Parallel Hybrid Turboprop Performance Modeling and Optimization

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NASA's Electrified Powertrain Flight Demonstration (EPFD) project conducts ground and flight tests of integrated Megawatt (MW) class hybrid-electric powertrain systems on regional turboprop aircraft demonstrators. To meet the increased demand for assessment of potential capabilities and benefits from these novel vehicle configurations, NASA is developing tooling and models to estimate the performance of hybridized regional turboprops. This paper covers the development of a parametrically driven performance model for a De Havilland Canada Dash 8-400 (Q400) regional turboprop integrated with a novel parallel hybrid architecture using the Gascon framework. Gascon is a modern reimplementation of the General Aviation Synthesis Program (GASP) built using the Condor mathematical modeling framework in Python. Within Gascon, a parametric representation of the parallel hybrid architecture was synthesized, which features the electric motor coupled to the power turbine. This capability allows for in-the-loop optimization of the parametric parallel hybrid architecture to characterize the mission capabilities and fuel savings of the design and determine optimal power scheduling strategies for efficient electric power management for a given mission. The study shows that a fuel savings of up to 20% can be achieved, but that increased fuel savings comes at the expense of payload capacity.

Introduction

Electrified aircraft propulsion (EAP) has been one of the preeminent technology development strategies to realize revolutionary improvements in reducing energy and fuel consumption for on-demand and regional air mobility transports [1]. EAP technologies not only show significant potential for improving fuel burn and greenhouse gas emissions, but can also reduce maintenance costs and improve the overall powertrain and energy efficiencies of commercial aircraft. Military aircraft can also benefit from EAP, with lower noise and lower exhaust heat signatures [2]. NASA's Electrified Powertrain Flight Demonstration (EPFD) project aims to identify, test, and demonstrate integrated Megawatt (MW) class EAP concepts through partnerships with U.S. industry to enable advancements in sustainable flight technologies [3]. While a multitude of varying hybrid-electric propulsion (HEP) architectures have been proposed, the flight demonstrators under the EPFD project focus on parallel hybrid architectures with an entry into service in 2035 [4]. Parallel hybrid electric aircraft use both conventional jet fuel and electric energy to power a gas turbine engine and an electric motor/generator in parallel. However, there is still a distinction to be made between two types of parallel hybrid architectures. Previous studies have presented on a true parallel hybrid (TPH) architecture, where the aircraft configuration features independent engines and motors; each propeller is driven by either a gas turbine engine or an electric motor, and the two systems remain physically decoupled [5, 6]. However, the TPH powertrain architecture is suited for four-engine aircraft. For the two-engine turboprop in this paper, the parallel hybrid configuration has the motor/generator and turbine engine coupled, driving the same propeller shaft. Frederick et al. used a single-aisle, 154 passenger turbofan aircraft concept and analyzed individual technologies compatible with the mild hybrid approach in turbofans [7]. Combining the technologies into a single, all-inclusive configuration results in the most significant benefits, with an 8.2% reduction in block fuel and a 7.7% reduction in CO_2e with a 3.5% increase in gross takeoff weight [7]. Milios used a similar 150 passenger aircraft model to perform a parametric optimization analysis, comparing a non-optimized electric aircraft to their optimized version [4]. For a 500 nautical mile mission, the optimized model used 10.34% less block fuel with respect to the non-hybrid baseline model [4]. There is also literature looking at the impact of applying the parallel hybrid approach to turboprops. A study of a parallel hybrid turboprop aircraft by Habermann found that a 200 nautical mile mission could produce a block fuel reduction of 9.6% but assumed characteristics of the battery increased fuel burn for longer missions [8]. This base aircraft only had a 48-passenger maximum capacity and was designed for shorter missions. Cinar et al. assessed the impacts of hybridization on range and fuel burn performance for a hybrid-electric Dornier 328 and was capable of 350 to 550 NM ranges assuming near-term battery specific energy levels (250 Wh/kg) where 34% fuel savings were expected for 25% hybridization during cruise [9].

The architecture presented in the current study is a parallel hybrid turboprop configuration with electrification of the baseline turboprop engines. The power turbine shaft from the conventional turboprop engine is coupled with an electric drive system to create an integrated MW-class powertrain capable of supplying electric power during climb and cruise. The parallel hybrid configuration represents a likely path to commercial electrification through retrofit, as most current aircraft are twin-engine. Therefore, an increased need for parametric representation and simulation of such an aircraft required upgraded tool development and modeling capabilities, which are realized using Gascon, a new analysis capability that allows for conceptual design, analysis, and optimization of new EAP concepts. Gascon is a modern vehicle synthesis and mission analysis code built on the Condor mathematical modeling framework in Python as a reimplementation of the legacy General Aviation Synthesis Program (GASP) developed at NASA Ames Research Center in Fortran in the 1970s. By leveraging modeling and analysis capabilities in Gascon, highly coupled optimization and vehicle performance assessments can be carried out to inform and guide future development of EAP aircraft concepts.

The purpose of this work is to evaluate the mission capabilities of a near-term, multi-MW parallel hybrid regional turboprop and identify optimal operational profiles to best leverage the benefits of this configuration, demonstrate novel optimization capabilities added to conduct vehicle benefit assessments address the need to conduct vehicle benefit assessments of novel hybrid-electric aircraft configurations to communicate the methodology, results, and design space for these future EAP concepts. Using Gascon, performance models and coupled optimization can be carried out to generate optimal operational profiles, assess range and payload capabilities, and determine fuel/energy savings to help benchmark performance and design objectives.

Parallel Hybrid Architecture

The parallel architecture for a turbofan is relatively well defined in previous studies, with electric motors on one or more spools of the engine [4, 7]. The concept is similar for turboprops, with some differences due to the architecture of free-turbine turboprops. In this study, we are applying the hybridization to only the free turbine, which will be referred to as the power turbine for the rest of this paper. The internal spools of the turboprop engine remain fully conventional, while the power turbine is connected to a motor. In this instance, the power turbine, instead of being connected to the propeller reduction gearbox, is connected to a combination reduction/combining gearbox, which also connects the motor as another input, and the propeller as the output. A conventional turboprop is shown in Figure 1 below. In the figure, the turbine engine has been reduced to a single box, which contains the inlet, compressor(s), shaft(s), burner, and turbine(s), including the power turbine. The mechanical connection shown is the power turbine shaft. In the conventional case, this is connected to the propeller through a reduction gearbox. In the hybrid configuration (Figure 2), the power turbine shaft instead connects to the combining/reduction gearbox, which is also connected to a motor shaft. The shaft from the combining/reduction gearbox then drives the propeller. While the figure is shown with a combined combining and reduction gearbox, the combining and reduction gearboxes could be separate gearboxes and the motor may need its own reduction, depending on its design speed.

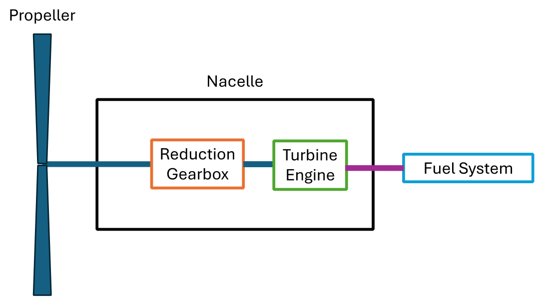

Figure 1. Conventional turboprop architecture

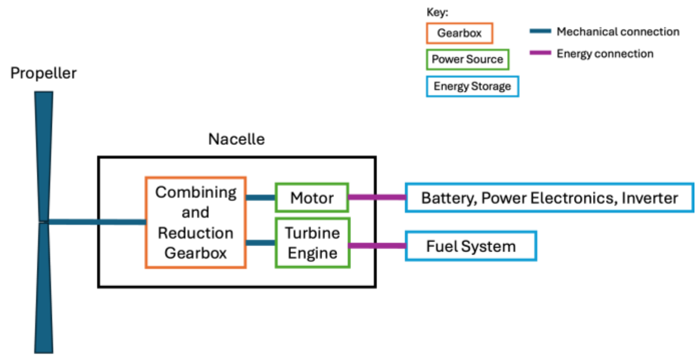

Figure 2. Parallel hybrid turboprop architecture

Tool Background and Development

Gascon is a new NASA-developed vehicle synthesis tool intended to replace the General Aviation Synthesis Program (GASP), a vehicle synthesis tool originally developed in the 1970s in Fortran and continually maintained and improved [10]. GASP is a vehicle synthesis and mission analysis tool for conceptual design and sizing of aircraft. It consists of several integrated subsystem modules such as aerodynamics, geometry, weight and balance, mission performance, and propulsion, to allow for mission specification and performance estimation. Gascon, or GASP on Condor, takes GASP and implements it in python on top of the NASA-developed Condor framework [11]. Condor is a new mathematical modeling framework built in python that enables the rapid development of mathematical modeling and optimization of engineering systems using a declarative, symbolic front-end and efficient off-the-shelf solvers. [12].

Gascon provides configurable Condor models to evaluate the static and mission performance of a vehicle and flight plan. The Gascon implementation for the model of the combined static and mission performance relies on many of the features provided by Condor including: (1) the use of symbolic calculus operations to define model expressions; (2) efficient solvers for systems of algebraic equations, trajectory performance models defined by ordinary differential equations with events, and mathematical optimization problems, to allow flexible modeling; (3) the specifying of a user interface for providing custom sub-models. These features give Gascon the flexibility of evaluating models at any level of abstraction and composing them into design problems modeled as an optimization. Gascon has the backwards compatibility of working with GASP input decks and the flexibility of working with new input data designed specifically for Gascon. Gascon has been validated by reproducing results generated by GASP across multiple vehicle models and has flexibility to allow continued quick development and improvement. The flexibility, reliability of results, optimization features, and quick development cycle were reasons Gascon was chosen as the tool for this project.

New vehicle analysis tool development within Gascon was required to be able to accurately model this parallel hybrid architecture. In Gascon, the propulsion model is assembled from components for which external models exist. In the case of the parallel hybrid, these components are a turboshaft engine, an electric motor, and a propeller. Additionally, a controller is needed to determine the power split between the turbine engine and the electric motor.

In the configuration for this aircraft, a reduction/combining gearbox connects the electric motor to the power turbine shaft such that the motor RPM must be equivalent to a gear ratio times the turboshaft power turbine RPM. The RPM of the power turbine is output from the turboshaft model and used as an input on the motor model. The torque from the two components is combined to achieve the desired output power for the propeller shaft. Due to the nature of the power turbine being a free turbine design, this study assumes that that motor torque has a negligible effect on the thermodynamic cycle of the turboshaft engine. Thus, the same turboshaft engine performance data, generated from a Numerical Propulsion System Simulation (NPSS) model, is used for both the conventional and hybrid propulsion models [13].

Because the model is designed to represent a retrofit, limits were put in place to avoid theoretically putting excessive or unsafe loads on the propeller, propeller shaft, or other potentially reusable components. Thus, the hybrid-electric propulsion model is limited to the maximum RPM, torque, and power provided to the propeller by the conventional aircraft.

This study focuses on hybridization for top-of-climb and cruise. This is primarily due to tooling maturity, although some quick test runs showed that due to the power and torque limits this study imposes, applying the hybridization to takeoff and low-altitude climb had little impact. Future tool development and studies for this parallel hybrid scheme will look at e-taxi and full climb hybridization, and may look at removing the maximum RPM, power, and torque limits imposed.

In the model, the control of the hybrid-electric system is determined by an input *motor-on altitude* – the minimum altitude for which the motor is engaged. Above this altitude, the control scheme depends on the phase of flight. In climb, the electric motor adds power up to the maximum limits previously defined. In cruise, a power split is used to determine how much power comes from the electric motor and the conventional engine. This power split can be pre-defined, defined by specific needs or constraints, or be a fallout variable in an optimization problem. These various possible configurations could allow the aircraft model to cruise higher than the unmodified aircraft's rated ceiling, or, in future work, allow for a re-sizing of the conventional engine to improve conventional engine efficiency throughout the flight. In descent, the electric motor is off, neither adding to nor pulling power from the power turbine shaft.

Baseline Aircraft Model

The aircraft model chosen for this study, the De Havilland Canada Dash 8-400 (also referred to as the DHC-8-400 or Q400), is a twin-engine turboprop regional airliner representative of state-of-the-art regional transports. The DHC-8-400 is powered by two Pratt & Whiney Canada PW150A turboprop engines each at rated 3,781 kW (5,071 shp) [14]. Each PW150A powerplant drives a Dowty R408 all-composite six-bladed propeller, which is modeled using the Hamilton Standard Propeller performance models from Worobel et al [15]. The baseline aircraft model geometry was modeled in OpenVSP (Figure 3) using publicly available data to estimate the zero-lift drag and inform the geometry inputs in the Gascon model. The aircraft engine performance was modeled in the Numerical Propulsion System Simulation (NPSS). The motor performance was modeled in MATLAB. The performance model of the aircraft, combining all these sub-models, was created in Gascon. Table 1, below, shows a comparison of the DHC-8-400 published data and the model.

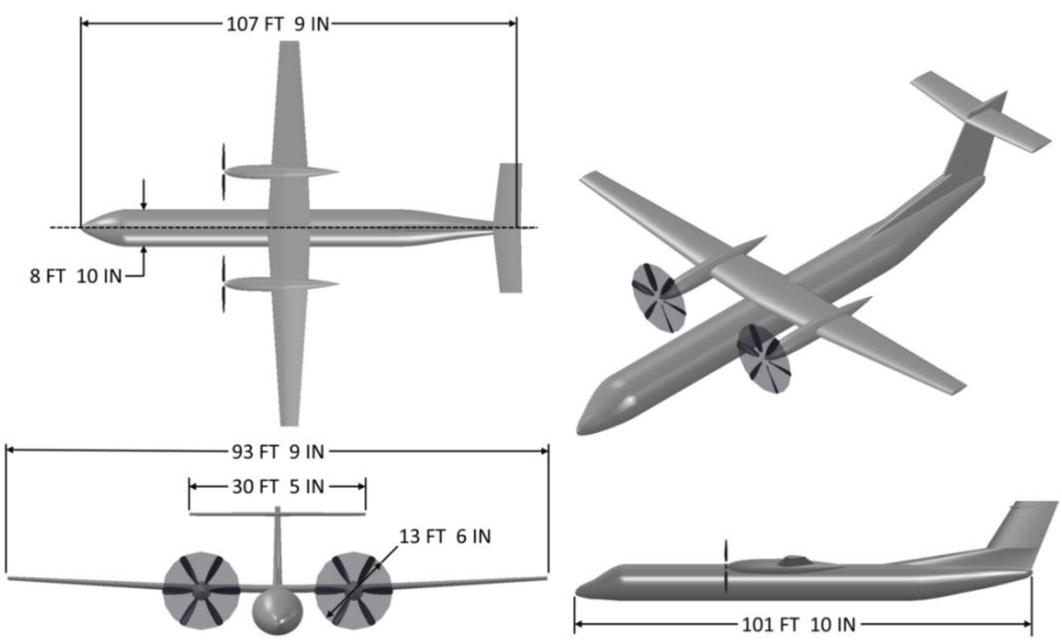

Figure 3. Three-view drawing of the baseline DHC-8-400 modeled in OpenVSP

The reference baseline DHC-8-400 model in Gascon was calibrated to match the key design parameters of gross takeoff weight, operating empty weight, block fuel for specified mission range, and engine-rated power stated in publicly available data. Specifically, this study uses the high-GTOW long range cruise configuration of the DHC-8-400. Most of the modeled parameters differ from the Q400 Airport Planning Manual (APM) reference values by less than ±1%, with the specified mission range total loaded fuel differing by about -3% (see Table 1). The payload versus range diagram (Figure 5) was generated from Gascon assuming takeoff and landing flap deflections of 10 degrees and 40 degrees respectively, where the blue stars are the Gascon model outputs and the black lines is the published data from the Q400 APM [14].

Table 1. Comparison of modeled key performance parameters

Vehicle Parameter	**DHC-8-400 from Ref** [14]	**Gascon DHC-8 Model**	**Percent Difference**
Gross Takeoff Weight, lbf	63,750	63,750	0%
Operating Empty Weight, lbf	37,804	38,168	0.95%
Max. Payload Weight, lbf	18,696	18,532	-0.88%
Engine Rated Power, shp **Max. Takeoff** **Max. Continuous**	 5,071 5,071	 5,071 5,071	 0% 0%
Wing Area, ft^2	680	680	0%
Wing Span, ft	93.25	93.30	0.05%
Total Loaded Fuel, lbf (750 NM)	7,250	7,038	-2.92%

The baseline mission for the Dash 8 assumed a design cruise altitude of 24,000 feet and 250 knots true airspeed targeting a design range of 750 NM for the maximum payload case.

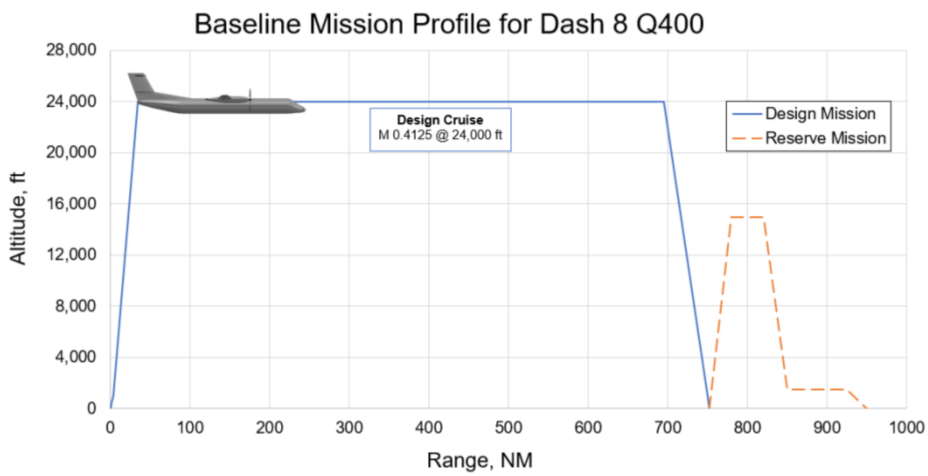

Figure 4. Baseline DHC-8 Q400 750 NM range design and reserve mission

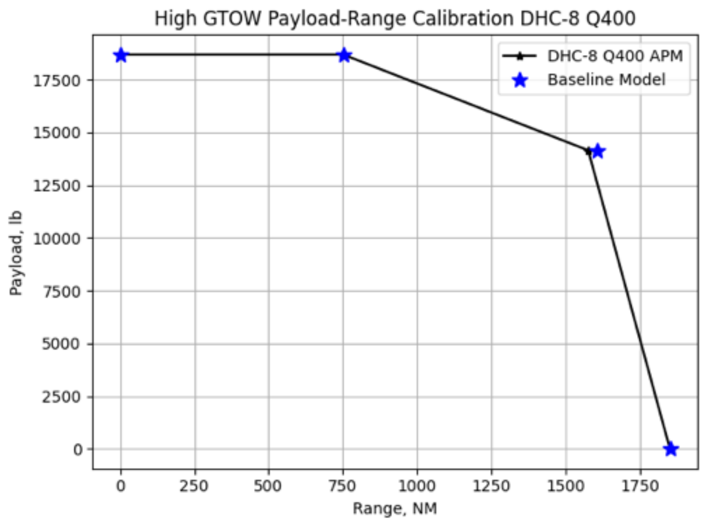

Figure 5. Calibrated DHC-8-400 Payload vs Range diagram

Hybrid-Electric Aircraft Model Development

Baseline payloads were determined for both the conventional and hybrid Q400. The baseline payload in this analysis for the conventional Q400 is 75 passengers, while the baseline payload for the hybrid Q400 is 62 passengers, both with an assumed per-passenger weight of 200 lb. Most analyses conducted in this study do not use these baseline numbers, instead fixing the takeoff weight of the model to the maximum gross takeoff weight (GTOW) of the DHC-8-400, 63,750 lbm, and allowing the payload weight to be an output, as long as the payload weight output is below the max payload weight defined in the APM. The assumptions for the hybrid configuration are listed below. The assumptions in this list apply to the analyses unless stated otherwise in the mission definitions.

Assumptions for the hybrid-electric model:

- Takeoff weight: 63,750 lbm
- Battery specific energy: 300 Wh/kg
- Motor size: 950 kW (1274 hp)
- E-boost on altitude: 15,000 ft
- Cruise altitude: 24,000 ft
- Cruise speed: Mach = 0.4125 (250 KTAS)

Assumptions for the electrical system components are listed in Table 2 below.

Table 2. Electrical system component assumptions

Electrical System Component	Parameter	Value	Reference
Electric Motor Generator (EMG)	Specific Power	10.0 kW/kg	[16]
Inverter/Converter (IC)	Specific Power η_{IC}	12.0 kW/kg 99%	[4] [17]
Electric Energy Storage (ESS)	Pack-Level Specific Energy η_{batt}	300 Wh/kg 99.5%	[11] [12]
AC/DC Cabling	Wire Density Voltage Transmission Efficiency	565 lbf/ft^3 850 V 97.5%	[4]
Thermal Management Systems (TMS)	Specific Weight	0.1834 kW/kg	[2]

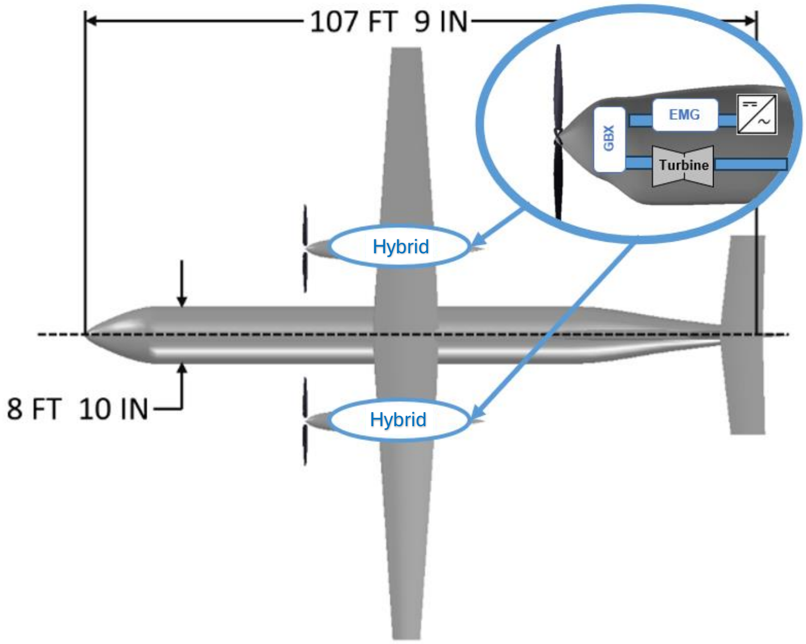

Figure 6. Parallel Dash 8 Q400 integrated power system schematic

Though not depicted in the system diagram, AC/DC cabling and transport lines for coolant (included in the TMS weight) are modeled for electric energy distribution and thermal control. Four mission profiles and their associated concepts of operation have been selected to define optimal operational altitude, speed, throttle settings, and range targets that will be quantified through the systems-level design exploration of the concept. These four missions primarily look at the 750 nautical mile design mission. This mission is equivalent to the maximum range of the aircraft with a full payload, as this hybrid aircraft is modeled to primarily focus on preserving the range capability of the baseline with an associated reduction of payload.

The results are reported out in terms of block fuel savings and fuel burn metric. Internally for each run, the optimization problem minimizes nominal fuel burn. Block fuel (BF) is the amount of fuel burned for the nominal mission, regardless of payload, which dynamically changes from point to point. Higher block fuel savings percentage means less fuel burned. The fuel burn metric (FBM) is a number normalizing fuel burn, payload, and range, which allows for corrections point-to-point when compared to the block fuel metric. The fuel burn metric is defined as:

$$FBM = \frac{\left(\frac{BF}{W_{Payload}}\right)}{\left(\frac{Range}{1000}\right)} \quad (1)$$

A lower fuel burn metric means that less fuel was burned per pound of payload normalized with respect to range. The fuel burn metric accounts for the penalty in payload capacity that is traded off for increased battery capacity that may be required for high C-rate maneuvers such as electric augmentation for top-of-climb and cruise. While increased electrification results in reduced fuel burn and emissions, the battery capacity required to sustain charge throughout the mission increases, which in turn reduces available payload capacity.

For the model comparisons, the conventional aircraft was only modeled at its design cruise point: 24,000 ft altitude, Mach 0.4125. The mission problems are set up as optimization problems, such that the data reflects the minimum fuel burn condition for each point. In the optimization problems, W_{OEW} is the operating empty weight, which accounts for all weight of the aircraft excluding the payload, fuel, and battery weights.

Results and Discussion

Mission 1 has the goal of determining the optimal cruise altitude with the selected configuration of top-of-climb E-boost only. The cruise altitude is swept here. The concept of operations is shown in Figure 7. Optimal cruise altitude here is defined as the altitude at which the fuel burn metric (FBM) is minimum. This may or may not be the same altitude as the minimum block fuel. For each point, the following constraints are in place.

$$
\begin{aligned}
\text{minimize} \quad & \text{fuel burn} \\
\text{with respect to} \quad & \text{payload} \\
\text{subject to} \quad & GTOW = MTOW = W_{OEW} + W_{Payload} + W_{Fuel} + W_{Battery} \\
& W_{Fuel} = W_{Fuel,\ burned} + W_{Fuel,\ reserve\ mission} + W_{Fuel,\ reserve} \\
& \text{battery energy required} \leq \text{battery energy available} \\
& \text{range flown} \geq \text{target range} \\
& \text{cruise altitude} = \text{defined cruise altitude}
\end{aligned}
$$

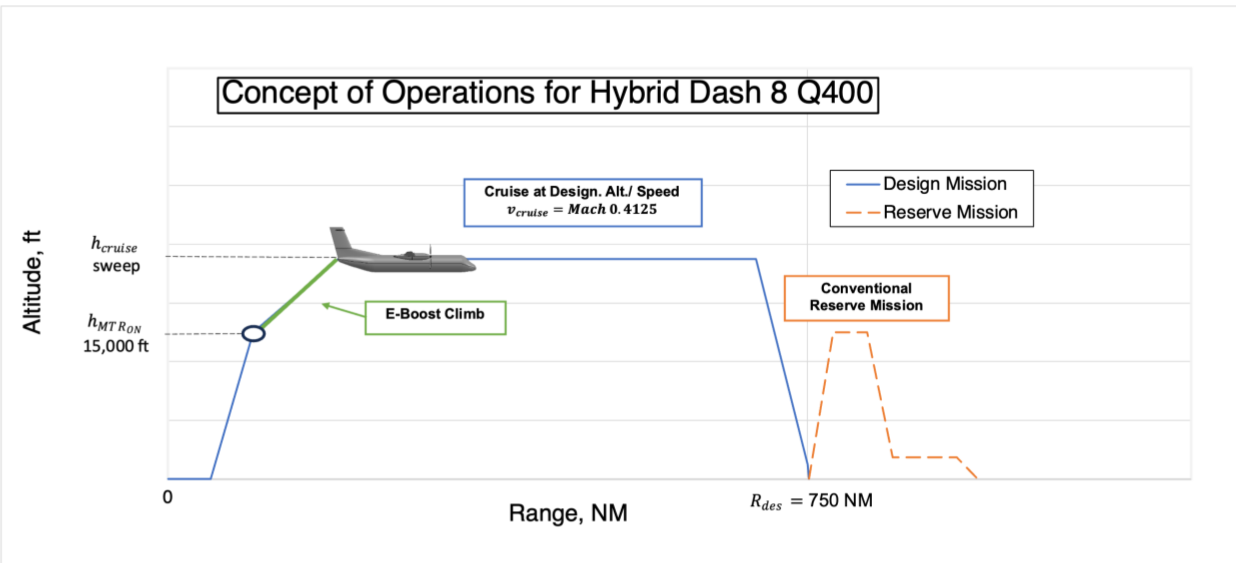

Figure 7. Concept of Operations for Mission 1: 750 NM Cruise Altitude

Mission 1 results (Figure 8, Figure 9) show the optimal cruise altitude for the hybrid aircraft. As the baseline Q400 has a maximum payload range of 750 NM and the total fuel load was fixed to match the baseline, the primary trade-off was between fuel savings from increased electrification at the cost of payload capacity. The results show the optimal cruise altitude for maximizing block fuel savings versus best FBM performance. This is due to the trade-off between battery weight for the hybrid system and payload capacity; cruising higher results in improved propulsive efficiency, but requires higher battery capacity to get to cruise, which results in higher required battery weight at the expense of payload capacity. Thus, there is less weight available for payload, which increases the fuel burn per pound of payload. This is also why the block fuel savings vary based on the altitude; there is less payload at the higher altitudes because of the increased required battery weight. The block fuel savings maxes out just under 5%. This lines up with the expected result because the 750 nautical mile design mission and hybrid aircraft design passenger count were targeting this range. However, even with the block fuel savings compared to the baseline conventional mission cruising at 24,000 ft, the hybrid aircraft carries a payload reduction equivalent to 15 fewer passengers. The fuel burn metric is a more precise representation of the data that an operator would use to determine fuel efficiency, so from this data, the optimal cruise altitude selected for the mission 2 and 3 runs was 21,000 ft.

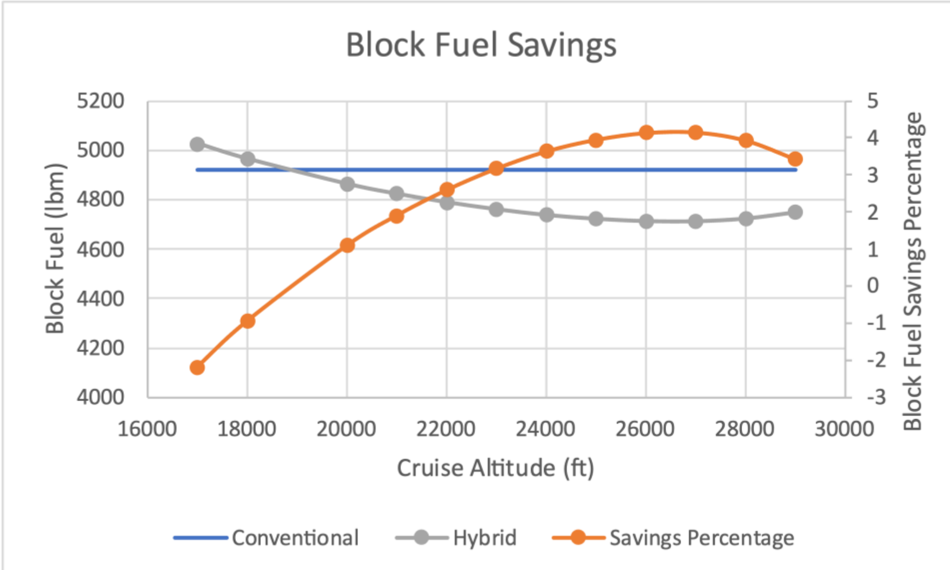

Figure 8. Block Fuel Savings for Mission 1: 750 NM Cruise Altitude

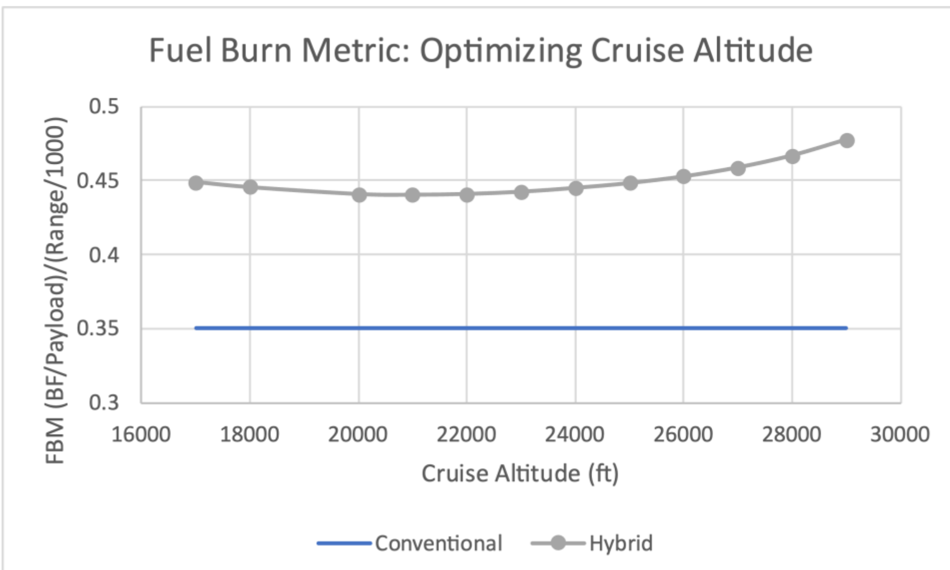

Figure 9. Fuel Burn Metric for Mission 1: 750 NM Cruise Altitude

Mission 2 has the goal of flying the full 750 nautical mile cruise mission at the optimal cruise altitude from Mission 1 with various electric power splits. The sweep for Mission 2 is run at the optimal 21,000 ft cruise altitude identified previously and a cruise Mach of 0.406, equivalent to the 250 KTAS speed of the design mission (cruise Mach of 0.4125 at 24,000 ft altitude). The concept of operations is shown in Figure 10 and evaluates the FBM sensitivity to block fuel and payload tradeoffs. For each point, the following constraints are in place.

$$
\begin{aligned}
\text{minimize} \quad & \text{fuel burn} \\
\text{with respect to} \quad & \text{payload} \\
\text{subject to} \quad & GTOW = MTOW = W_{OEW} + W_{Payload} + W_{Fuel} + W_{Battery} \\
& W_{Fuel} = W_{Fuel,\ burned} + W_{Fuel,\ reserve\ mission} + W_{Fuel,\ reserve} \\
& \text{battery energy required} \leq \text{battery energy available} \\
& \text{range flown} \geq \text{target range} \\
& \text{cruise power split} = \text{defined cruise power split}
\end{aligned}
$$

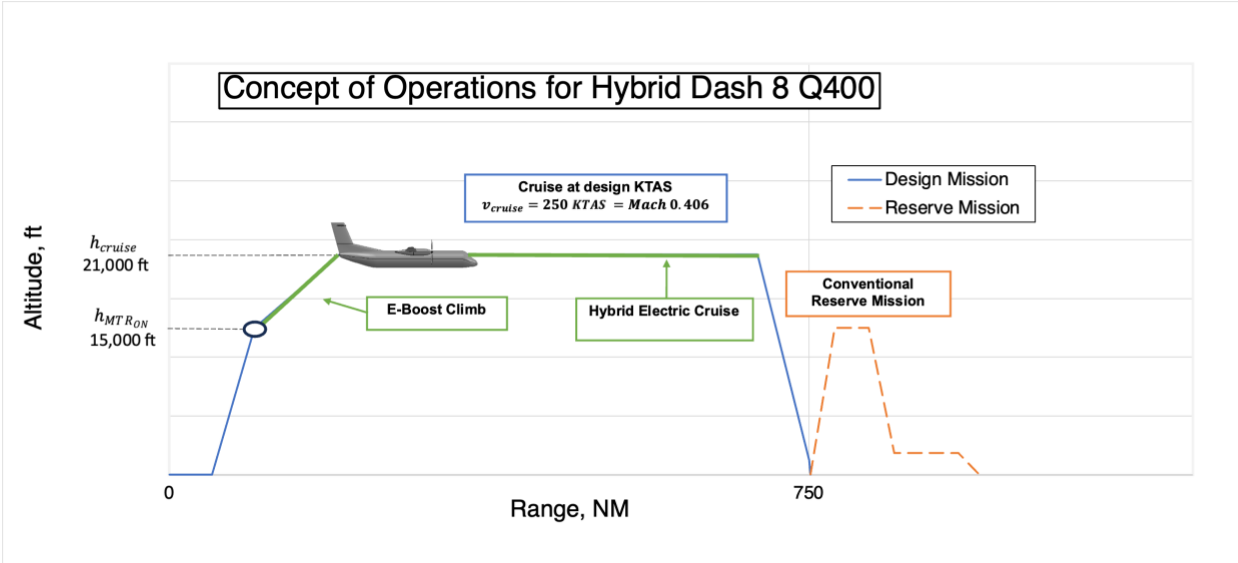

Figure 10. Concept of Operations for Mission 2: 750 NM Cruise Power Split

Mission 2 results (Figure 11) indicate that block fuel savings can be achieved if the operator is willing to exchange payload weight to accommodate higher battery weight, which results in fuel burn reduction benefits relative to the baseline aircraft. The design point comparison for this hybrid aircraft indicates an approximate 7% block fuel savings at the design mission of 750 nautical miles and design payload of 62 passengers. Higher fuel savings can be realized by off-loading payload weight in exchange for higher battery weight to sustain hybridized climb and cruise operations. Flying with only 20 passengers, 20% fuel savings is possible at 750 nautical miles, but 20 passengers is less than 25% of the design payload for the aircraft. The impact of this payload reduction is evident in the FBM results. At the selected 300 Wh/kg representative of state-of-the-art lithium-ion battery technologies, this penalty is significant when considering the resulting fuel burn per pound of payload for the modified parallel hybrid Dash 8 Q400 concept; however, improvements in battery specific energy could improve this metric. This is shown in Figure 12, where no crossover point between the baseline DHC-8-400 aircraft and proposed hybrid concept exists. However, volume-constrained cargo operations and short-haul reduced payload missions are feasible for this concept with current EAP technology levels.

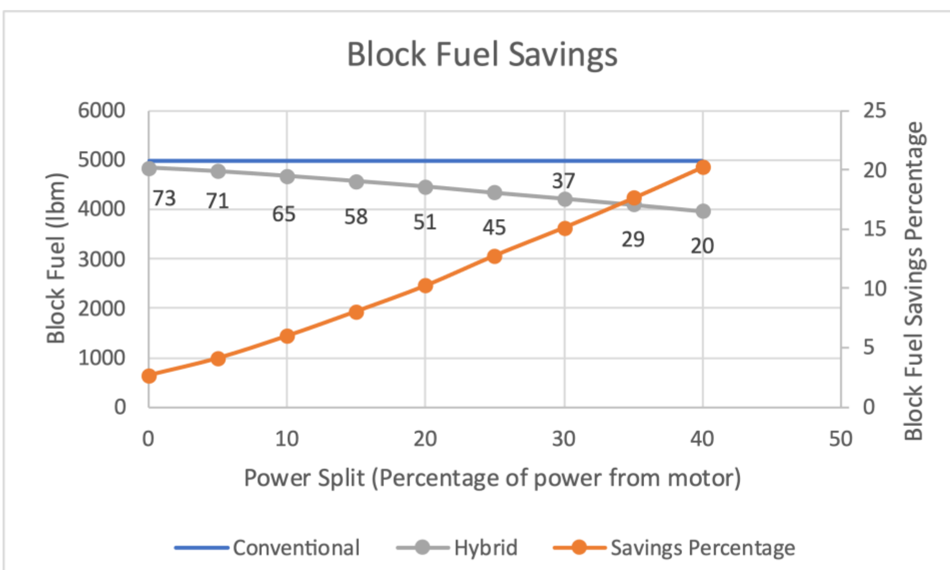

Figure 11. Block Fuel Savings for Mission 2: 750 NM Cruise Power Split

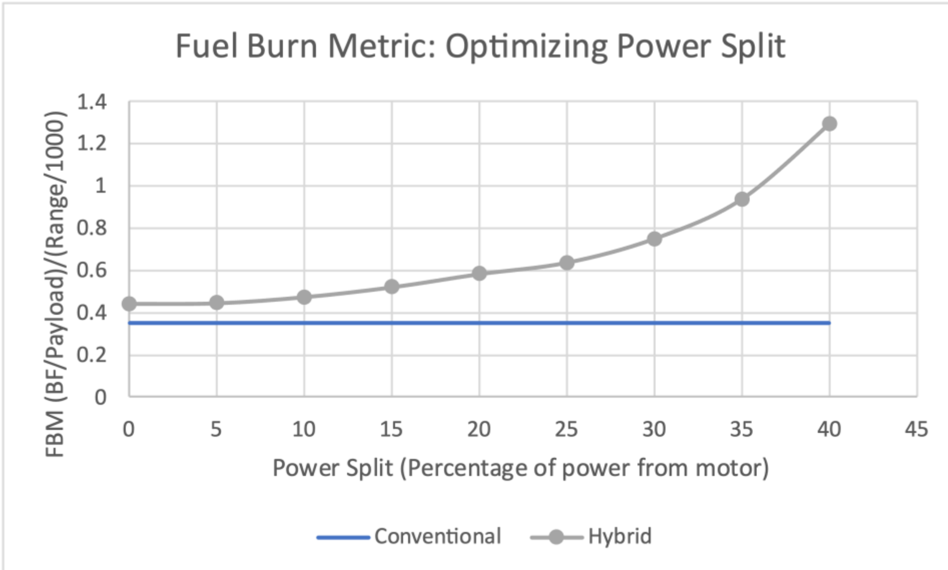

Figure 12. Fuel Burn Metric for Mission 2: 750 NM Cruise Power Split

Mission 3 examines flying the hybrid aircraft at selected cruise altitude from Mission 1 at various ranges. This mission is where the hybrid aircraft has the most pronounced advantage over the baseline aircraft in this study. The concept of operations is shown in Figure 13. In this mission, the payload was held fixed at the design payload of 62 passengers. For the hybrid aircraft, the electric power split was optimized based on minimizing fuel burn for the specified range. For the conventional aircraft, the takeoff weight was allowed to fluctuate for each point. This mission is the only comparison point where the conventional model was run at multiple points and where the conventional model takeoff weight was allowed to fluctuate. For each point, the following constraints are in place.

minimize	fuel burn
with respect to	takeoff weight (conventional)
	cruise power split (hybrid)
subject to	$MTOW \geq GTOW = W_{OEW} + W_{Payload} + W_{Fuel} + W_{Battery}$ (conv.)
	$GTOW = MTOW = W_{OEW} + W_{Payload} + W_{Fuel} + W_{Battery}$ (hybrid)
	$W_{Fuel} = W_{Fuel,\ burned} + W_{Fuel,\ reserve\ mission} + W_{Fuel,\ reserve}$
	battery energy required $\leq$ battery energy available
	range flown $\geq$ target range

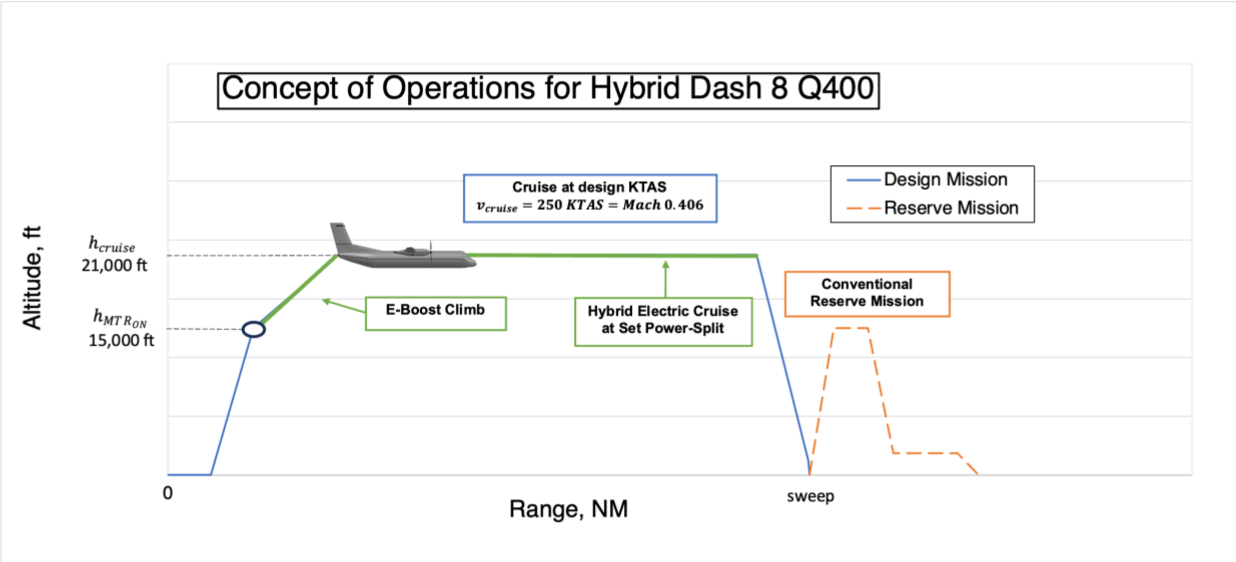

Figure 13. Concept of Operations for Mission 3: Off-design Range Sweep

Mission 3 shows a block fuel savings compared to the conventional vehicle of up to 6% at shorter ranges (Figure 14). This mission was the only one that varied the takeoff weight of the conventional aircraft model instead of using the 750 NM design mission. The takeoff weight of the conventional aircraft varies up to 7,000 lbm lighter than the takeoff weight of the hybrid aircraft. For the hybrid aircraft, the takeoff weight is fixed at the maximum takeoff weight and the payload of the hybrid aircraft was fixed at the design 62 passengers. Mission 3 is also the only mission where the hybrid configuration has a better FBM than the conventional vehicle design (750 NM) mission FBM. The crossover point is between 500 and 600 miles in this configuration. However, when factoring in the FBM from the conventional runs at each range, there is no crossover and the conventional aircraft consumes less fuel than the hybrid aircraft at every range, with the hybrid performance being closer to the conventional performance at shorter ranges (Figure 15). Because shorter ranges are where the benefit is more pronounced, additional hybridization strategies could be looked at in future studies to make the hybrid performance FBM better than the conventional.

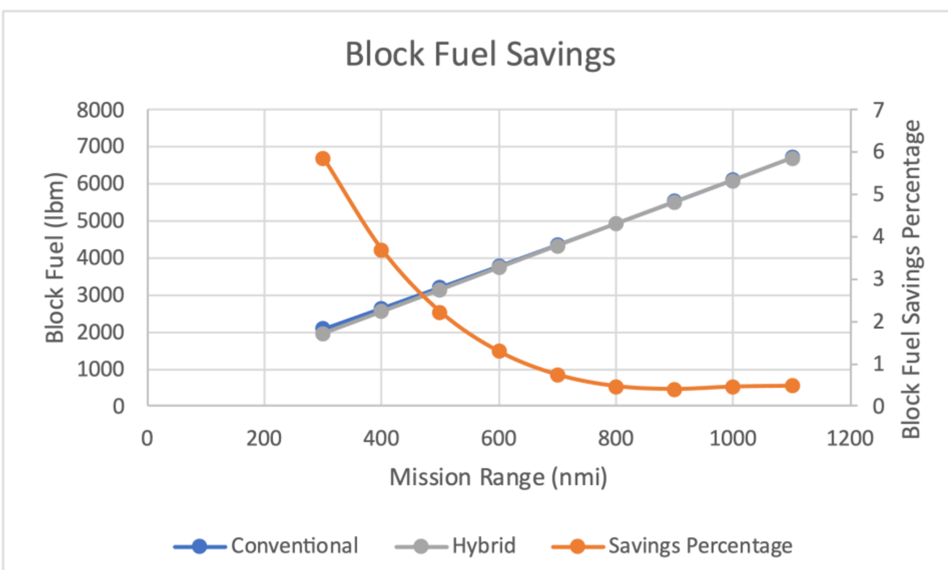

Figure 14. Block Fuel Savings for Mission 3: Off-design Range Sweep

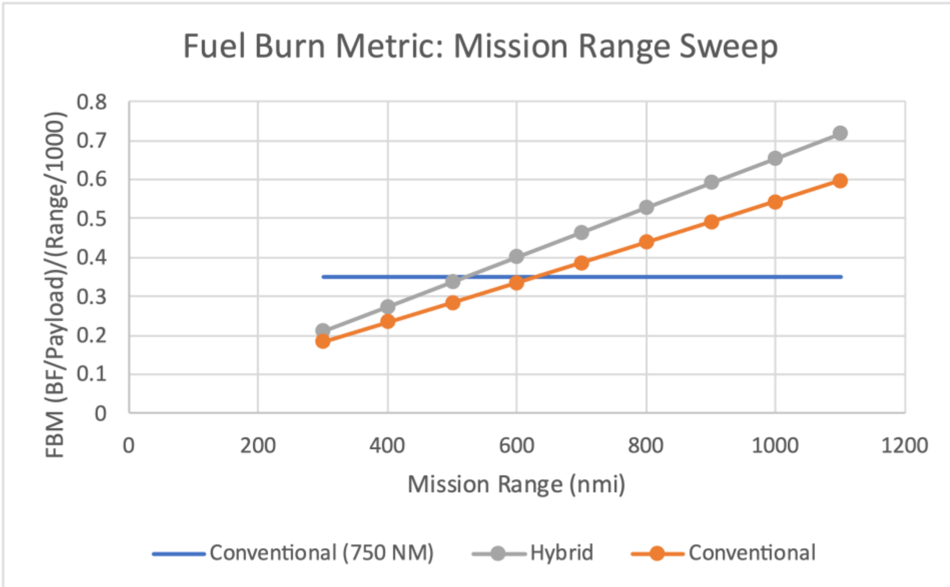

Figure 15. Fuel Burn Metric for Mission 3: Off-design Range Sweep

The goal of Mission 4 is to determine optimal cruise altitude where e-boost only takes effect above conventional aircraft ceiling. This mission is very similar to Mission 1, with the primary difference being the altitude at which the motor turns on is 25,000 ft instead of 15,000 ft. The concept of operations is shown in Figure 16. Hybrid cruise can be used by the model if the aircraft's conventional engines cannot provide enough thrust at high altitude. For each point, the following constraints are in place; these are the same constraints as in Mission 1.

minimize	fuel burn
with respect to	payload
subject to	$GTOW = MTOW = W_{OEW} + W_{Payload} + W_{Fuel} + W_{Battery}$
	$W_{Fuel} = W_{Fuel,\ burned} + W_{Fuel,\ reserve\ mission} + W_{Fuel,\ reserve}$
	battery energy required $\leq$ battery energy available
	range flown $\geq$ target range
	cruise altitude = defined cruise altitude

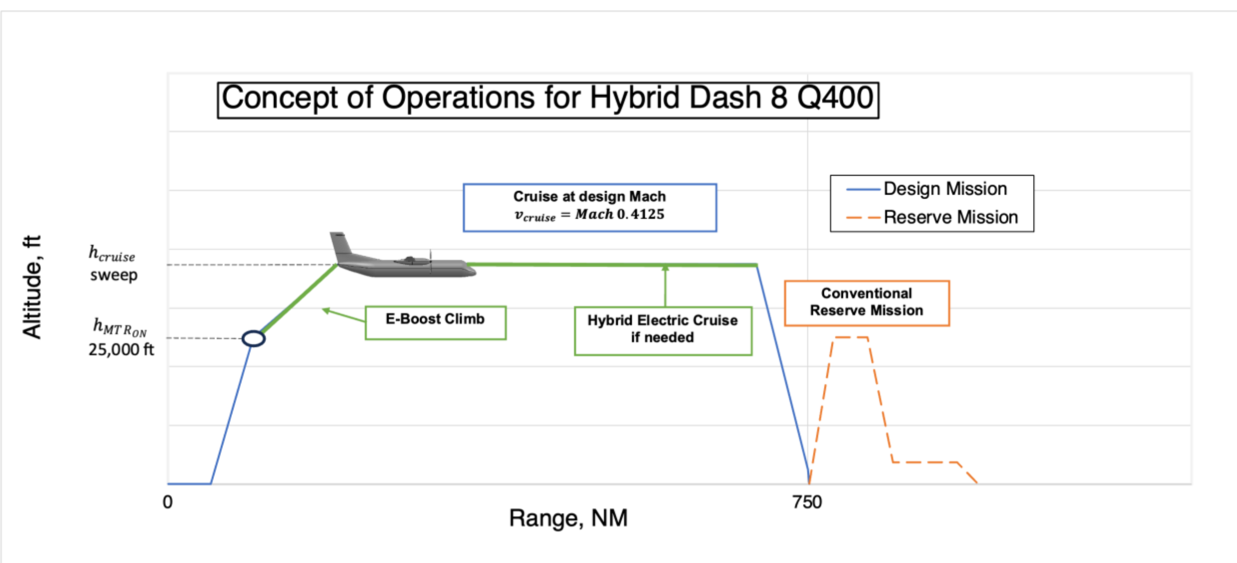

Figure 16. Concept of Operations for Mission 4: 750 NM High E-boost On Altitude

Mission 4 shows similar results to Mission 1, where the lowest FBM is the highest altitude flown without adding any battery weight, 25,000 ft (Figure 18). At higher altitudes, where battery weight is added at the expense of payload, the FBM climbs away from the conventional baseline. The block fuel savings are highest at a higher altitude though, 27,000 ft. Because of the added weight of the EAP system, the block fuel savings are less than 2% at most. Even though there is a block fuel savings at 26,000 to 29,000 ft cruise altitude, these ranges also have payload reduction (Figure 17). The fuel burn metric is lower for Mission 4 than Mission 1, as the higher e-boost on altitude means that less battery energy is needed to complete the mission, thus less battery weight, thus the aircraft can carry more payload, thus the fuel burn metric is lower. However, the fuel burn metric is still well above that of the baseline conventional aircraft.

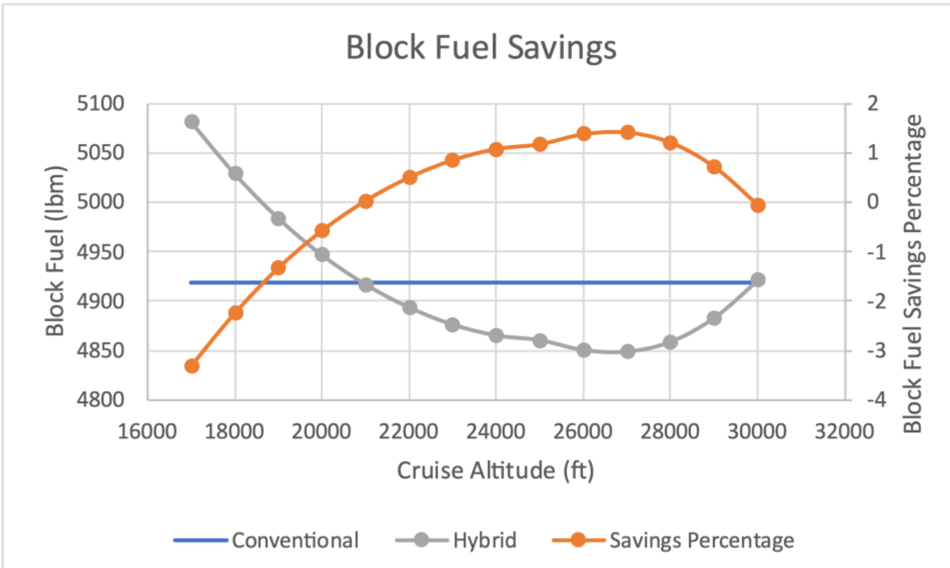

Figure 17. Block Fuel Savings for Mission 4: 750 NM High E-boost On Altitude

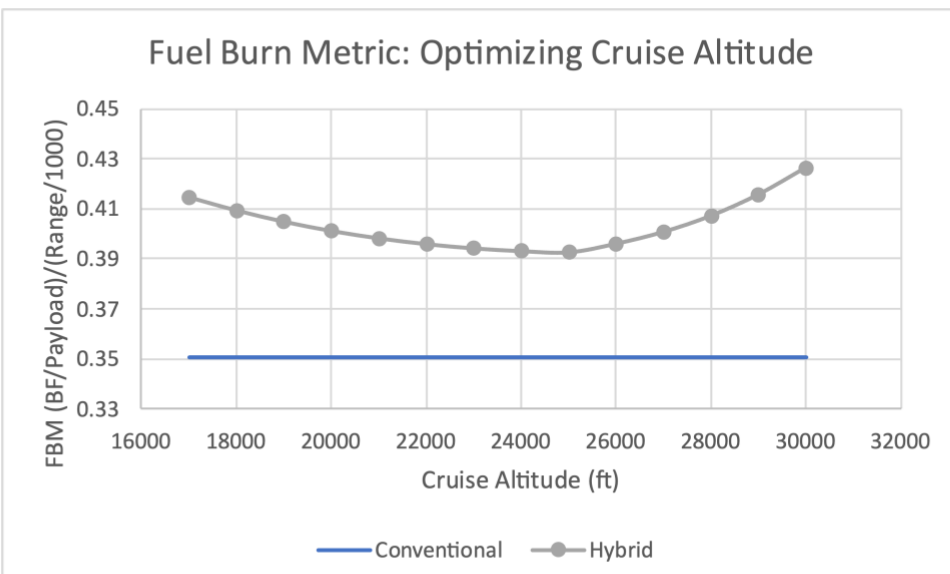

Figure 18. Fuel Burn Metric for Mission 4: 750 NM High E-boost On Altitude

Conclusion and Future Work

This paper presented new tooling development and results of a parallel hybrid DHC-8-400 turboprop model in Gascon. New tooling was required to analyze the parallel hybrid architecture, which consists of an electric motor connected via gearbox to the power turbine shaft of a turbine engine. Once the tooling was implemented, a study was conducted to parametrically identify the performance of both a conventional and hybrid-electric DHC-8-400 turboprop. The parametric model was created to match published key performance parameters of the conventional aircraft. A hybrid-electric model was then developed from the conventional model. The conventional and hybrid-electric models were compared to characterize the maximum range and fuel savings, and to explore electric power scheduling strategies for a 750 nautical mile design mission.

The parallel hybrid turboprop concept is a stepping stone from conventional to all-electric flight. With state-of-the-art technology, this hybrid configuration of the DHC-8-400 does not compete with the conventional aircraft based on fuel burn metric (FBM). Adding the motors, inverters, converters, and cabling adds weight that results in either increased empty weight or reduced payload capacity relative to the conventional baseline vehicle. However, minor block fuel savings can still be achieved, especially at lower payloads or shorter ranges, while maintaining some payload capabilities. Future work could evaluate the network environment for this class of aircraft to determine an acceptable penalty to range in return for improved fuel burn or determine whether a clean-sheet hybrid aircraft would be more competitive than this retrofit-style analysis.

This paper is the start of investigations of parallel hybrid configuration modeling and optimization. This study focuses only on approximately state-of-the-art technologies; increasing battery specific energy could have a significant impact on these results and could be studied in the future. Two major technologies which were not looked at in this study which could make this concept more competitive on the basis of FBM are e-taxi and re-sizing the conventional engines. Future work may include exploring those technologies, additional optimization tests, tradeoffs between fuel, battery, and payload weight, and the use of e-boost for other parts of the mission. Additional studies could be done to define the full trade space, looking at a range of technology improvements including increased battery specific energy and improved turbine engine efficiency. Although this study looked at only a single, large two-engine turboprop, future studies could also investigate a range of turboprop sizes to evaluate how vehicle benefits and power/energy requirements scale with aircraft size.

Acknowledgements

The authors would like to acknowledge Aaron Anderson, Caroline Kuhnle and Lee Kohlman at NASA Glenn Research Center for providing the MATLAB motor model and NPSS PW150A engine model used for this study. This work was supported by the Electrified Powertrain Flight Demonstration (EPFD) project, with special acknowledgements to Kevin D. James and Andrew J. Meade, EPFD Systems Analysis leads.

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