Advanced 2030 Turboprop Aircraft Modeling for the Electrified Powertrain Flight Demonstration Program

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***Abstract*—Electrified aircraft propulsion concepts are rapidly emerging due to their huge potential in fuel saving and mitigating negative environmental impact. In order to perform a linear technology progression and fairly assess the impacts of powertrain electrification, it is important to first establish parametric state-of-the-art baseline vehicle models with advanced technologies matured by 2030. For a thin haul (19-passenger) turboprop size class and a regional turboprop (50-passenger) size class, a current state-of-the-art technology reference aircraft (TRA) is identified and modeled using a multi-disciplinary analysis and optimization environment. Viable technologies for airframe and conventional propulsion system are then identified which are expected to be available by 2030. These technologies are parametrically infused in the TRA models to create advanced technology aircraft models, which will serve as the baseline models for future studies of powertrain electrification.**

I. Introduction

Integrated electrified aircraft propulsion (EAP) concepts, which have been under development by NASA and industry for over a decade, are rapidly emerging as potentially transformative concepts are applied to propulsion systems. NASA is investigating the utilization of flight demonstrations to rapidly mature and transition integrated EAP technologies and associated EAP-based vision systems for introduction into the US fleet no later than 2035. In order to isolate the impacts of powertrain electrification, it is important to first establish parametric state-of-the-art baseline vehicle models, which is the goal of this paper.

Specifically, two size classes are of interest with the turboprop configuration: the thin haul airliner and the regional airliner, which carry about 19 and 50 passengers, respectively. For each size class, a technology reference aircraft (TRA) model is first created based on the public domain data of an existing commercial airliner (Sec. III). Then, viable technologies are identified which are estimated to mature by 2030 (Sec. IV). These technologies are subsequently infused on the both TRA models with airframe and engine resizing to establish advanced technology aircraft (ATA) models (Sec. V), which will serve as the baseline models in future studies of powertrain electrification. The work presented in this paper builds on previous work by Cinar et al. [1], who explored the design space for similar thin-haul regional aircraft with EAP. This paper improves the results of the baseline modeling which align better with the scope of the Electrified Powertrain Flight Demonstration Program.

II. Aircraft Modeling & Simulation Environment

In this study, both the TRA and the ATA models are set up using Electrified Propulsion Architecture Sizing and Synthesis (E-PASS) [2], [3], a MATLAB-based multi-disciplinary analysis and optimization environment which enables the design and performance evaluation of aircraft concepts with any type of propulsion system architecture.

E-PASS is initialized by the following sets of parametric inputs: top level aircraft requirements, initial vehicle configuration and layout, design mission profile, propulsion system architecture definition, and power management strategy. These inputs for the TRA and the ATA models are presented in the following sections. This information is passed on to the disciplinary and mission analysis blocks. The disciplinary analysis block is comprised of regression-based functions and physics-based models are used to estimate the weight breakdown, aerodynamics, and propulsion performance of the given vehicle. The energy-based mission analysis block calculates the vehicle state and performance throughout the mission profile by using the force balance equations. Nested iterations between the disciplinary and mission analysis blocks take place within the sizing process until a vehicle design which satisfies all the top level aircraft requirements is obtained.

The output of E-PASS is a fully sized vehicle with detailed information about the vehicle's geometry, weight breakdown, drag polar, propulsion system properties, and a time-history of the flight mission.

While this paper primarily focuses on the calibration of baseline models and infusion of advanced technologies, the reader is referred to a relevant paper for more detail regarding the electrified aircraft modeling and simulation environment [4].

TABLE I
GENERAL SPECIFICATIONS OF SELECTED TECHNOLOGY REFERENCE AIRCRAFT

Item	Thin Haul Airliner	Regional Airliner
Reference aircraft	B1900D	ATR 42-600
Source of data	[5], [6]	[7], [8]
Design capacity	19 pax	48 pax
Design payload (kg)	1896	4560
Design range (nmi)	382	703
Reserve range (nmi)	100	150
Cruise altitude (ft)	25 000	25 000
Cruise speed (keas)	167	200
Wing loading (kg/m^2)	271.4	341.3
Power-to-weight ratio (kW/kg)	0.2441	0.1731
Maximum takeoff weight (kg)	7815	18 600
Operating empty weight (kg)	4932	11 700
Fuselage length (m)	17.6	22.7
Wing planform area (m^2)	28.8	54.5
Wing span (m)	17.6	24.6
Wing aspect ratio	10.0	11.1
Wing taper ratio	0.418	0.492
Wing quarter-chord sweep (deg)	0	2.3
Horizontal tail planform area (m^2)	6.32	11.4
Vertical tail planform area (m^2)	4.86	16.2
Engine (2x)	PT6A-67D	PW127M
Rated power, each (kW)	954	1610
Propeller diameter (m)	2.79	3.93
Propeller blades	4	6
Propeller speed, takeoff (RPM)	1700	1200
Propeller speed, in-flight (RPM)	1550	984

III. TECHNOLOGY REFERENCE AIRCRAFT MODEL DEVELOPMENT

A literature review is conducted for both the 19-pax thin-haul airliners and the 50-pax regional airliners to identify the best candidates as the TRA. For each size class, the TRA is selected based on the following criteria:

- **Technology level**: The candidate should be equipped with technologies close to the current state-of-the-art;
- **Data availability**: There should be sufficient data of the candidate in the public domain to allow calibration regarding the weight build-up and mission performance;
- **Market share**: When multiple candidates satisfy the above two criteria, the one claiming relatively high market share should be selected.

A. Specifications of Thin Haul Turboprop Technology Reference Aircraft

The Beechcraft B1900D entered commercial services in the 1990s as the latest variant of the B1900 family and one of the most popular 19-pax airliners. Equipped with two Pratt & Whitney Canada PT6A-67D turboprop engines certified in 1994 [6], it is able to carry 19 passengers over a distance of 707 km (382 nmi). The specifications of the B1900D used for model calibration are presented in Table I. The mission profile is briefly described as follows, where an asterisk (*) denotes segments without distance credit:

1) **Taxi-out***: Taxi for 6 min
2) **Takeoff***: Take off and initial climb from sea level to 1500 ft for 1 min
3) **Climb**: Climb to 10 000 ft at 160 KEAS, then to 25 000 ft while linearly decelerating to 130 KEAS
4) **Cruise**: Level cruise at 167 KEAS
5) **Descent**: Descend to sea level at 200 KEAS and a vertical speed of 1500 ft/min
6) **Approach**: Descend to 1500 ft at a vertical speed of 750 ft/min while decelerating to 160 KEAS
7) **Missed approach***: Missed approach and climb to 5000 ft at 160 KEAS
8) **Hold***: Level cruise at 160 KEAS for 5 min
9) **Reserve climb**: Climb to 15 000 ft using the same speed schedule as in the primary climb segment
10) **Diversion**: Level cruise at 160 KEAS
11) **Reserve***: Level cruise at 160 KEAS for 45 min
12) **Reserve descent**: Descend to 5000 ft at 200 KEAS and a vertical speed of 1500 ft/min
13) **Reserve approach***: Descend to 1500 ft at a vertical speed of 750 ft/min while decelerating to 160 KEAS
14) **Landing***: Final approach and landing for 3 min
15) **Taxi-in***: Taxi for 4 min

B. Specifications of Regional Turboprop Technology Reference Aircraft

The ATR 42-600 is the only 50-pax turboprop airliner still in production. As the latest member of the ATR 42 family, it features essentially the same airframe design and seating capacity as the original ATR 42 in the 1980s, with some improvements in the aerodynamic characteristics, avionics, and cabin design. It is equipped with two Pratt & Whitney Canada PW127M turboprop engines certified in 2007 [8] which is de-rated to the same power as the PW127E, and is able to carry 48 passengers over a distance of 1302 km (703 nmi) [9]. The specifications of the ATR 42-600 used for model calibration are presented in Table I. The mission profile is briefly described as follows, where an asterisk (*) denotes segments without distance credit:

1) **Taxi-out***: Taxi for 6 min
2) **Takeoff***: Take off and initial climb from sea level to 1500 ft for 1 min
3) **Climb**: Climb to 25 000 ft at 160 KEAS
4) **Cruise**: Level cruise at 200 KEAS
5) **Descent**: Descend to 3000 ft at 200 KEAS and a vertical speed of 1200 ft/min
6) **Approach***: Descend to 1500 ft while decelerating to 160 KEAS
7) **Reserve climb**: Missed approach and climb to 15 000 ft at 160 KEAS
8) **Diversion**: Level cruise at 200 KEAS
9) **Reserve***: Level cruise at 200 KEAS for 45 min
10) **Reserve descent**: Descend to 3000 ft at 200 KEAS and a vertical speed of 1200 ft/min
11) **Reserve approach***: Descend to 1500 ft while decelerating to 160 KEAS
12) **Landing***: Final approach and landing for 3 min
13) **Taxi-in***: Taxi for 4 min

TABLE II
VALIDATION OF 19-PAX TRA MODEL

Item	Ref. [5]	TRA	Error
Maximum takeoff weight (kg)	7815	7815	–
Operating empty weight (kg)	4932	4932	–
Engine rated power (kW)	954	954	–
Wing planform area (m^2)	28.8	28.8	–
Range at max payload (nmi)	133	142	+6.77%
Ferry range (nmi)	1245	1234	−0.88%

TABLE III
VALIDATION OF 50-PAX TRA MODEL

Item	Ref. [9]	TRA	Error
Maximum takeoff weight (kg)	18 600	18 600	–
Operating empty weight (kg)	11 700	11 700	–
Engine rated power (kW)	1610	1610	–
Wing planform area (m^2)	54.5	54.5	–
Block fuel, 200 nmi (kg)	565	582	+3.01%
Block fuel, 300 nmi (kg)	783	780	−0.38%

C. TRA Model Calibration, Results, and Validation

The TRA models are calibrated against the data in Table I and evaluated at a few off-design missions for validation. Tables II and III summarize the results of calibration and validation, based on which the quality of the calibrated models are considered to be good enough to represent the TRA.

IV. IDENTIFICATION AND SELECTION OF VIABLE TECHNOLOGIES

The electrified aircraft aim at entry-into-services in the early 2030s, when some novel technologies for airframe and turboprop engines will also become mature. In order to isolate the impact of electrification, it is necessary to first establish an advanced technology aircraft (ATA) model for each size class, which shall carry the applicable 2030 technologies while maintaining the conventional propulsion system architecture.

The 2030 technologies selected for the advanced aircraft cover the disciplines of aerodynamics, structure, propulsion, and subsystems. These technologies are mostly selected from the technology portfolio of the NASA Advanced Air Transport Technology (AATT) project [10]. From a list of technologies provided by the portfolio and other literature, the selections are determined by the Technology Readiness Level (TRL), the effectiveness of the technology, and the compatibility of the technology with propeller-driven regional aircraft. Table IV summarizes the technologies being implemented in the advanced 19-pax and 50-pax aircraft. The impacts of these technologies on aircraft performance are captured by the Technology Impact Matrix (TIM) and modeled through a set of multiplicative factors applied to aircraft aerodynamic, weight, and propulsive characteristics. The values of these multiplicative factors are determined based on preceding studies.

A. Aerodynamic Technologies

Aerodynamic technologies aim to decrease aircraft drag or noise. Natural laminar flow control reduces skin friction drag by optimizing airfoil shape to encourage favorable pressure gradient which delays the transition to turbulence [10], [11], [12]. The rectangular or V-shaped riblets placed in the turbulent region of wing and fuselage reduce skin friction drag by constraining the motion of vortices at the near-wall region [10], [11]. The variable-camber continuous trailing-edge flap facilitate by flexible skin reduces the overall drag by filling the gaps between control surfaces and providing active morphing wing shape control [10], [13], [14]. Excrescence reduction decreases parasite drag by imposing stricter tolerances in design and manufacturing [10], [15]. Landing gear integration reduces aircraft noise by streamlining the cross-section geometry of landing gear struts to discourage the formulation of highly turbulent wakes, although at a cost of slightly increased weight [10], [16].

TABLE IV
SELECTED 2030 TECHNOLOGIES

Technologies	19-pax	50-pax
Riblets	√	√
Natural laminar flow	√	√
Variable-camber continuous trailing-edge flap		√
Flexible skins		√
Excrescence reduction	√	
Landing gear integration	√	
Composite technologies	√	√
Advanced sandwich composites	√	√
Out-of-autoclave composite fabrication	√	√
Lightweight cabin furnishing		√
Advanced engine cycle	√	√
Advanced engine components	√	√

B. Structural Technologies

Structural technologies aim to decrease aircraft operating empty weight. Composite technologies reduce aircraft structural weight by using materials like fiber metal laminates, glass fibers, or other materials to replace traditional metal materials like aluminum [10]. The structural weight reduction introduced by composite technologies can be further enhanced by advanced sandwich composites; this type of composite has a higher stiffness-to-weight ratio, higher bending strength-to-weight ratio, and better fatigue resistance compared to the composite material with honeycomb or hexagonal core [10], [17]. The manufacturing of advanced sandwich composites is enabled by the out-of-autoclave composite fabrication which uses a process of vacuum bag forming and lower temperature post cure [10], [18]. The lightweight cabin furnishing applied on the 50-pax advanced aircraft is selected based on the ARMONIA cabin design proposed by ATR and Giugiaro, in which the utilization of lightweight materials reduces the cabin weight by the equivalent of two passengers [19].

C. Propulsion Technologies

The advanced turboprop engine models developed for advanced 19-pax and 50-pax aircraft are established based on expected evolutionary improvements in the aerodynamics, materials, and manufacture of engine components, as well

TABLE V
IMPACT OF TECHNOLOGY INFUSION ON 19-PAX AIRCRAFT

ID	Technology	Δ-GW	Δ-OEW	Δ-BF
1	Composite Technologies	-2.8%	-4.2%	-2.5%
2	Advanced Sandwich Composites	-2.5%	-3.6%	-2.3%
3	Out-of-Autoclave Composite Fabrication	-0.2%	-0.3%	-0.2%
4	Excrescence Drag Reduction	-0.1%	-0.0%	-0.3%
5	Riblets	-0.4%	-0.2%	-1.7%
6	Natural Laminar Flow	-1.4%	-0.7%	-8.7%
7	Advanced Engines	-2.8%	-1.3%	-14.5%
	Cumulative	-10.3%	-10.3%	-30.2%

TABLE VI
IMPACT OF TECHNOLOGY INFUSION ON 50-PAX AIRCRAFT

ID	Technology	Δ-GW	Δ-OEW	Δ-BF
1	Composite Technologies	-3.2%	-4.6%	-2.8%
2	Advanced Sandwich Composites	-2.7%	-3.8%	-2.4%
3	Out-of-Autoclave Composite Fabrication	-0.2%	-0.3%	-0.2%
4	Light-weight Cabin Furnishing	-0.6%	-0.8%	-0.5%
5	Landing Gear Integration	+0.2%	+0.2%	+0.2%
6	Variable-Camber Continuous Trailing-Edge Flap	-0.4%	-0.5%	-0.6%
7	Flexible Skins	-0.2%	-0.1%	-1.1%
8	Natural Laminar Flow	-1.8%	-0.8%	-10.8%
9	Advanced Engines	-4.2%	-3.5%	-14.6%
	Cumulative	-13.0%	-14.2%	-32.9%

as expected advances in engine cycle design approaches. Using projections available from numerous published sources, such as the NASA Revolutionary Vertical Lift Technology study [20], higher compressor pressure ratio, higher turbine temperature, and higher compressor and turbine efficiencies are assumed in advanced engine models.

D. Aircraft-Level Impacts of Advanced Technologies

Tables V and VI present the individual and cumulative impacts of selected technologies on aircraft gross weight (GW), operating empty weight (OEW), and design mission block fuel (BF). With the technologies applied progressively, the aircraft is resized for the same design mission, keeping the same power-to-weight ratio, wing loading, and tail volume coefficients as for the TRA. With all the technologies applied, the 19-pax aircraft sees an overall fuel improvement of 30.2%, and the 50-pax aircraft sees an overall fuel improvement of 32.9%, compared to the respective TRA.

V. ADVANCED TECHNOLOGY AIRCRAFT MODEL DEVELOPMENT

In addition to the technology infusion, the design mission is also updated for the ATA models. For the 19-pax aircraft, the nominal weight per passenger (including luggage) is increased from $210\,\mathrm{lb}$ ($95.3\,\mathrm{kg}$) to $215\,\mathrm{lb}$ ($97.5\,\mathrm{kg}$). For the 50-pax aircraft, the design range is reduced from $703\,\mathrm{nmi}$ to $500\,\mathrm{nmi}$. The overall mission profile, including the reserve range, remains unchanged for both aircraft.

TABLE VII
RANGES OF DESIGN PARAMETERS

Parameter	19-pax		50-pax	
	Min	Max	Min	Max
PWR (kW/kg)	0.2075	0.2563	0.1472	0.1818
WSR (kg/m^2)	244.2	298.5	307.2	375.4

It is expected that the infusion of advanced technologies and changes in the design mission affect aircraft point performance, mission performance, and therefore the overall aircraft sizing. Therefore, a parametric sweep is performed on the aircraft-level design point, namely the sea level rated power-to-weight ratio (PWR) and wing loading (WSR), in order to assess their impact on aircraft weights and fuel consumption. Table VII presents the ranges of the design parameters for both aircraft models.

A Design of Experiment is performed in the design space, and surrogate models are created for key responses such as the design mission block fuel, the gross weight, the wingspan, and the sea level rate-of-climb. A constraint diagram is generated for both aircraft from the surrogate models, as shown in Figs. 1 and 2. For both aircraft, WSR is held constant in order to maintain similar approach speed and landing performance to the TRA, while PWR is varied to minimize the block fuel of the revised design mission, subject to the constraint of all-engine-operative sea level rate of climb.

- For the 19-pax aircraft, the all-engine-operative sea level rate of climb must be no less than $2140\,\mathrm{ft/min}$, which maintains the same performance as the TRA.
- For the 50-pax aircraft, while the ATR 42-600 is capable of a sea level rate of climb of $1851\,\mathrm{ft/min}$ [7], this is achieved using a de-rated engine whose sea-level power available does not decrease when propeller speed is reduced from takeoff setting to climb setting. Since the advanced engine is properly optimized for the takeoff and cruise conditions, its torque limit causes a decrease of power from takeoff to initial climb. In this case, enforcing the same rate of climb requirement will lead to an increase in takeoff power-to-weight ratio relative to TRA and significantly oversized engines for cruise, worsening the fuel consumption. Therefore, the TRA is first retrofitted with the advanced engine sized for the same takeoff power, and the resulting sea level climb performance is used as the constraint value, which is $1475\,\mathrm{ft/min}$.

Based on the objective and constraint, the TRA and ATA design points are marked in Figs. 1 and 2. Table VIII compares the key performance parameters between the TRA models and the ATA models: for the 19-pax aircraft, the advanced technologies, revised design mission, and design optimization together lead to a 9.7% decrease in maximum takeoff weight and a 30.6% decrease in block fuel; for the 50-pax aircraft, the overall impacts are a 15.8% decrease in maximum takeoff weight and a 35.1% decrease in block fuel.

TABLE VIII
COMPARISON BETWEEN TECHNOLOGY REFERENCE AIRCRAFT MODELS AND ADVANCED TECHNOLOGY AIRCRAFT MODELS

Item	Unit	19-pax			50-pax		
		TRA	ATA	Change	TRA	ATA	Change
Design range	nmi	382	382	–	703	500	−28.9%
Design payload	kg	1810	1853	+2.4%	4560	4560	–
Power-to-weight ratio	kW/kg	0.2441	0.2332	−4.5%	0.1731	0.1600	−7.6%
Maximum takeoff weight	kg	7815	7056	−9.7%	18 600	15 654	−15.8%
Operating empty weight	kg	4932	4429	−10.2%	11 700	9846	−15.8%
Wing planform area	m^2	28.8	26.0	−9.7%	54.5	45.9	−15.8%
Wing span	m	17.6	16.7	−5.1%	24.6	22.5	−8.5%
Engine rated power, each	kW	954	823	−13.7%	1610	1252	−22.2%
Block fuel at ATA design range	kg	579	402	−30.6%	1147	744	−35.1%
Cruise average BSFC	kg/kW/h	0.3249	0.2867	−11.8%	0.2817	0.2488	−11.7%
	lbm/hp/h	0.5341	0.4713	−11.8%	0.4631	0.4090	−11.7%
Cruise average TSFC	g/N/s	0.012 65	0.011 09	−12.3%	0.013 02	0.011 58	−11.1%
	lbm/lbf/h	0.4466	0.3914	−12.3%	0.4597	0.4087	−11.1%

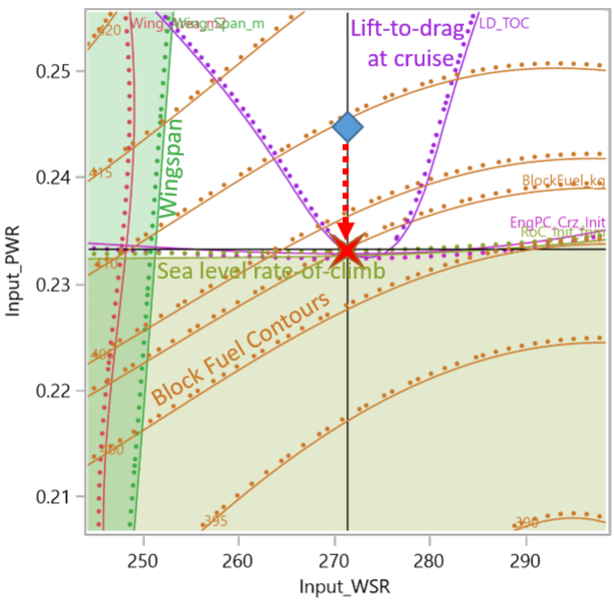

Fig. 1. Constraint diagram for 19-pax advanced technology aircraft

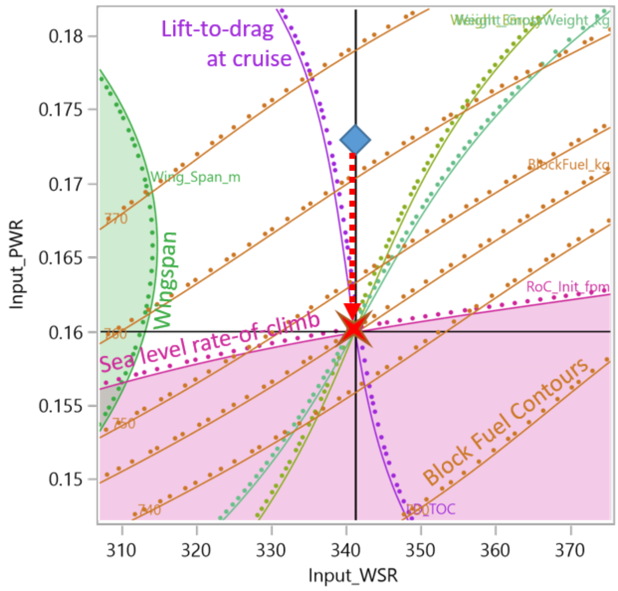

Fig. 2. Constraint diagram for 50-pax advanced technology aircraft

VI. CONCLUSION

This paper presents the process to establish advanced technology aircraft models with conventional (non-electrified) propulsion systems for a thin haul (19-passenger) turboprop size class and a regional (50-passenger) turboprop size class. The Beechcraft 1900D and the ATR 42-600 are identified as state-of-the-art technology reference aircraft (TRA) based on their technology level, data availability, and market share. Parametric models are created for both TRA in E-PASS, which uses FLOPS to perform structural weight estimation and aerodynamics analysis and uses NPSS to perform gas turbine engine sizing. These models are then calibrated against top-level specifications including gross weight, empty weight, geometry, and fuel consumption.

Viable 2030 advanced technologies are identified and modeled which improve the structural, aerodynamic, and propulsive efficiency of the reference aircraft. With revised design payload and range, a constraint optimization is performed on the takeoff power-to-weight ratio which minimizes the block fuel consumption. It is estimated that the technologies and the revised design mission together bring 30.6% fuel burn benefit for the 19-pax aircraft and 35.1% for the 50-pax aircraft. These advanced technology aircraft models serve as the baselines against which the benefit of the electrified propulsion architecture described in Ref. [4] will be assessed in future work.

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