- 22 Foot Subsonic Tunnel
    - Continue acquisition of low-speed (high-lift) performance database, collect in-ground-effect data, prelim. icing effects
  - Transonic Buffet wind tunnel test in NASA ARC 11-ft Transonic Wind Tunnel
    - Determine ability to accurately predict buffet onset, both at high and low lift coefficients

TTBW Low-Speed Model in NASA LaRC 14x22

TTBW Buffet Model in NASA ARC 11-ft



SUGAR – Future Objectives

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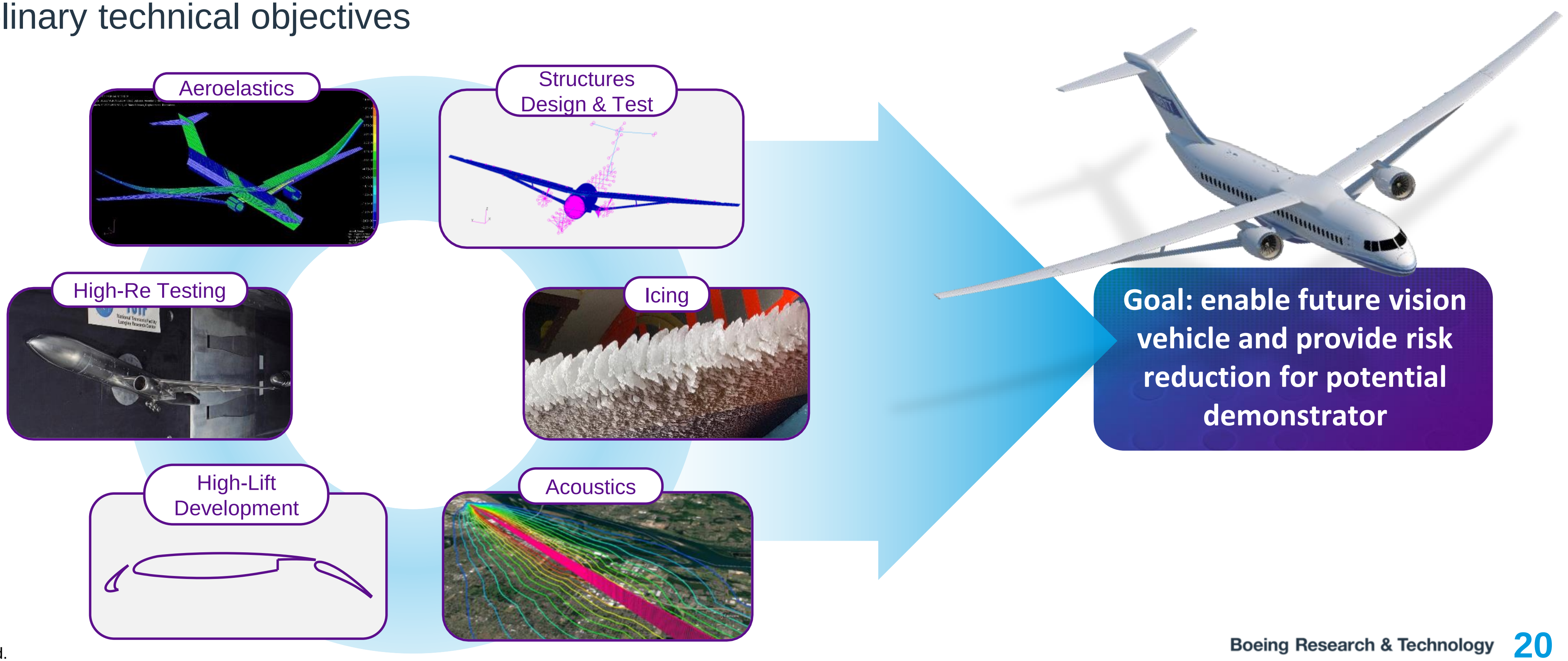
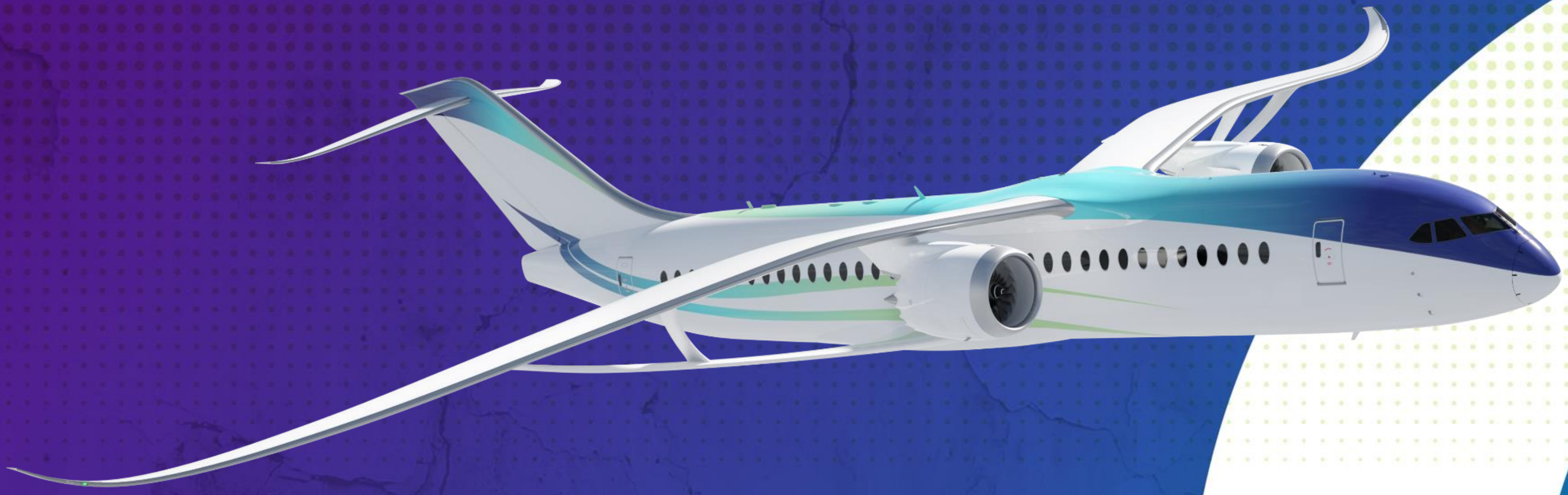
- **NASA AATT continuing TTBW tech development for vision vehicle in parallel with potential demonstrator program**
  - Target period of performance beginning mid 2021
  - Multidisciplinary technical objectives





X-Plane Demonstrator

CLEANER, QUIETER, MORE EFFICIENT

Inspiring Innovation in U.S. Commercial Aviation Industry through National X-Plane Demonstration

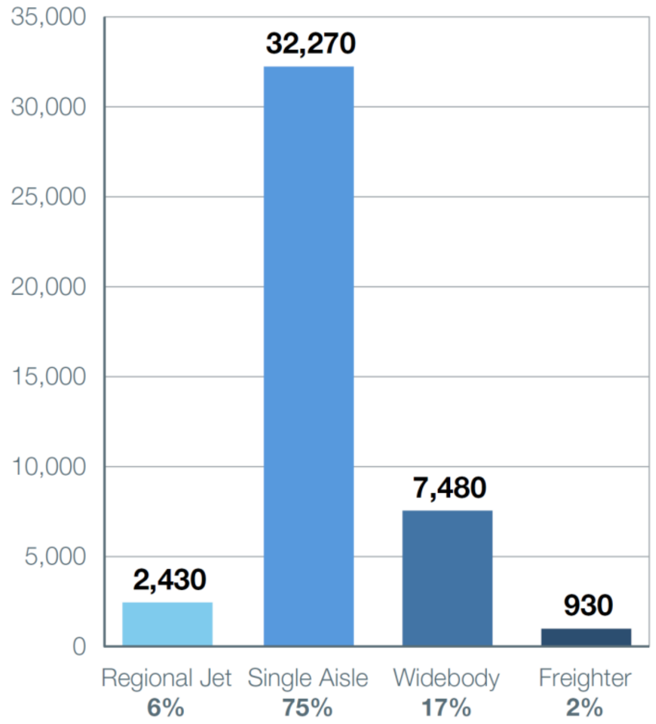
Future Market Share Determined by Investments Today

Essential Technologies for Future Fleet

- Focus on Safety and Sustainability
- Electrified Aircraft Propulsion
- Small Core Gas Turbine
- Transonic Truss-Braced Wing
- High Rate Composite Manufacturing

20-year forecast (2020-2039)

43,110 new airplane deliveries



2020 → **Research & Development** · **Technology Maturation** · **Design & Certification** · **Advanced Production**

2030	2031	2032	2033	2034	2035…

Source: http://www.boeing.com/commercial/#/about-our-market

Anatomy of an X-Plane – Accelerating Critical Technologies

High Rate Composite Manufacturing

Stronger, lighter, efficient to manufacture carbon composite wings

Electrified Aircraft Propulsion

More electrification reduces fuel burn and emissions

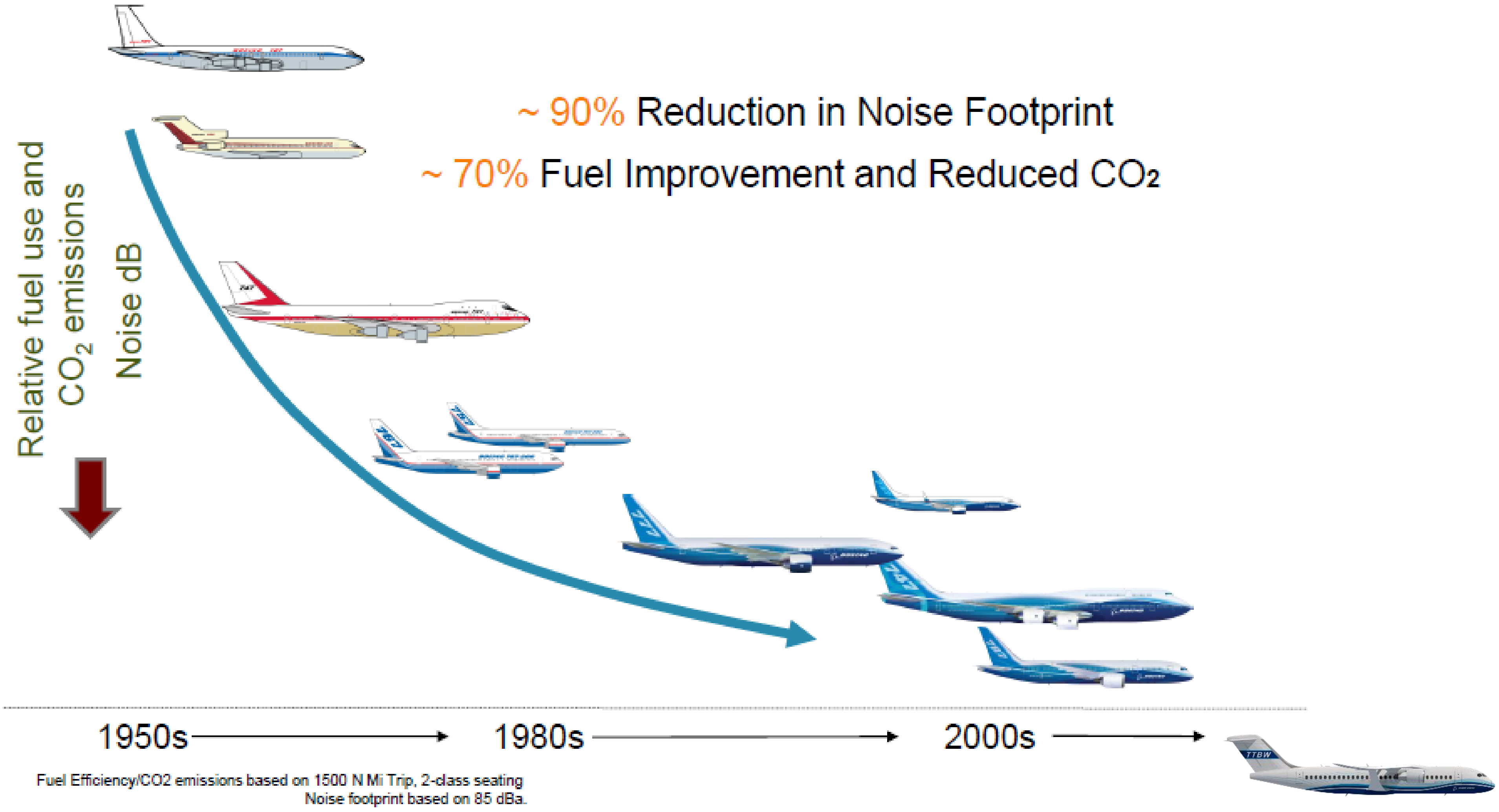
Transonic Truss-Braced Wing

Truss supports structural load to enable a thinner, more aerodynamic wing that burns less fuel per flight

Small Core Gas Turbines

Compact engines enhance aerodynamics and feature next generation combustion technologies

A Strong Environmental Track Record



Subsonic X-Plane Demonstrator is a National Imperative

Lead and Inspire for Sustained Competitive Advantage

U.S. Economic Prosperity

- Increases GDP and create jobs
- Enhances export position

U.S. Technology R&D

- Enhances competitiveness
- Innovates for carbon-neutral growth

U.S. Public/Private Partnerships

- Necessary for technical readiness
- Exceeds market requirements
- Bolsters industry base and talent pipeline

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