# Analysis and Optimization of Baseline Single Aisle Aircraft for Future Electrified Powertrain Flight Demonstration Comparisons

Carl J. Recine, Dahlia D. V. Pham, Jeffrey V. Bowles, Kenneth R. Lyons, Benjamin W. L. Margolis, and Joseph A. Garcia

*NASA Ames Research Center, Moffett Field, CA, USA*

**The purpose of this study is to provide baseline single-aisle vehicles for future comparisons with NASA's Electrified Powertrain Flight Demonstration (EPFD) turbofan-powered Vision Systems. State-of-the-art single-aisle transports with varying design capacities of 100 to 150 passengers are modeled using NASA Ames Research Center's General Aviation Synthesis Program (GASP) as well as GASPy. GASPy is a modernized Python-based version of GASP built on the OpenMDAO framework to allow for future, efficient gradient-based optimization and coupled airframe-propulsion design. In order to meet projected NASA Aeronautics goals for 2035, advanced aircraft technologies must be incorporated into these vehicle systems. Methodology to parametrically infuse baseline aircraft models with advanced technologies simulating improvements in aerodynamics, structures, and propulsion systems is detailed, along with the results of technology sensitivity studies. Comparison of the baseline and advanced configurations will allow for future analysis of the benefits of future hybrid and fully electric aircraft concepts in the EPFD project, where fuel consumption and emissions will be modeled and assessed. This study has been conducted under the EPFD project to establish benchmark turbofan models and demonstrate System Analysis capabilities in multi-disciplinary aircraft design, analysis, and optimization for advanced turbofan concepts.**

## Nomenclature

AATT = Advanced Air Transport Technology
APM = Airport Planning Manual
ARC = NASA Ames Research Center
ARMD = Aeronautics Research Mission Directorate
DDTF = Direct Drive Turbofan
EAP = Electric Aircraft Propulsion
EPFD = Electrified Powertrain Flight Demonstration
FPR = Fan Pressure Ratio
GASP = General Aviation Synthesis Program
GRC = NASA Glenn Research Center
GTF = Geared Turbofan
NLF = Natural Laminar Flow
OPR = Overall Pressure Ratio
PRSEUS = Pultruded Rod Stitched Efficient Unionized Structure
SME = Subject Matter Expert
SOTA = State-of-the-Art
TRL = Technology Readiness Level

## I. Introduction

NASA has actively been developing electric aircraft propulsion (EAP) technologies that offer new possibilities for reducing fuel and energy consumption in the civil aviation sector as part of efforts to meet NASA Aeronautics Research Mission Directorate (ARMD) Strategic Thrust goals for the projected subsonic transport vehicles relative to current performance. These performance goals are summarized in NASA's 2019 Aeronautics Strategic Implementation Plan document and shown in Table 1 [11] which show target dates and performance levels for demonstrating the readiness of technologies advanced enough to enable initial application in commercial aircraft; this study will focus on the mid-term goals in the 2025-2035 timeframe.

*Table 1. NASA Targeted Improvements in Subsonic Transport System-level Metrics [11]*

| TECHNOLOGY BENEFITS | TECHNOLOGY GENERATIONS (Technology Readiness Level = 5-6) | | |
|---|---|---|---|
| | Near term 2015-2025 | Mid term 2025-2035 | Far term Beyond 2035 |
| Noise (cumulative below Stage 4) | 22 – 32 dB | 32 – 42 dB | 42 – 52 dB |
| LTO $NO_x$ Emissions (below CAEP 6) | 70 – 75% | 80% | >80% |
| Cruise $NO_x$ Emissions (relative to 2005 best in class) | 65 – 70% | 80% | >80% |
| Aircraft Fuel/Energy Consumption (relative to 2005 best in class) | 40 – 50% | 50 – 60% | 60 – 80% |

To estimate the benefits of using EAP in the year 2035+ time frame for NASA's Electrified Powertrain Flight Demonstration (EPFD) turbofan vision systems, it is important to establish a set of baseline non-electrified vehicle performance models to serve as benchmark cases for future systems analysis efforts. Towards achieving this, the current paper describes a large single-aisle (150-200 passengers) and a small single-aisle (~100 passengers) vehicle generated using NASA's General Aviation Synthesis Program (GASP) [6]. In addition, this paper will utilize GASPy, a modernized Python-based version of the GASP program built on the OpenMDAO framework, that will enable gradient based optimization for future coupled airframe and propulsion optimization problems relevant to the EPFD project.

## II. Modeling Approach

Modeling and simulation of the baseline vehicles was conducted using both GASP and GASPy. GASP is an aircraft synthesis and mission analysis code written in FORTRAN that was developed at NASA Ames in the 1970s. The code was later enhanced at Georgia Tech in the 1990s. [6] It uses engineering-level analysis to perform vehicle sizing and provides an estimate of the vehicle's performance characteristics appropriate for the conceptual design phase. GASPy is a Python-based update of GASP in the OpenMDAO [5] environment and was developed in 2021 without proprietary data tables so it can be made publicly available in the future to the community. There are several advantages to building GASPy in the OpenMDAO environment; most notable is that analytic derivatives are available to the optimizer enabling high degree-of-freedom optimizations. Another benefit is the ease with which other disciplines can be integrated, such as propulsion system modeling with pyCycle [3]. The pyCycle software is a thermodynamic cycle modeling library that was designed to model engine performance and was based on NASA's Numerical Propulsion System Simulation (NPSS) software. The pyCycle software was integrated into GASPy to allow the engine to be optimized along with the airframe.

To meet the performance goals detailed in Table 1, advanced aircraft technologies that improve aerodynamic, structural, and propulsive efficiencies are of interest to the EPFD project, as well as the Advanced Air Transport Technology (AATT) project under NASA ARMD. Within this study, advanced technologies will be incrementally added to the state-of-the-art (SOTA) vehicle models to represent a range of advanced tube-and-wing vehicles with an entry into service of approximately 2035. Technology factors within GASP were applied to account for advanced composites, aerodynamic improvements, and advanced geared turbofans, a capability recently added in 2022. The baseline reference aircraft models along with the methodology used to create the advanced configurations will be used as benchmark cases for novel EAP-enabled concepts developed under the EPFD project. Additionally, the sensitivity to changes in technology can provide information about which areas are important to focus on for both risk reduction and technology development. For the sake of simplicity, and to align with the EPFD goals, mission block fuel will be used as the merit function to be optimized. In future vehicle comparisons, noise, $NO_x$ emissions, and life-cycle cost will also be included, but are not included in this paper.

Establishing and optimizing baseline vehicles for a particular entry into service is beneficial for the EPFD project because it will provide a basis for any predicted benefit of future electrified aircraft. This ensures that predicted benefits are a result of Electrified Aircraft Propulsion (EAP) and are not simply the result of a delayed entry into service. It is important not to improperly attribute the advantage of technological developments that would also benefit a conventional tube and wing aircraft at that time.

## III. Reference Turbofan Vehicles and Calibration of Vehicle Models

The two existing turbofan vehicles that were chosen as baselines are summarized in Table 2. The Boeing 737 Max 8, with 2017 Entry into Service, was chosen as the state-of-the-art large single-aisle aircraft. The 737 Max 8 can carry 189 passengers for approximately 2,900 nautical miles. The E190-E2 is a regional jet that has been used since 2018, it will be used as the state-of-the-art for a small single-aisle aircraft. The E190-E2 can carry 104 passengers and has a design range of 3,337 nautical miles. These vehicles have been compared to and calibrated against available data. Performance data and a detailed weight breakdown will provide the primary metrics that will be assessed to check the accuracy of our baseline models.

*Table 2. Summary of Baseline Aircraft*

| | Boeing 737 MAX 8 | Embraer E190-E2 |
|---|---|---|
| **MTOW (lbf)** | 176,254 | 124,341 |
| **Engine** | CFM LEAP-1B | PW1922G |
| **Thrust (lbf/engine)** | 28,928 | 23,800 |
| **Cruise Mach** | 0.8 | 0.78 |
| **Cruise Altitude (ft)** | 35,000 | 35,000 |
| **Design Range (NM)** | 2,900 | 3,337 |
| **Passengers** | 189 | 104 |
| **Weight per Passenger (lbf)** | 225 | 220 |
| **Payload Weight (lbf)** | 42,525 | 22,880 |

### Boeing 737 Max 8

Using the payload-range diagram provided by the Boeing 737 Max 8's Airport Planning Manual (APM) [1] as shown in Figure 1, and assuming that all 189 seats are filled, we are able to approximate the maximum range for a mission and the fuel required. A GASP model of the 737 MAX 8 was then developed for a 2,900 nautical mile mission with 189 passengers.

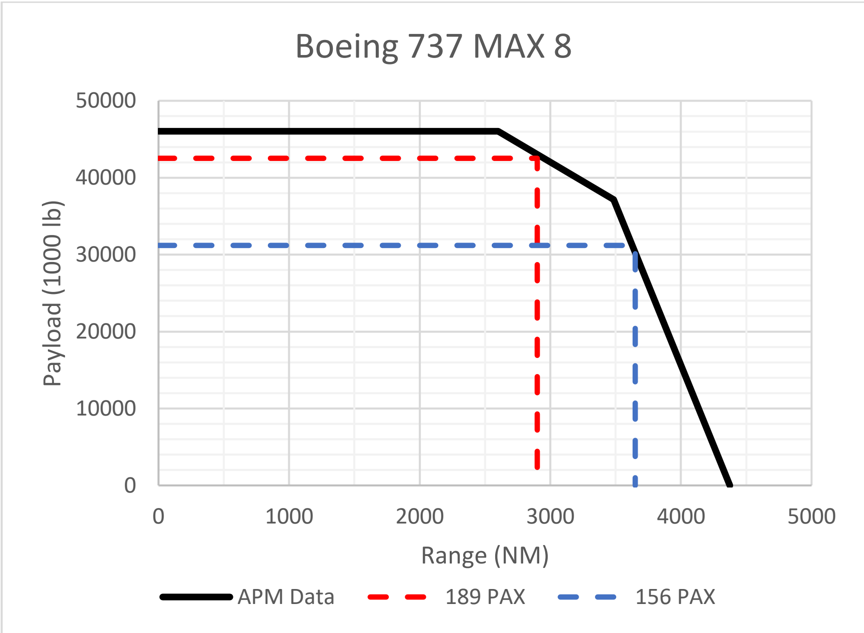


*Figure 1. Boeing 737 MAX 8 Payload-Range Diagram [**Error! Reference source not found.**]*

Comparison of the closed GASP model closely matched Boeing's reported values to within 1.25% as shown in Table 3 below. This provided confidence in our modelling method and allowed us to proceed with modeling the vehicle in GASPy.

*Table 3. Boeing 737 Max 8 Key Characteristics*

| 737 MAX 8 | APM [1] | GASP | % Diff |
|---|---|---|---|
| **GTOW (lbf.)** | 182,200 | 181,700 | 0.27% |
| **Fuel Weight (lbf.)** | 40,315 | 39,814 | 1.24% |
| **Range (NM)** | 2900 | 2885 | 0.52% |
| **Wingspan (ft.)** | 117.83 | 117.4 | 0.36% |
| **Fuselage Length (ft.)** | 128.25 | 128.4 | -0.12% |
| **SLS Thrust (lbf./engine)** | 28,690 | 28,690 | 0% |

Table 4 provides a comparison of the GASP weight breakdown in pounds (lbs.) to the GASPy results to validate the new method which shows excellent agreement with approximately 3% differences at the group level. Although individual components may have larger percent differences, they are on the order of several hundred pounds, which represents a fraction of a percent of the overall aircraft weight. Details of validation of the GASPy software to GASP for the 737 MAX 8 can be found in reference 9.

*Table 4. Computed Baseline Boeing 737 Max 8 Weight Breakdown*

| System (lbf.) | GASP | GASPy | % Diff |
|---|---|---|---|
| **Propulsion Group** | **15,853** | **15,811** | **0.26** |
| Primary engines | 12,260 | 12,260 | 0.00 |
| Engine Installation | 1,716 | 1,716 | 0.00 |
| Fuel System | 1,877 | 1,835 | 2.24 |
| **Structures Group** | **53,275** | **53,376** | **-0.19** |
| Wing | 16,578 | 16,420 | 0.95 |
| Horizontal Tail | 2,275 | 2,387 | -4.92 |
| Vertical Tail | 1,872 | 1,805 | 3.58 |
| Fuselage | 21,593 | 21,274 | 1.48 |
| Landing Gear | 7,268 | 7,797 | -7.28 |
| Engine Section | 3,689 | 3,693 | -0.11 |
| **Flight Controls Group** | **3,901** | **3,963** | **-1.59** |
| **Fixed Equipment** | **21,176** | **21,317** | **-0.67** |
| **Empty Weight** | **94,205** | **94,467** | **-0.28** |
| **Fixed Useful Load** | **5,156** | **5,321** | **-3.20** |
| **Mission Block Fuel** | **39,814** | **39,880** | **-0.17** |
| **Payload** | **42,525** | **42,525** | **0.00** |
| **Gross TO Weight** | **181,700** | **182,193** | **-0.27** |

Embraer E190-E2

The same validation and calibration process was used for the smaller Embraer E190-E2 vehicle. Using the payload-range diagram provided by the E190-E2 APM [**Error! Reference source not found.**] as shown in Figure 2 and assuming all 104 seats of the aircraft are occupied, the range and fuel consumption can be approximated. Key aircraft dimensions and performance characteristics were cited from the APM and compared against values obtained from GASP.

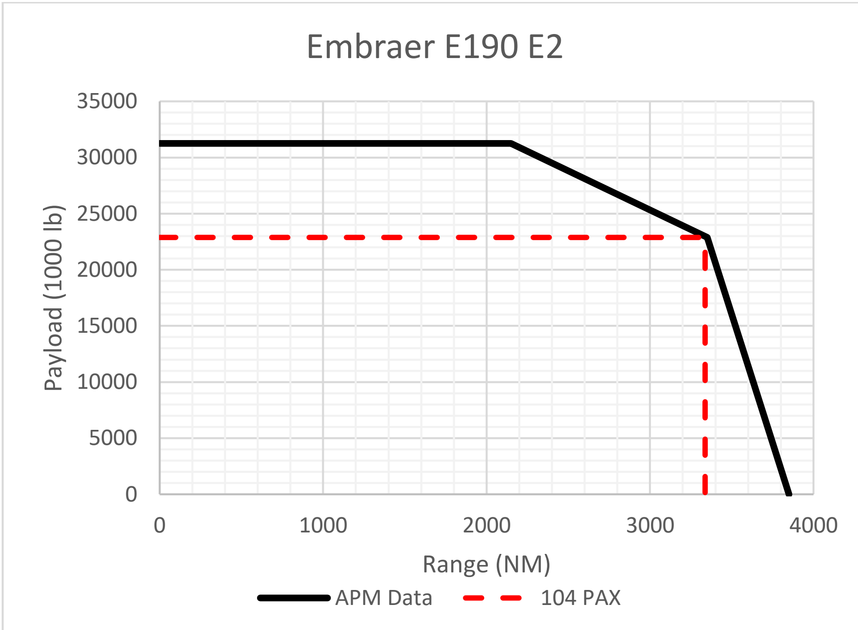


*Figure 2. Embraer E190-E2 Payload-Range Diagram [**Error! Reference source not found.**]*

The E190-E2 vehicle model synthesized in GASP closely matches the values reported by Embraer in the APM within a margin of 3.00%. Table 5 shows the comparison of the vehicle parameters, where GASP's sizing module approximates the range as 3,358 nautical miles, which is within 1% of the reported value for range.

*Table 5. Embraer E190-E2 Key Characteristics*

| E190-E2 | APM [Error! Reference source not found.] | GASP | % Diff |
|---|---|---|---|
| **GTOW (lbf.)** | 124,341 | 123,358 | 0.80% |
| **Fuel Weight (lbf.)** | 29,760 | 30,642 | -2.88% |
| **Range (NM)** | 3,337 | 3,358 | -0.63% |
| **Wingspan (ft.)** | 110.6 | 110.6 | 0% |
| **Fuselage Length (ft.)** | 119.19 | 119.5 | -0.26% |
| **SLS Thrust (lbf./engine)** | 23,800 | 23,800 | 0% |

Similar to the Boeing 737 Max 8 validation and calibration results, the E190-E2 model synthesized in GASP compares favorably to the reported parameters in the APM. A detailed weight breakdown was performed for the E190-E2, where Table 6 contains the comparison of the GASP weight breakdown in pounds (lbs.) to the GASPy results for the E190-E2. The results show that all groups are within a 5% margin, except for the flight control group which is 7.85% larger in GASP than GASPy. However, this is only a 222-pound difference out of the gross takeoff weight of 123,358 pounds.

*Table 6. Computed Baseline E190-E2 Weight Breakdown*

| System (lbf.) | GASP | GASPy | % Diff |
|---|---|---|---|
| **Propulsion Group** | **12,754** | **12,724** | **0.24** |
| Primary engines | 10,248 | 10,248 | 0.00 |
| Engine Installation | 1,435 | 1,435 | 0.00 |
| Fuel System | 1,071 | 1,041 | 2.80 |
| **Structures Group** | **35,672** | **35,142** | **1.49** |
| Wing | 12,776 | 12,583 | 1.51 |
| Horizontal Tail | 1,716 | 1,685 | 1.81 |
| Vertical Tail | 940 | 925 | 1.60 |
| Fuselage | 13,015 | 12,784 | 1.77 |
| Landing Gear | 4,848 | 4,789 | 1.22 |
| Engine Section | 2,376 | 2,375 | 0.04 |
| **Flight Controls Group** | **2,827** | **2,698** | **4.56** |
| **Fixed Equipment** | **15,901** | **15,848** | **0.33** |
| **Empty Weight** | **67,154** | **66,412** | **1.10** |
| **Fixed Useful Load** | **3,723** | **3,751** | **-0.75** |
| **Mission Fuel** | **32,162** | **31,254** | **2.82** |
| **Payload** | **21,840** | **21,840** | **0.00** |
| **Gross TO Weight** | **123,358** | **122,114** | **1.01** |

## IV. Advanced Technologies Trade Study

The impacts of advanced technologies on top-level aircraft performance metrics were studied by parametrically infusing the baseline vehicle models with the estimated technology improvements from a portfolio of technologies mentioned in the FY2019 AATT technologies report [10]. A technology buildup trade study was performed for both reference vehicles. It is projected that the application of advanced technologies within the categories of materials, aerodynamics, and propulsion can reduce fuel consumption and operating costs when added to the baseline SOTA vehicles. Current approximations for improvements in these technologies were obtained in accordance with expected improvements by 2035 based on a variety of studies. The technology matrix and implementation of these benefits in GASP are shown in Table 7.

*Table 7. Advanced Technology Assumptions*

| Category | Technology | Impact (min, median, max) |
|---|---|---|
| **Aerodynamics** | **Riblets (wing)** | **Reduction in skin friction drag (4%, 5%, 8%) [13]** |
| | **Riblets (fuselage)** | **Reduction in skin friction drag (1%, 2%, 6%) [13]** |
| | **NLF (wing)** | **Reduction in profile drag (0%, 6.22%, 8.79%) [16]** |
| | **Excrescence Reduction** | **Reduction in excrescence drag (0%, 50%, 100%)** |
| **Structure** | **PRSEUS (wing)** | **Reduction in structural weight (21%, 26%, 39%) [8]** |
| | **Active Load Alleviation** | **Reduction in load factor used for sizing (0, 41%, 47%) [12]** |
| **Propulsion** | **GRC Geared Turbofan** | **Uncertainty on advanced model weight (-5%, 0%, 5%) [4]** |

| | Advanced Engine Cycle | Uncertainty on advanced model TSFC (-5%, 0%, 5%) [4] |
|---|---|---|

**Advanced Aerodynamics:**

A variety of advanced aerodynamic technologies were considered. Both riblets and NLF were considered; however, riblets reduces drag associated with turbulent flows, and thus are incompatible with laminar flow. Additionally, NLF performance is severely impacted by off-design and icing conditions which makes it a high sensitivity technology. On the other hand, riblets have been applied to the surfaces of large single-aisle aircraft such as the Airbus A320 and several Boeing 777F airliners as recently as 2023. Ultimately, riblets were chosen for both the small and large single-aisle aircraft, due to the sensitivity of NLF performance in off-design and icing conditions [16]. Although NLF offers the potential for greater drag reduction compared to riblets, riblets offer more consistent benefits. Excrescence reduction was also considered, assuming that new manufacturing techniques would be able to reduce drag by eliminating or reducing the impact of rivets, panel gaps, and other excrescences.

**Advanced Structures:**

Advanced composite structures offer the potential for significant operating empty weight reduction and thus, reduced fuel consumption and emissions. An example of advanced composites technology with applications to aeronautics includes Pultruded Rod Stitched Efficient Unitized Structure (PRSEUS) composites. PRSEUS [**Error! Reference source not found.**,8] uses built in stringers and stitched interfaces to create seamless transitions and eliminate the need for many joints and fasteners. This results in a structure that is stronger and lighter than traditional composites. Additionally, the damage arresting nature of PRSEUS structures allows for safe operation in the case of failure, similar to current aluminum designs. When structural designs can continue to function even after buckling, which PRSEUS has demonstrated during testing, structural weight can be reduced as individual members are allowed to carry higher loads. Conversations with a subject matter expert (SME) from NASA [8] suggested a 26% weight savings relative to aluminum wings for turbofan aircraft. Because composites are generally more expensive to produce, aircraft fuselages were assumed to continue to be aluminum in the 2035 timeframe, as such, PRSEUS weight savings have only been applied to the wing. Finally, there are no revolutionary technologies that are currently expected to have a significant impact on the design and weight of landing gear on conventional tube and wing aircraft.

**Advanced Engines:**

For this study, NASA Glenn Research Center (GRC) provided a family of turbofan engines with a technology level consistent with an entry into service of roughly 2035. The engine family included both geared turbofan (GTF) and direct drive turbofans with a variety of fan pressure ratios. The geared turbofan with a fan pressure ratio (FPR) of 1.45 was selected as the advanced engine that would be used for the advanced 737, while a GTF with an FPR of 1.50 was selected for the E190-E2 [**Error! Reference source not found.**].

The uncertainty on each of the technology benefits was modeled with a Monte Carlo analysis that ran 10,000 cases per technology combination. Figure 3 shows the convergence of the medians by plotting the absolute value of the percent difference between the current set of cases and the previous one. For example, the point for Empty Weight at 5,000 cases indicates that the increasing the number of cases from 1,000 to 5,000 resulted in a change of approximately 0.01% for the median value.

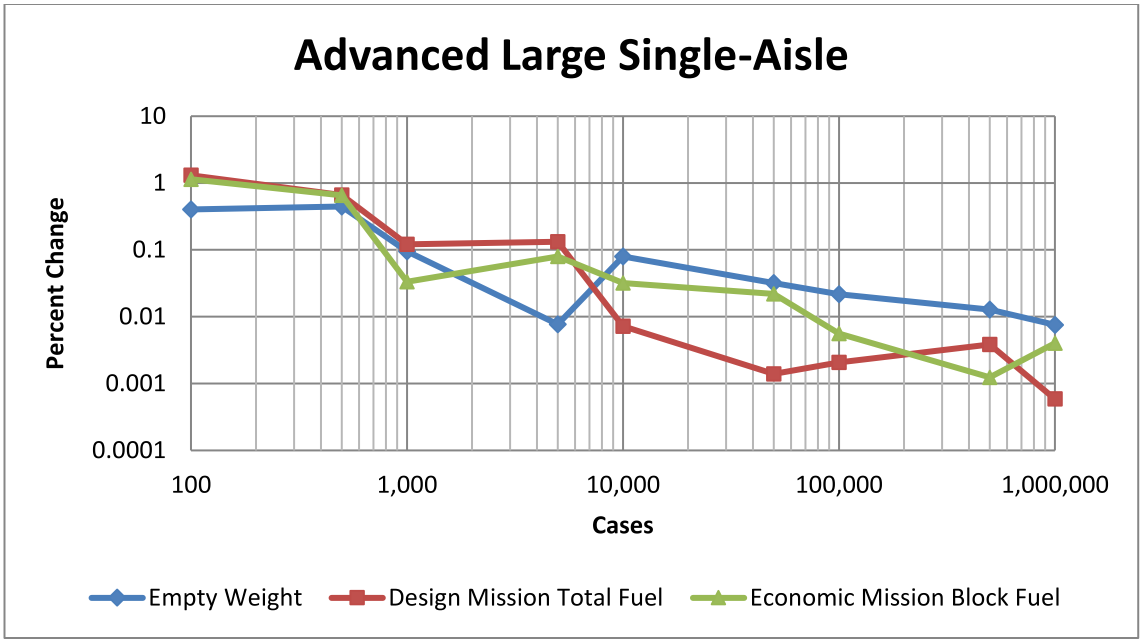


*Figure 3. Change in Median Relative to Last Set*

The Air-Breathing Propulsion System Analysis Branch at Glenn Research Center (GRC-LTA0) produced engine decks that contained the thrust, fuel flow, and required airflow each as a function of Mach, altitude, and engine throttle. Also provided were several key parameters that GASP needed for engine sizing [4]. Table 8 shows a comparison of the direct drive LEAP-1B engine that is standard on the 737 MAX 8 and the advanced GTF engine.

*Table 8. Comparison of LEAP-1B and GRC advanced GTF engine*

| Engine Parameter | Baseline LEAP-1B | Advanced FPR 1.45 | Advanced FPR 1.50 |
|---|---|---|---|
| Fan Pressure Ratio | 1.45 | 1.45 | 1.50 |
| Bypass ratio | 9.0 | 13.8 | 11.7 |
| OPR | 45 | 49 | 49 |
| $T4_{MAX}$ (°R) STD+27° | 3280 | 3200 | 3300 |
| SLS Thrust (lbf) | 29,500 | 28,620 | 23,800 |
| Thrust Lapse (39Kft / Mach 0.80 to SLS) | 0.155 | 0.203 | 0.188 |
| Fan Diameter (in) | 69.4 | 88.3 | 67.0 |
| SLS Airflow (lb/sec) | 995 | 1400 | 1002 |
| Engine Weight (lbs) | 6130 | 6740 | 5945 |
| Bare Engine Thrust-to-Weight | 4.76 | 4.25 | 4.51 |
| TSFC@M0.8/39Kft (lb/hr/lb) | 0.548 | 0.513 | 0.518 |

The advanced geared turbofan has a higher bypass ratio and larger fan diameter than the direct drive LEAP-1B. Although it is heavier compared to the baseline turbofan and has a lower thrust to weight ratio, the advanced geared turbofan (GTF) has lower thrust-specific fuel consumption. Additionally, the GTF has a lower turbine inlet temperature, which typically corresponds to a longer service life.

Table 9 shows the result of the technology build up for the 737 MAX 8 based vehicle by applying all the median values of the respective advancements outlined in Table 7. For the SOTA vehicle, an engine with the same technology as the LEAP-1B was used, but the vehicle was allowed to resize the engine to minimize fuel burn. In each of the combinations of the advanced technologies, the vehicle was reclosed for 189 passengers, 2,900 nautical miles, and holding all fuel in the wings. For any aircraft with a wingspan greater than 118 feet, a wing fold, and associated weight penalty, was added to the model.

*Table 9. Large Single-Aisle Advanced Technology comparison to SOTA*

| Parameter | SOTA: B737 Max 8 LEAP 1B | Advanced: B737 FPR 1.45 GTF | % Improved |
|---|---|---|---|
| Gross TO Weight (lbs) | 175,858 | 163,385 | -7.09% |
| Empty Weight (lbs) | 87,930 | 82,836 | -5.79% |
| Wing Aspect Ratio | 8.83 | 10 | 13.25% |
| Span (ft) | 105.3 | 106.8 | 1.42% |
| Wing Loading (psf) | 140.1 | 143.2 | 2.21% |
| Engine SLS Thrust ($lb_f$) | 22,012 | 21,393 | -2.81% |
| Engine Sizing Condition | OEI Climb Rate | Cruise Drag | |
| T.O. T/W | 0.250 | 0.262 | 4.61% |
| Flat Plate Area ($ft^2$) | 25.04 | 22.15 | -11.54% |
| Cruise Altitude (ft) | 35,000 | 32,600 | -6.86% |
| Cruise CL | 0.611 | 0.56 | -8.35% |
| Cruise L/D | 17.96 | 18.67 | 3.95% |
| Cruise TSFC ($lb_f/hr/lb_f$) | 0.5662 | 0.5169 | -8.71% |
| Part 25 AEO TOFL (ft) | 8,461 | 8,522 | 0.72% |
| Approach Speed (KEAS) | 151.5 | 150.9 | -0.40% |
| Design Mission Total Fuel Load (lb) | 40,340 | 32,989 | -18.22% |

Table 10 includes the results of a similar build up for the small single-aisle aircraft that was based on the E190-E2. Again, the SOTA aircraft used an engine with the same technology as an E190-E2, but that engine was allowed to resize for optimum fuel burn. All vehicles in the buildup were closed to carry 104 passengers for 3,300 NM with all fuel in the wings. None of the aircraft had wingspans greater than 118 ft, so no wing folds were necessary.

*Table 10. Small Single-Aisle Advanced Technology comparison to SOTA*

| Parameter | SOTA: E190-E2 PW1922G | Advanced: E190 FPR 1.50 GTF | % Improved |
|---|---|---|---|
| **Gross TO Weight (lbs)** | 125,888 | 113,592 | -9.77% |
| **Empty Weight (lbs)** | 65,894 | 58,912 | -10.60% |
| **Wing Aspect Ratio** | 11.03 | 11.03 | 0.00% |
| **Span (ft)** | 111.0 | 105.5 | -4.95% |
| **Wing Loading (psf)** | 112.6 | 112.6 | 0.00% |
| **Engine SLS Thrust ($lb_f$)** | 20,640 | 17,406 | -15.67% |
| **Engine Sizing Condition** | Cruise Drag | Cruise Drag | |
| **T.O. T/W** | 0.328 | 0.306 | -6.54% |
| **Flat Plate Area ($ft^2$)** | 21.47 | 19.29 | -10.14% |
| **Cruise Altitude (ft)** | 33,500 | 37,500 | 11.94% |
| **Cruise CL** | 0.484 | 0.582 | 20.25% |
| **Cruise L/D** | 17.57 | 18.7 | 6.43% |
| **Cruise TSFC ($lb_f$/hr/$lb_f$)** | 0.5391 | 0.5083 | -5.71% |
| **Part 25 AEO TOFL (ft)** | 6,341 | 6,720 | 5.98% |
| **Approach Speed (KEAS)** | 140.7 | 140.5 | -0.14% |
| **Design Mission Total Fuel Load (lb)** | 30,612 | 25,363 | -17.15% |

Starting with the baseline configuration, each category of technologies was applied individually to assess impacts on weight. An advanced configuration with just structural and aerodynamic improvements was considered as well, to represent a case where advanced engines are either not ready for certification or are prohibitively expensive. Finally, a fully advanced vehicle was considered as well. As projecting the benefits achievable from advancements in technology 10-15 years in the future is highly uncertain, ranges were used for each of the advanced technologies. In the box and whisker portion of **Error! Reference source not found.**, the whiskers represent the 5$^{th}$ and 95$^{th}$ percentiles rather than the minimum and maximum points in order to minimize the impact of any outliers created during the Monte Carlo analysis. For the 900 NM economic mission, the results presented are for the mission block fuel instead of the total fuel load. The total fuel load includes the Part 121 reserves in addition to the block fuel; for the shorter mission, the reserve fuel is a significant portion of the total fuel which causes it to obscure some of the benefits to fuel burn reduction.

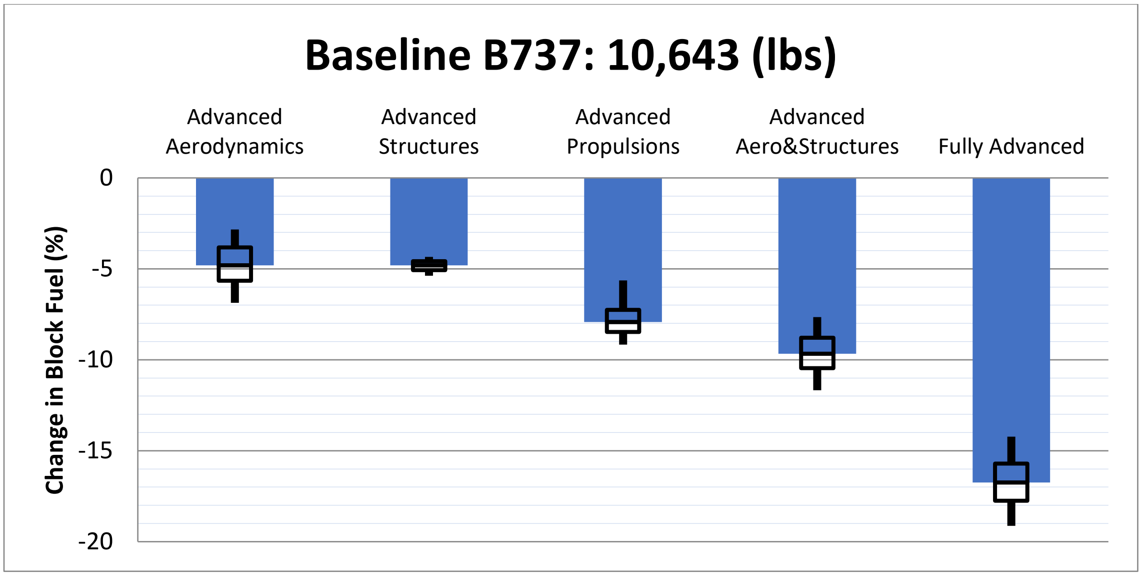


*Figure 4. Fuel Burn Reduction for 900 NM Mission*

**Error! Reference source not found.** shows the benefits on economic mission fuel burn from individual technologies as well as the cumulative benefits. **Error! Reference source not found.** demonstrates that the uncertainty bars are wide enough that the order of the most impactful technologies could change. Additionally, it indicates that even with the least optimistic projections, at least 15% fuel savings could be realized by 2035 without including EAP.

The weight breakdown of each configuration studied during the technology buildup is shown in Figure 5. As expected, the use of advanced composites had the greatest contribution to reducing structural weight. Additionally, the advanced geared turbofan had the greatest effect on fuel savings.

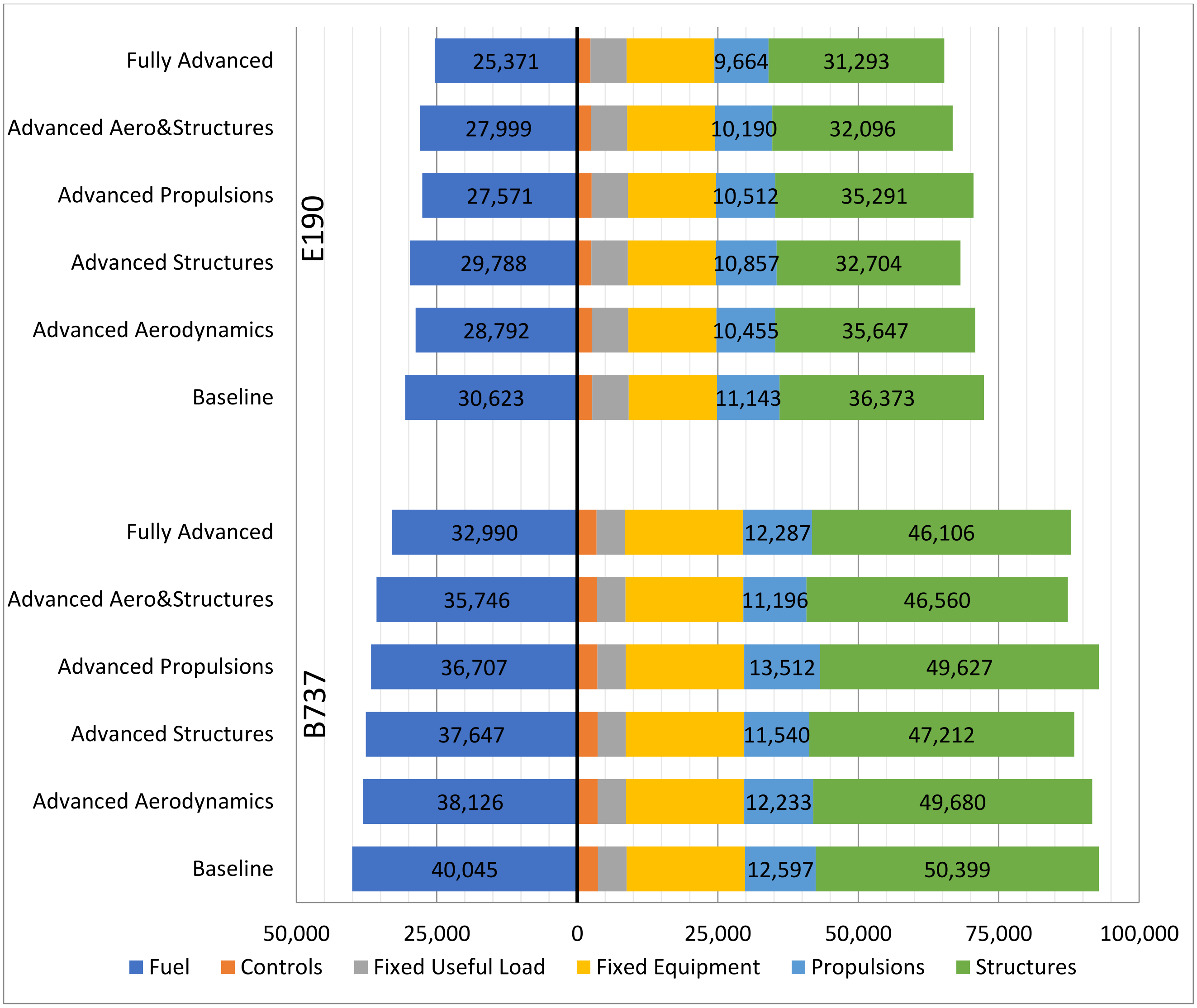


*Figure 5. Weight Breakdown from Technology Buildup for the Single-Aisle Vehicles*

Several interesting interactions can be observed from the weight breakdown. Although the advanced engines result in an increased empty weight for the large single aisle, they did result in significant fuel savings. This benefit is further improved by drag reduction technologies that decrease the amount of thrust required during cruise. As with the large single-aisle, advanced propulsion provided the greatest fuel burn reduction; however, for the small single-aisle, advanced aerodynamics offered more of a benefit than the advanced structures.

Application of advanced aerodynamics reduces the skin friction drag on applied components, which results in reduced fuel consumption and thus lower emissions and operating costs. However, there is an increased structural weight from the application of certain drag reduction technologies: high aspect ratio wings are susceptible to higher loads which impacts the weights and require support for a higher wingspan. Additionally, certain drag reduction technologies involve application of passive and active systems to enable the reduction in skin friction, which contributes to the weight.

## V. Conclusions

In this paper, baseline state-of-the-art single-aisle turbofan aircraft models based on the Boeing 737 Max 8 and Embraer E190-E2 were established as references vehicles for future comparisons to the vision systems being developed under NASA's Electrified Powertrain Flight Demonstration (EPFD) project. It was determined that compared to the performance reported by the manufacturers, the vehicles synthesized by using NASA Ames Research Center's General Aviation Synthesis Program (GASP) compared favorably, with acceptable differences, between published and modeled values. Results from GASP were then compared to the modernized, Python-based version of the program GASPy where it was determined that the estimated weights, key performance metrics, and general performance predictions were also within acceptable agreement.

A trade study was performed on these reference vehicles to understand the potential performance benefits of incorporating advanced technologies into these vehicles. When combining all advanced technologies, there is a significant impact on fuel burn that results from more efficient engines, thinner wings, and lighter structure. If all available advanced technologies, with the exception of electrified propulsion, are incorporated into the large single-aisle aircraft using expected 2035 technologies, a 15-20% reduction in fuel consumption during the design mission and 14-19% for the short-range mission is shown to be possible. Similarly, the small single-aisle aircraft shows reduced design mission fuel consumption by 18-25% and a reduction in short-range fuel of 17-24%.

## References:


1. "Boeing 737 MAX Airplane Characteristics for Airport Planning – Rev. G," May 2022.
2. "E-JETS E2 Airport Planning Manual – Rev. 21", September 2017.
3. E. S. Hendricks and J. S. Gray, "Pycycle: a tool for efficient optimization of gas turbine engine cycles," *Aerospace*, vol. 6, iss. 87, 2019.
4. Glenn Research Center, Air-Breathing Propulsion System Analysis (GRC-LTA0), "Geared Turbofan Engine Performance Model", 2021.
5. Gray, J. S., Hwang, J. T., Martins, J. R., Moore, K. T., and Naylor, B. A., "OpenMDAO: An open-source framework for multidisciplinary design, analysis, and Optimization," *Structural and Multidisciplinary Optimization*, vol. 59, 2019, pp. 1075–1104.
6. Hague, D., "GASP – General Aviation Synthesis Program. Volume 1: Main Program. Part 1: Theoretical Development," Tech. Rep. NASA-CR-152303-VOL-1-PT-1, National Aeronautics and Space Administration, Jan. 1978.
7. Jegley, D. and Velicki, A., "Status of advanced stitched unitized composite aircraft structures," in 51st AIAA Aerospace Sciences Meeting, Grapevine, TX, 2013, AIAA 2013-0410.
8. Jegley, D., "Weight Reduction from the Use of PRSEUS Composites," 4/27/2021.
9. Lyons, K.R., Margolis, B.W.L., Bowles, J.V., Gratz, J.D., Schnulo, S.L., Aretskin-Hariton, E.D., Gray, J.S., Falk, R.D., "Advancement of the General Aviation Synthesis Program Using Python to Enable Optimization-Based Hybrid-Propulsion Aircraft Design", *submitted for publication at the 2023 AIAA/EATS conference.*
10. Mavris, D. et al., " FY2019 Advanced Air Transportation Technologies Systems Analysis Report: Technology Portfolio," Georgia Tech Aerospace Systems Design Laboratory, 2019.
11. NASA Aeronautics Research Mission Directorate (ARMD), "Strategic Implementation Plan," 2019.
12. Pham, D.D.V., Bowles, J.V., Recine, C.J., and Go, S., "Advanced Turboprop Transport Aircraft Modeling for the Electrified Powertrain Flight Demonstrator Program", *submitted for publication at the 2023 AIAA/EATS conference.*
13. P.R Viswanath, "Aircraft viscous drag reduction using riblets," in Progress in Aerospace Sciences, Volume 38, Issues 6–7, 2002, Pages 571-600, ISSN 0376-0421
14. R. Hansman, "Peformance degradation of natural laminar flow airfoils due to contamination by rain or insects", OSTIV Publications, Vol. 9, No. 3, 1985
15. Velicki, A. and Jegley, D., "PRSEUS Structural Concept Development," in AIAA Aerospace Sciences Meeting, National Harbor, MD, 2014, AIAA 2014-0259.
16. Zhong-Hua Han, Jing Chen, Ke-Shi Zhang, Zhen-Ming Xu, Zhen Zhu, and Wen-Ping Song "Aerodynamic Shape Optimization of Natural-Laminar-Flow Wing Using Surrogate-Based Approach", AIAA JOURNAL Vol. 56, No. 7, July 2018 DOI: 10.2514/1.J056661