Project 082(A) CAEP Stringency Analysis Modeling

Georgia Institute of Technology

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- FAA Award Number: 13-C-AJFE-GIT-117
- Period of Performance: September 21, 2022, to March 31, 2025
- Task:
  1. Development of Future Aviation Technology Portfolio for Trends Analysis

Project Funding Level

The Federal Aviation Administration (FAA) provided $514,500 in funding, and Georgia Tech has agreed to a total of $514,500 in matching funds. This total includes salaries for the project director, research engineers, and graduate research assistants, as well as funds for computing, financial, and administrative support, including meeting arrangements. Georgia Tech has also agreed to provide tuition remission for the students, paid from state funds.

Investigation Team

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Project Overview

This project has provided technical support to the FAA for the assessment of the 13th cycle of the International Civil Aviation Organization's (ICAO) Committee on Aviation Environmental Protection (CAEP/13) stringency analysis, including cost estimates of various stringency options (SO). Prior CAEP stringency analysis included a cost–benefit assessment of different scenarios on the basis of outdated information and relied on industry subject-matter input. This project has enhanced and updated the assumptions, on the basis of a quantitative assessment of technological benefits and the costs associated with achieving those benefits. The results will provide the FAA with a data-driven process for decision making, including the interdependencies between fuel burn and noise, as well as the costs associated with their mitigation.

Task 1 – Development of Future Aviation Technology Portfolio for Trends Analysis

Georgia Institute of Technology

Objective

During this period of performance, the CAEP/13 analysis support had finalized and focus turned towards preparation for the CAEP/14 trends analysis. As such, the objective of this task to prepare for the next cycle is to synthesize technology assessments from multiple academia and industry studies in recent years and develop a unified technology portfolio for predicting future aircraft performance improvements to support the trends analysis. ASDL at Georgia Tech has conducted numerous technology studies for the FAA, National Aeronautics and Space Administration (NASA), and other entities over the years. Each study employed different scopes, assumptions, methodologies, reference aircraft, resulting in diverse technology characterization across analyses. These inconsistencies arise from various approaches. For example, ICAO's Long Term Aspirational Goals (LTAG) (ICAO, 2022) and Independent Expert Integrated Review (IEIR) (ICAO, 2017) follow a top-down methodology using aggregated technology "buckets" representing combined effects across time frames 2030-2050, while NASA's Advanced Air Transport Technology (AATT) (Georgia Tech, 2019) uses a bottom-up approach evaluating individual technologies. Discrepancies between LTAG and IEIR include varying levels of conservative assumptions.

The goal of this task is to create a consolidated technology database providing comprehensive and consistent technology assessments for any stakeholder, including the FAA and NASA. This database will incorporate overlapping technologies identified across LTAG, IEIR and AATT with updated findings from recent academic and industry publications post 2020, ensuring the database reflects current technology predictions along with technology readiness levels (TRL) and compatibility assessments.

Research Approach

The first step was to establish a correlation between the overlapping LTAG and IEIR technologies' impact prediction values. This information would help identify how each one of them approached future prediction and assist in implementing a similar approach for this task. Once the overlapping technologies between IEIR & LTAG were identified, they were also matched with similar technologies in the AATT report. These were documented to be worked on first. Then these technologies were consolidated into subgroups of technologies such as aerodynamics, structures, composites, and propulsion.

A comprehensive literature review was conducted focusing on individual technologies with the highest impacts. The review targeted publications from official and reputable sources specifically documenting improvements since 2020. Technologies from AATT were reviewed and incorporated into expanding the library. For each technology, recent findings were documented and compared against previous claims from LTAG, IEIR, and AATT, with emphasis on quantifying performance impacts and corresponding implementation in Georgia Tech's Environmental Design Space (EDS) tool. For each technology in the consolidated library, the team documented estimated years to TRL level 9, quantified performance impacts, and identified technological incompatibilities. The database structure is set up such that it supports both bottom-up and top-down technology assessments, ensuring its impact can be applied across different aircraft types, classes, and project requirements.

Aerodynamic Technologies

Aerodynamic technologies aim to decrease aircraft drag and noise. Aerodynamic technologies and their impact play a significant role in predicting the future fleet of aircraft. Current review classifies aero technologies broadly into two categories based on the type of drag they reduce and how they achieve improvement in aerodynamic efficiency.

The technologies that correspond to reducing the viscous drag are riblets, natural laminar flow control, excrescence reduction, and hybrid laminar flow control.

a. Riblets: Riblets are small rectangular fences that create spanwise viscous forces acting on the turbulent boundary layer to reduce drag. This technology is incompatible with morphing surfaces and select advanced composite technologies.
b. Natural laminar flow control (NLFC): NLFC attempts to increase the region of laminar flow through airfoil design, thereby decreasing wing skin friction drag. Incompatible with DRE and Hybrid Laminar Flow Control (HLFC).
c. Hybrid laminar flow control (HLFC): HLFC is an active technique that uses suction to delay airflow transition from laminar to turbulent, improving aerodynamic efficiency. Incompatible with DRE, and some composite technologies influence the performance of HLFC.
d. Excrescence drag reduction: Excrescence drag reduction refers to all surface imperfections and irregularities leading to a significant source of airframe drag. This technology has interactions with NLFC, HLFC, and riblets technologies.

Table 1 summarizes the evolution of key drag reduction technologies, comparing original impact claims with recent studies findings. Riblets, initially projected to achieve 5-8% skin friction drag reduction with 2-3% total drag reduction (Walsh, 1986; Viswanath, 2002; El-Samni et al., 2007; Bushnell & Hefner, 1990), now demonstrates 4-9.9% skin friction reduction but only a 0.8% total drag reduction (Cornish, 2024; Smith & Yagle, 2025). Natural laminar flow control, originally had the capacity to maintain up to 70% laminar flow with suction (Joslin, 1998), and recent flight demonstration validated through flight test puts its around 50% laminar flow over the wing (Gibson et al., 2021). For hybrid laminar flow control with suction device positioned at 15% chord achieves 50-60% laminar flow (Green, 2008) and recent studies shows that this technology additionally delivers up to 4% reduction in fuel consumption (Clean Aviation, 2023). Excrescence drag reduction technologies was aimed at reducing the 15-24% of profile drag caused due to surface imperfections, which accounted for 8-12% of cruise drag (Kundu et al., 1998), now achieves a fuel burn reduction of 1-5% (Pfeiffer & Lednicer, 2014; Hue & Molton, 2020; Cretin et al., 2024).

Table 1. Aerodynamic technology aircraft drag results comparison.

Technology	Original Impact	Recent study
Riblets	5-8% skin friction drag reduction (Walsh, 1986) 2-3% total drag reduction (Viswanath, 2002; El-Samni et al., 2007; Bushnell & Hefner, 1990)	4-9.9% skin friction drag reduction (Cornish, 2024) 0.8% total drag reduction (Smith & Yagle, 2025)
Natural Laminar Flow Control	Up to 70% laminar flow on certain wings with suction (Joslin, 1998)	Flight test demonstrated natural laminar flow over 50% of the wing (Gibson et al., 2021) Aero shape optimization showed a 10% reduction in total drag (Husain et al., 2024)
Hybrid Laminar Flow Control	Suction device placed at 15% of the chord typically yields 50-60% laminar flow (Green, 2008)	Up to 4% reduction in fuel consumption (Clean Aviation, 2023)
Excrescence Drag Reduction	Surface imperfections account for 15-24% of profile drag, or 8-12% of cruise drag (Kundu et al., 1998)	Cruise fuel burn reductions of up to 1-5% (Pfeiffer & Lednicer, 2014; Hue & Molton, 2020; Cretin et al., 2024)

Another set of aerodynamic technologies that contribute to improvement to aerodynamic performance is Adaptive Aeroelastic Wing Shape Control. Current and future-generation aircraft wing technologies are moving towards lightweight, flexible, high-aspect-ratio wing designs. Flexible high-aspect ratio wings reduce off-design drag, gust sensitivities, and flutter risk. Adaptive aeroelastic wing shape control is the dynamic adjustment of a wing's shape during flight to optimize its aerodynamic performance, which maximizes aerodynamic efficiency by maintaining optimal lift-to-drag (L/D) ratio throughout the flight.

a. Variable-camber continuous trailing-edge flap (VCCTEF): VCCTEF provides continuous control surfaces with reduced drag compared to traditional control surfaces, as they allow for active wing shaping and eliminate gaps between control surfaces. These systems minimize drag during cruise and off-design by adjusting the camber of the wing. Recent studies found cruise drag reduction of 1-5% (Reist et al., 2022) and total drag reduction of up to 8.4% (Nguyen et al., 2019; Ting et al., 2018). This technology is incompatible with cruise slotted flap, continuous distributed control surface.

b. Adaptive wing variable camber: This technology alters the wing geometry in real-time to improve aerodynamic performance in different flight conditions, mostly applied to trailing-edge wing shapes. 5% increase in aerodynamic efficiency is expected (Pecora, 2021). This technology is incompatible with continuously distributed control surfaces and slotted flaps.
c. Advanced winglets: These wingtip devices are designed to reduce induced drag by weakening wingtip vortices, with up to 6.1% L/D improvement leading to a 3-5% fuel saving (Segui et al., 2021). Incompatible with certain active control surfaces.
d. Morphing wing: These are shape-adaptive wing structures that modify geometry in-flight (camber, twist, span) to optimize aerodynamic efficiency at each flight phase with seamless shape transitions. They are expected to reduce drag by 3-10% (Cumming et al., 2016; Giuliani et al., 2022), reduce fuel burn by 5-7% (Cumming et al., 2016; Pecora, 2021), and reduction in wing structural weight and approach noise is also expected (Giuliani et al., 2022). Morphing wings are incompatible with wingtip devices and highly rigid structures, and they interact with advanced composites.

Structure/Composite Technologies

Structural technologies help decrease aircraft operating empty weight. Composite technologies reduce aircraft structural weight by using materials such as fiber metal laminates, glass fiber, and other materials that can replace traditional metallic materials such as aluminum. Composite structures can be applied to smaller elements, such as elevators, as well as complex structures, like entire wings and fuselage sections.

a. Damage-arresting stitched composites: This technology integrates skins, stiffeners, and joints into condensed composites using stitching, which arrests delamination and improves damage tolerance for a 32-47% increase in flexural improvements with optimized stitch angles (Alaziz et al., 2024). This technology is incompatible with continuous distributed control surfaces.
b. Tow-steered composites: Tow-steered composite ply can be oriented along the curvilinear structure direction compared to straight-fiber laminates, thereby reducing the need for overlap, reducing overall weight with wing weight reduction of 6.3-14% for high aspect wing (Brooks et al., 2017) and fuel burn reduction of 0.4-2.4% (Brooks et al., 2020; Brooks et al., 2017; Stodieck et al., 2017). They are incompatible with damage-arresting stitched composites, unitized metallic structures, and advanced sandwich composites.
c. Advanced load alleviation: Load alleviation on the wings aims to reduce structural requirements by lowering root bending moments by actively using flight control surfaces to counter the bending moment induced by maneuvers or gusts. Advantages include reduced wing weight by reducing the material used to support bending moments, fuel burn reduction between 11 and 13.3% (Breitenstein et al., 2024; Xu & Kroo, 2014), and drag reduction up to 1.8% (Krengel, 2022). This technology requires a fly-by-wire control system, and when combined with laminar flow technology, fuel burn reduction increases notably (Xu & Kroo, 2014).
d. Active structural control: This flight control technology integrates actuators and sensors into an aircraft's wing structure to actively manipulate structural responses. Active structural control enables flexible wings, which enables lighter structures and higher aerodynamic efficiencies. Also, it supports active flutter suppression and gust load alleviation. It achieves a wing weight reduction of 10-20% (Stalla et al., 2024; Takarics et al., 2020) and 1-5% fuel burn reduction (Toffol et al., 2024). It is possibly incompatible with VCCTEF for trailing-edge flap.
e. Advanced sandwich composites: These composites are a structural technology consisting of two thin composite face plates and a lightweight core. The face plates resist in-plane and bending loads, while the core resists transverse forces. Advantages include 5-10% airframe weight reduction depending on the sandwich composite technology. It is incompatible with damage-arresting stitched composites, unitized metallic structures, and tow-steered composites.

Milestones

- Established a correlation between LTAG and IEIR technology impact predictions and identified discrepancies.
- Consolidated technologies mentioned in LTAG, IEIR, and AATT into one database.
- Completed review of aerodynamic technologies and structural technologies that were found common across all three reports.
- Reviewed additional technologies from AATT that were related to core technologies but were not explicitly mentioned either in LTAG not IEIR.

Major Accomplishments

- Reviewed and documented a total of eight aerodynamic technologies, ranging from Riblets, HLFC, and NLFC to Advanced Wing Shape Control technologies that lead to improving aerodynamic performance. These technologies were explored in detail with publications in recent times to reflect newer findings and enable better future aircraft models.
- Reviewed a total of five structural technologies that would help lower the operating weight of the aircraft, either through lighter composite materials, reducing loads carried by the wing, or active control surfaces.

Publications

None.

Outreach Efforts

Attended ASCENT meetings.

Awards

None.

Student Involvement

This task involves two graduate students, Srikanth Tindivanam Varadharajan and Kevin Florian.

Plans for Next Period

- Complete the remaining set of composite technologies. Once all composite technologies have been identified, create a compatibility matrix that accounts for incompatibility between different composite technologies.
- Review other subgroups of technologies under systems integration and flight control.
- Review folding wing tip technology and derive a regression model for wing weight penalty as a function of wing fold location. Use this model to work with Task 2 to explore their infeasible case with relaxed constraints for wingspan.
- Collaborate with Task 3 to add propulsion technology to the database.

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