Hybrid Electric Turboprop Commercial Freighter (HETCOF) Market Study

Jacob M. Wishart[1]
Volpe National Transportation Systems Center, Cambridge, MA, 02142, United States of America

Ralph H. Jansen[2]
NASA Glenn Research Center, Brook Park, OH, 44135, United States of America

Kendall Mahavier, Kaitlin Coppinger[3]
Volpe National Transportation Systems Center, Cambridge, MA, 02142, United States of America

The dedicated air cargo and freight market has the potential to be a critical early pathway for emerging technologies in low to zero emission propulsion. This study analyzes the cargo aviation market to understand current market trends and future market viability of a mid-sized all-electric or hybrid-electric concept aircraft. While cargo aviation's overall emissions footprint is small relative to commercial passenger aviation, it remains an important and challenging transportation sector to decarbonize. Past research has focused on small, less than 19-seat electrified aircraft propulsion concepts that could serve both passenger and air cargo markets. This study extends the electrified market space into larger aircraft classes, considering if a purpose-built large hybrid electric turboprop freighter can compete in the market currently served primarily by conversion narrowbody freighters. Specifically, this paper focuses on the mid-sized cargo market with payload ranges of 40,000-50,000lbs, and an all-electric range potential up to 750 miles. The concept aircraft is based on a 4-engine turboprop configuration, with wing mounted battery packs and an aft cargo door to allow for standardized palletization. The market analysis indicates broad market coverage with 73% of the existing mid-sized cargo network within the range of 750 miles. A breakeven analysis of operating and capital costs shows potential for market competition; however, this would require additional energy and acquisition cost savings from the concept aircraft. Evidence from the breakeven analysis also points to higher rates of aircraft utilization being a critical path to lowering costs and increasing cost effectiveness.

I. Introduction

This study focuses on the market size and cost requirements for a purpose-built Hybrid Electric Turboprop COmmercial Freighter (HETCOF) operating in a market that is currently served primarily by repurposed large narrowbody freighters. We refer to the concept as the HETCOF aircraft. For the purposes of this work, we assume technical performance and operational approaches to evaluate the economics. Other studies and papers are underway and being written to describe the technical and operational advancements beyond the state of the art that would be needed to realize the HETCOF freighter. The HETCOF freighter concept is based on an airframe like the Lockheed LM-100 with an advanced hybrid electric system at the technology levels needed for the HETCOF narrowbody aircraft. This combination allows fully electric operation for a portion of the aircraft range and hybrid electric operation

[1] Economist, US Department of Transportation.
[2] Technical Management, Aeronautics Mission Office, NASA Glenn Research Center, AIAA Member
[3] Economist, US Department of Transportation.

to full range. We consider if this set of characteristics allows a large portion of operations to be done in electric mode while retaining the ability to perform a small number of longer-range flights when required.

Research and development into electric aircraft has developed rapidly within the last several years. While much of the initial development has been geared toward urban air taxis, there has been movement in larger electric and hybrid aircraft designs. Wright is developing a zero-emissions, 100-passenger plane designed for short-haul flights, with an initial limit of a one-hour flight time. Wright's goal is to have the initial version of the Wright Spirit ready for deployment by 2027 [1]. Ampaire is also developing electric passenger planes, with plane designs currently ranging from 3 to 19 passengers [2]. MagniX is an electric motor manufacturer for electric aircraft and has had multiple successful test flights with a variety of aircraft. In 2023, a hydrogen electric De Havilland Dash 8, powered by a magni650 emergency power unit (EPU) broke the record for the longest electric flight [3]. These examples indicate that there is emerging interest in electric aircraft similar to the HETCOF concept.

The paper is structured as follows: Section II defines the aircraft concept; Section III presents the cargo aviation market size analysis; Section IV provides the breakeven cost requirements with various assumptions; and Section V provides a conclusion of the market analysis and breakeven analysis results.

II. Cargo Aircraft Concept Design and Description

The HETCOF aircraft concept design leverages the advanced electrified aircraft propulsion (EAP) system under development in the subsonic single aft engine (SUSAN) regional narrowbody concept and implement it on a large 4 engine turboprop based on the existing Lockheed Martin LM-100 airframe, creating an initial hybrid electric freighter concept. The Lockheed LM-100 is the commercial market version of the widely used C-130 military transport. The purpose-built HETCOF is intended to compete in the regional mid-sized market currently served by repurposed narrow body aircraft. A key question to address is whether the addition of an advanced EAP system can reduce the total operating costs enough to be competitive. Market size, operating and ownership costs, and technical questions need to be addressed to make the determination of cost and market competitiveness. The aircraft is equipped with 4 turboprop engines (see Figure 1) designed to use a mix of electrified or jet fuel energy sources: initially 2 turboprops will be replaced with multi megawatt electric engines.[4] Removable battery packs are mounted on the wing of the aircraft in place of the reserve jet-fuel tankers. For more information on the technical and performance characteristics of the HETCOF concept, please refer to recent study by Pham et al. (2024) [4, 5].

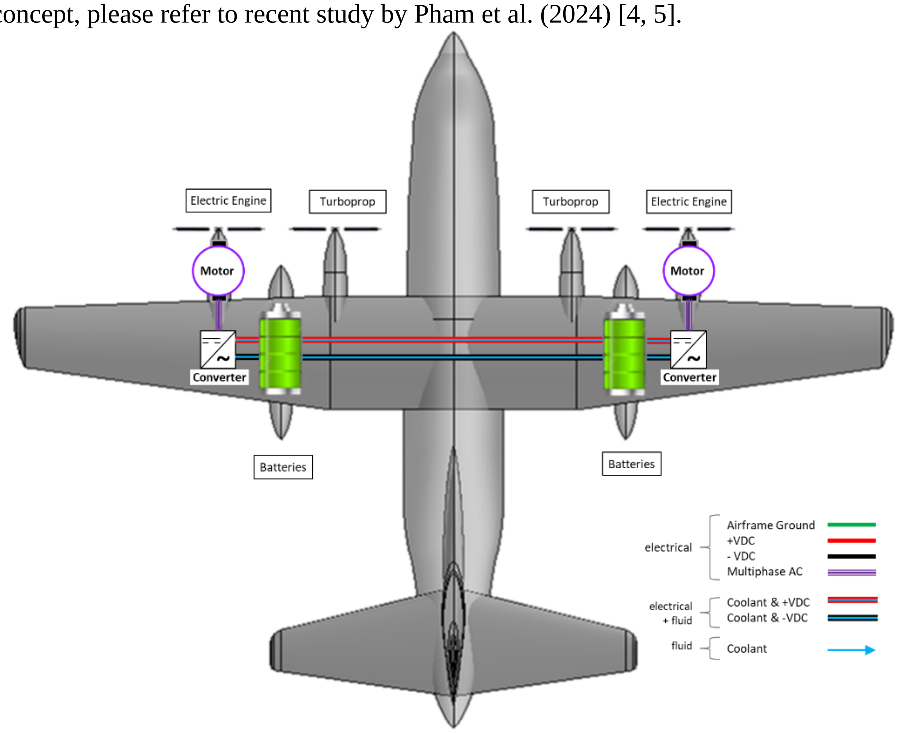


Fig. 1 HETCOF Propulsion Diagram

[4] Additionally, the engines are assumed to be capable of using drop-in sustainable aviation fuels (SAF).

The aircraft is designed to have similar operating characteristics as the existing C-130 aircraft, with up to 40,000lbs (maximum of 50,000lbs) of useful cargo capacity, translated into 4,950 ft^3 of cargo volume. Since the battery packs are assumed to be wing-mounted, there are no limitations to the available payload or volume in the fuselage. Moreover, the aircraft utilizes an aft cargo door which can hold up to 8 standardized pallets. Assumptions on all-electric ranges are based on battery technology levels to allow for flights up to 250, 500 and 750 miles, with a standard maximum range of 2,400 miles in hybrid flight. Based on these design characteristics, the aircraft is expected to compete directly with existing narrowbody freighters based on converted passenger aircraft, namely the B737 family of aircraft.[5]

III. Cargo Aviation Market Analysis

Air cargo provides a critical link to the global supply chain, transporting high value and time sensitive goods (e.g., computer chips, manufacturing equipment, robotics, luxury goods, and medical equipment). The air cargo market in 2021 transported over $6 trillion in goods and represented 35% of global trade valuation while making up less than 1% of total freight volume [6]. The combined US domestic and international air cargo market makes up a significant portion of total freight ton miles (FTM) with 28% of the world share in 2023 [7]. Historically, the US market has been dominated by two carriers, FedEx and UPS, with additional carrier services provided by third party contractors for the big two. Amazon Air has also recently entered the market space, with daily cargo flights reaching over 200 by March 2023 [8] (not including third-party contractors, FedEx and UPS had 832 and 481 flights per day in 2022, respectively).[6]

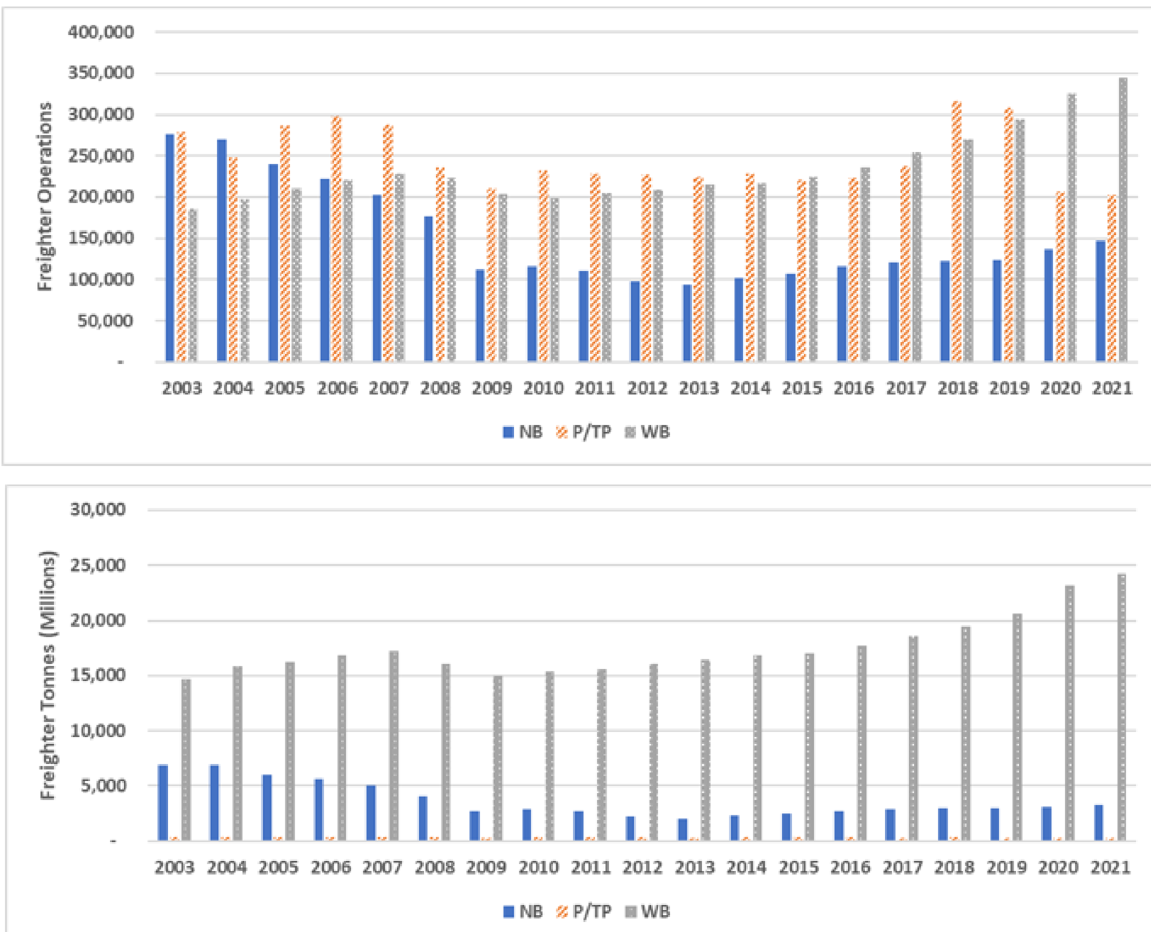


Fig. 2 US Domestic Freighter Operations and Freight Tons by Aircraft Type

Figure 2 presents a comparison of domestic US operations and freight tons by cargo aircraft types over the period 2003-2021, sourced from the Bureau of Transportation Statistics (BTS) T-100 air carrier statistics. Widebody (WB)

---

[5] The B737 converted freighters have approximately the same payload and volume capacity. More details are provided in Table 4 in Section IV.

[6] A comparison of total freight by domestic US air cargo carriers is presented in the appendix.

cargo aircraft make up a significant majority of freight tons over the course of historical time series, mainly being served by mix of purpose-built and passenger conversion A300s, A330s, B767s, B747s and B777s. The narrowbody (NB) market has seen its market share slowly diminish over this period, holding 31% of freight share in 2003 dropping to 11% by 2021. The narrowbody market is also entirely composed of passenger conversion aircraft, with older B727s replaced with larger B737s and B757s over the historical period. Finally, the turboprop and small piston (P/TP) cargo aircraft make up less than 1% of total freighter, however, they are still an important contributor to carrier networks providing feeder service to smaller, regional airports.

Focusing on the narrowbody network, one of the key considerations for this market analysis is to measure the share of operations that occur within the all-electric range assumptions of 250, 500 and 750 miles. Figure 3 presents a heat map of the narrowbody cargo domestic market identifying the operational density by payload and distance in 2019. The blue call-out box isolates the space the HETCOF is anticipated to have full-electric range coverage, with a majority of the network appearing to be covered in terms of operations. Table 1 breaks down the cumulative operations by distance ranges for this market further, showing 28% operations occur up to 250 miles, 53% of operations up to 500 miles, and 73% of operations up to 750 miles. The range coverage up to 750 miles is also consistent with the network maps for FedEx and UPS, which broad distance coverage from their respective mega-hubs (FedEx – Memphis, TN, and UPS – Louisville, KY).[7] Taken together, these results indicate broad market coverage for the all-electric thresholds of the HETCOF.

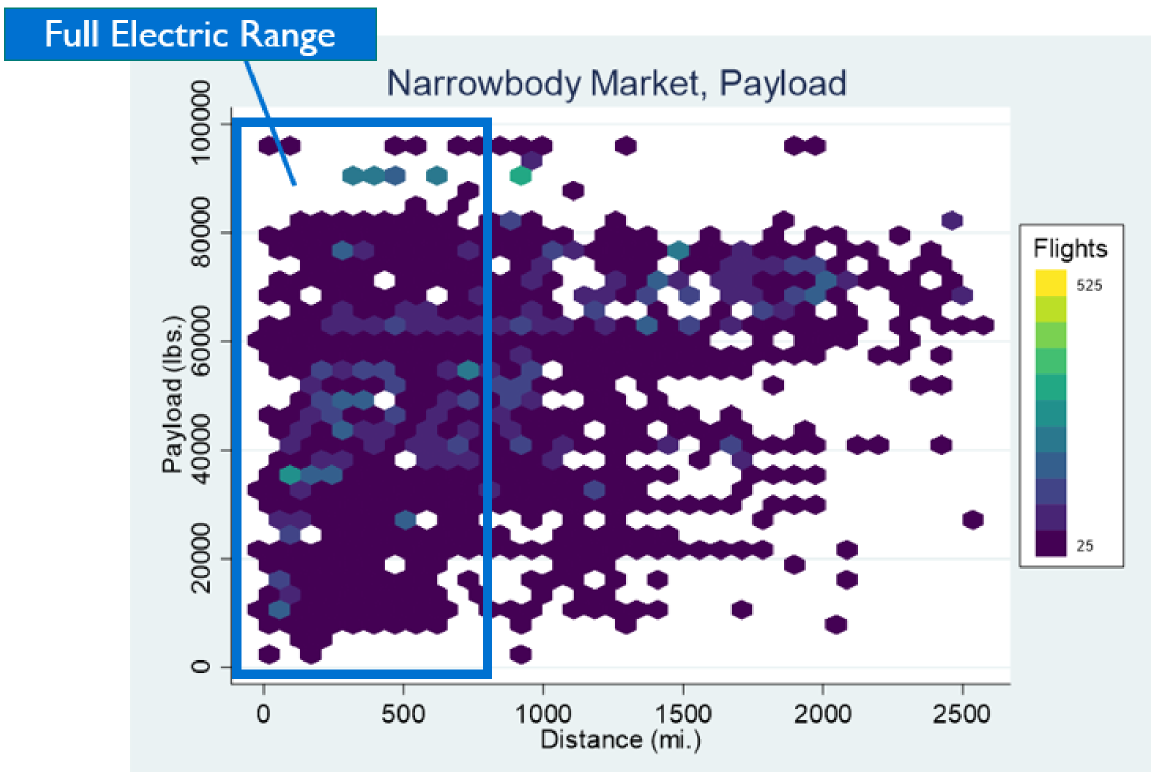


Fig. 3 Operations Heatmap of Narrowbody Market by Payload and Distance Range

[7] Network figures presented in the appendix.

Table 1 Narrowbody Cargo Operations in 2019 by Distance Ranges

Distance Band	Narrowbody Cargo Operations in 2019	
	Count of Flights	Cumulative Total Flights
0-250 miles	34,352	28%
251-500	31,098	53%
501-750	24,279	73%
751-900	8,062	80%
901-1100	9,970	88%
1101-1500	7,447	95%
1501-2000	8,068	99%
2001-2500	582	100%
2501-3000	7	100%
2019 Total by Market Type	123,865	100%
Relevant Flights (<750)	89,729	73%

Source: BTS T-100

In addition to the network and range requirements, it is also important to consider fleet delivery and utilization rates in the air cargo market and how this could apply to the HETCOF concept aircraft. Table 2 details delivery rates for passenger and cargo aircraft families over a program lifecycle. The passenger aircraft families listed include the B737 NextGen (NG) and MAX programs, in addition to the B757, and the B767 families, and show large volumes of production (or expected production in the MAX case), which is a critical requirement for OEM's return on investment and profitability. Large, sustained production levels allow for an iterative cycle of 'learning by doing' and economies of scale that bring down costs, while also allowing for bulk order discounts for airlines. However, no such market exists for the narrowbody purpose-built cargo market. Boeing was able to leverage its existing B767 passenger program into a successful purpose-built cargo aircraft with nearly 300 combined order and deliveries, compared to only 114 deliveries of the legacy civilian version of the LM100 that saw limited production over its program life.

The second key metric to consider is the utilization rates of aircraft by market, which are presented in Table 3. Narrowbody passenger aircraft perform twice as many operations and nearly 3 times more block hours (gate to gate time) annually compared to the freighter narrowbodies. Widebody cargo utilization differs marginally by type, with purpose-built cargo aircraft operating similarly to those in the passenger market. The core reason for this comes down expected utilization rates and the need for carriers to seek higher utilization by new aircraft, which will have lower operational costs, to justify the higher cost of capital. Air cargo carriers can only accomplish this by operating aircraft at similar rates to passenger aircraft, which does occur in the purpose-built widebody cargo market.

The current business model for air cargo carriers seems to favor the use of secondhand, converted freighters for narrowbody cargo operations and a mix of purpose-built and converted widebodies. The potential development of a purpose-built narrowbody cargo aircraft ultimately comes down to the level of demand and the cost of owning and operating the aircraft. On the demand-side, narrowbody cargo aircraft still fill an important transportation role for air carriers, especially for smaller, regional airports where larger widebody aircraft would not be able to operate due to runway or facility limitations. Moreover, Boeing's 2022 World Cargo Forecast expects the global market to demand over 1,300 aircraft for fleet growth and replacement, which will currently be met by conversion aircraft only [9]. Since conversion aircraft typically reenter service a generation behind current technology levels, costs factors could play a more central role in determining the feasibility of purpose-built narrowbody aircraft as carriers look to lower costs associated with fuel and maintenance. The next section explores the cost space for the HETCOF concept aircraft and at what levels costs breakeven relative to the current conversion option.

Table 2 Aircraft Family Deliveries (Program Lifecycle)

Aircraft Family	Total Deliveries	Orders
B737 (NextGen) [10]	6,953	-
B737 (MAX)	1,313	4,485
B757	1,050	-
B767	1,052	-
B767-F	236	44
C130J (Updated Variant) [11]	496	-
LM100 (Civilian-Legacy)	114	-

Table 3 Aircraft Utilization by Market Type

Market	Utilization Rate (Annual Block Hours per Aircraft)	Annual Operations Per Aircraft
Narrowbody Passenger	3,447	1,536
Narrowbody Cargo (Conversion)	1,240	709
Widebody Passenger	4,097	725
Widebody Cargo Purpose-Built	2,945	662
Widebody Cargo Conversion	2,052	683

Breakeven Cost Analysis

To better understand the potential range of cost requirements for the HETCOF concept, a breakeven analysis was conducted to identify areas where the lifecycle costs of the concept aircraft are roughly equivalent to the lifecycle costs for a competitor aircraft. Expected cost equivalence between the aircraft is determined by the level at which cost decreases from one source (e.g., fuel/energy) balance cost increases from other sources (e.g., maintenance or capital expenditures).

1. *Methodology and Assumptions*

The methodology for the breakeven analysis leverages a similar framework developed by the authors in their previous SUSAN passenger market analysis (Wishart et al, 2023) and applied specifically to the cargo aviation market [12]. The HETCOF aircraft utilizes the characteristics of the LM-100J as its base specification and is compared against a converted passenger B737-8 aircraft across three key metrics: capital costs, maintenance costs, and fuel costs. The data and assumptions are described in Table 4.

Table 4 Breakeven Analysis Assumptions

Data Type	B737-8 Passenger Conversion	HETCOF Aircraft
Annual Operations	Varies by scenario: 700, 1100, 1500	
Distance Ranges (Miles)	250, 500, 750	
Cruise Speed (MPH)	296 (250 miles), 389 (500 miles), 432 (750 miles)	220 (250 miles), 294 (500 miles), 310 (750 miles)
Annual Block Hours	Defined as gate-to-gate time in hours. Product of operations, cruise speed and block hour adjustment factors.	
Fuel Burn	Cruise and Landing/Take-Off (LTO) sourced from FAA's AEDT [13]	Initial cruise and LTO sourced from FAA's AEDT; varies based on breakeven test
Total Cost of Fuel Burn	Fuel Burn converted to gallons and combined with price estimate of $2.18/gallon (2018$) (scenario $5/gallon)	
Maintenance Cost Per Block Hour	$574.40 – sourced from FAA BCA guidance [14]	Initially set to $574.40; varies based on breakeven test
Purchase Price	$42 million in 2018$ (discounted list price) [15]	Initially set to match B737; varies based on breakeven test
Passenger to Cargo Conversion Cost	$4.2 million in 2018$ [16]	N/A
Starting Age	27 (average narrowbody conversion fleet age in 2018)	0 (new purpose-built)
Finance Rate	7.2% [17]	
Depreciation Rate	3.4% [18-22]	

The breakeven analysis measures and compares the total operational lifecycle costs from an operator's perspective between two aircraft (excluding disposal costs). This analysis is conducted on a per-aircraft level assuming a 25-year useful life of the aircraft. Given the B737-8 is a conversion aircraft, the starting age is set to 27, whereas the HETCOF concept aircraft is purpose-built and enters service new (age 0). All other operating costs, such as crew salaries, route and landing charges etc., were assumed to be equal between the B737 conversation aircraft and HETCOF and were not included in the calculations. Additional second order costs associated with electrification were not included at this time but are worth future consideration.[8]

Block hours are the primary operation metric used in the fuel (energy) and maintenance cost metric, while capital costs are based on the individual aircraft. To maintain consistency between the aircraft where possible, the breakeven analysis assumes equivalent payload, volume, and operation levels between the aircraft, while cruise speed is allowed to vary at given distance ranges based on the difference in engine types between the aircraft. Therefore, the number of block hours required, which is calculated as the product of operations, cruise speed and block hour adjustment factors[9], to meet the set number of annual operations will vary between the two aircraft, with the HETCOF requiring more block hours due to slower cruise speeds. Block hours are assumed to be held constant by year with no change in utilization rates as the aircraft age.

The specific operating cost components under consideration in the breakeven analysis and the calculation of each cost are detailed below:

- **Fuel and energy costs:** estimated on a per block hour basis as a function of distance range specific fuel burn coefficients. The summation of cruise and LTO fuel costs is taken to estimate total fuel costs. Data on fuel burn rates were sourced from FAA's AEDT tool for the B737-8 and C130-J as a proxy for base fuel burn rates of the HETCOF concept aircraft. The breakeven analysis then varies the fuel burn rates for the HETCOF to estimate a range of expected energy savings from electrification.
- **Maintenance costs:** estimated per block hour as a function of age and the maintenance cost factor detailed in Table 4. The specific calculation for maintenance costs per block hour is the following function:[10]

$$Maintenance = maintenance.cost \times block.hours \times (3.5 - 2.5 \times (e^{-(0.0305 \times age)^{2.85}}) \qquad (1)$$

  The maintenance cost curve implies maintenance costs increase as a function of age on average by a factor of 1.5 by age 20, 2 by age 27 and 3 by age 40 [23, 24]. For the breakeven analysis, the maintenance costs are allowed to vary for the HETCOF concept aircraft.
- **Capital costs:** acquisition and cost of owning capital, as a function of age, the purchase price of the aircraft and the finance and depreciation rates. Finance and depreciation costs are estimated separately and summed together to calculate total capital costs, with finance costs decreasing and depreciation costs increasing as the aircraft age. The capital costs account for the age of the aircraft and change by year through the 25-year analysis period. The equation for the finance costs is the following function:

$$Finance = aircraft.price \ \times e^{(-depreciation.rate \times age)} \times finance.rate \qquad (2)$$

  While the equation for the depreciation costs is as follows:

$$Depreciation = aircraft.price \times (e^{(-depreciation.rate \times age)} - e^{(-depreciation.rate \times (age+1))}) \qquad (3)$$

Initially, the purchase price of the aircraft is set to be equal between the aircraft, with an additional cost included in year one for the conversion aircraft to account for the aircraft overhaul going from passenger to cargo service. Since the conversion aircraft enters service at age 27, the cost of ownership is significantly discounted relative to the new purpose-built aircraft, as the finance cost reduction vastly outweighs costs associated with depreciation. The tradeoff, however, is maintenance on an older aircraft is expected to be more costly (approximately twice as much on average

---

[8] These additional costs include aircraft infrastructure upgrades to meet electrification requirements, spare batteries and battery storage, and labor costs associated with battery technicians (training and salaries).

[9] The block hour adjustment factors were estimated using BTS Form 41 data on aircraft specific flight time and block time (in hours) to constructed ratios for each aircraft type: adjustment factor = block hours/flight hours.

[10] Parameterization of the maintenance cost curve based on US government modeling support for ICAO CAEP environmental analyses.

by age 27). All else being equal, this tradeoff goes in the favor of operating the conversion aircraft under the baseline case and validates one of the key conclusions from the market analysis in the previous section: no market exists for purpose-built cargo aircraft simply because they are more expensive on average to operate. Therefore, cost savings will need to be realized to justify OEMs entering this market, and the breakeven analysis explores this space by varying the fuel, maintenance, and capital costs.

To identify when the HETCOF aircraft is cost-effective relative to competitors, the cost elements from the competitor aircraft are subtracted from the HETCOF aircraft costs for a given year and are then summed over the entire 25-year analysis period. If the total difference is negative, this means that the HETCOF aircraft is cost-effective, as the savings from one cost element outweigh the increases in others. If the total difference is positive, then the HETCOF aircraft is more costly, as the increases from one set outweigh the reduction in the other. A value of 0 is determined to be the breakeven point at which the cost increases are exactly balanced by the cost reductions.

2. Breakeven Results

The breakeven cost results are presented in Table 5 and breakeven lines are presented in Figures 4-6 for the three distance ranges (250, 500 and 750 miles) and fuel burn reduction scenarios (-30, -40, and -50%) under consideration. The initial set of results assumes 700 annual operations at each distance range, which is consistent with current cargo narrowbody operation levels. At an average 250-mile distance range per operation, the results indicate additional cost reductions are needed in purchase price or maintenance costs at all three fuel burn reduction scenarios for the HETCOF to be cost equivalent to the conversion aircraft. Setting the distance to 250 miles limits the benefits gained from lower energy costs as utilization levels, measured by total block hours, are too low to balance the increase cost of owning the new aircraft relative to the second-hand conversion. At the highest fuel burn reduction level (-50%), the purchase price would also need to be reduced by 13% (holding maintenance constant) or maintenance costs would need to fall -56% (holding purchase price constant).

At 500 miles, the additional required reduction in other cost categories is minimized, and by the highest fuel burn reduction scenario, the results nearly breakeven with almost no changes required from other sources. Increasing the average distance to 500 miles improves the overall cost-effectiveness of the HETCOF by increasing the total block hours flown and thus the gains from fuel cost savings. This effect, combined with lower average maintenance costs (per block hour) relative to the conversion aircraft, balances out the higher cost of capital.

The results at the highest average distance range (750 miles) show the strongest cost-effectiveness results for the HETCOF, with every fuel burn scenario breakeven line in Figure 6 above and to the right of the origin. This result suggests that at a given fuel burn reduction level, costs could increase for either capital or maintenance and the HETCOF would still breakeven relative to the conversion aircraft. At the highest fuel reduction scenario, maintenance costs could increase by 73% (holding purchase price constant) or purchase prices could increase by 37% (holding maintenance costs constant) and the HETCOF would still breakeven. A clear pattern emerges when considering the results at the three distance range assumptions where the HETCOF is most competitive when the annual level of block hours is increased for the two aircraft. The reason for this, as discussed above, is straightforward: increasing the level of utilization of the HETCOF improves the cost-effectiveness of the aircraft, allowing it to take advantage of improved energy efficiency and lower maintenance costs over a larger number of block hours performed, lowering the impact of higher relative capital costs.

Table 5 Breakeven Cost Analysis Results

Fuel Burn Change	***Distance Range – 250 Miles***		***Distance Range – 500 Miles***		***Distance Range – 750 Miles***	
	Purchase Price Change	**Maintenance Cost Change**	**Purchase Price Change**	**Maintenance Cost Change**	**Purchase Price Change**	**Maintenance Cost Change**
-30%	0%	-86%	0%	-35%	0%	34%
-30%	-20%	0%	-13%	0%	17%	0%
-30%	-30%	41%	-20%	21%	10%	14%
-40%	0%	-71%	0%	-16%	0%	53%
-40%	-17%	0%	-6%	0%	27%	0%
-40%	-30%	56%	-20%	41%	15%	24%
-50%	0%	-56%	0%	-4%	0%	73%
-50%	-13%	0%	1%	0%	37%	0%
-50%	-30%	71%	-20%	60%	20%	33%

Note: Results based on 700 annual operations, negative values indicate reduction in costs.

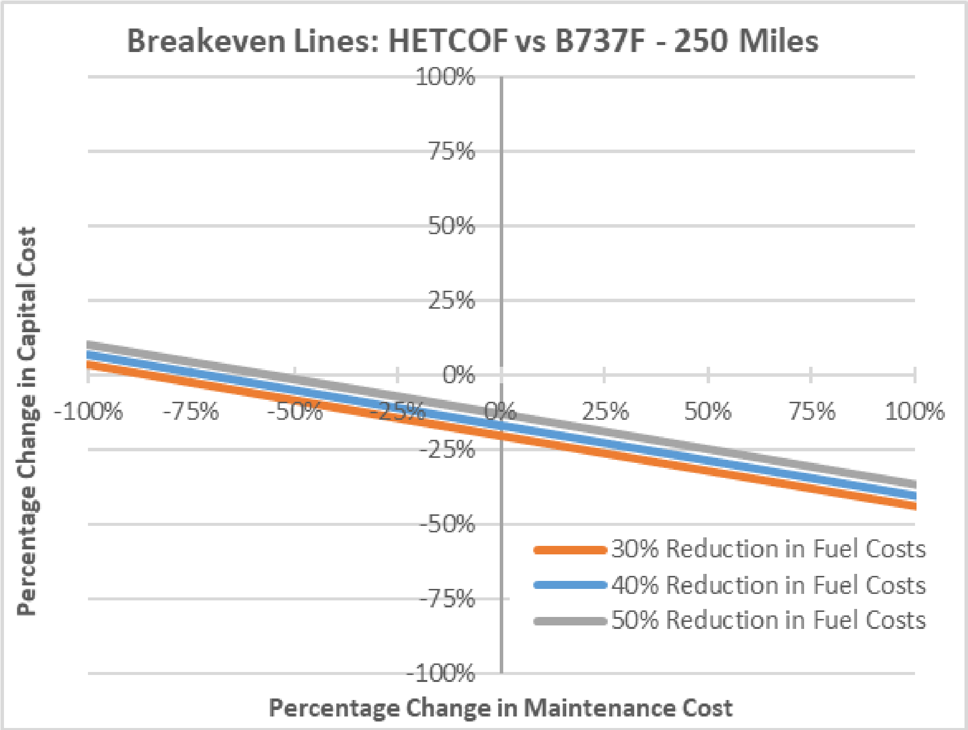


Fig. 4 Breakeven Rates at 250 Miles by Fuel Reduction Scenarios

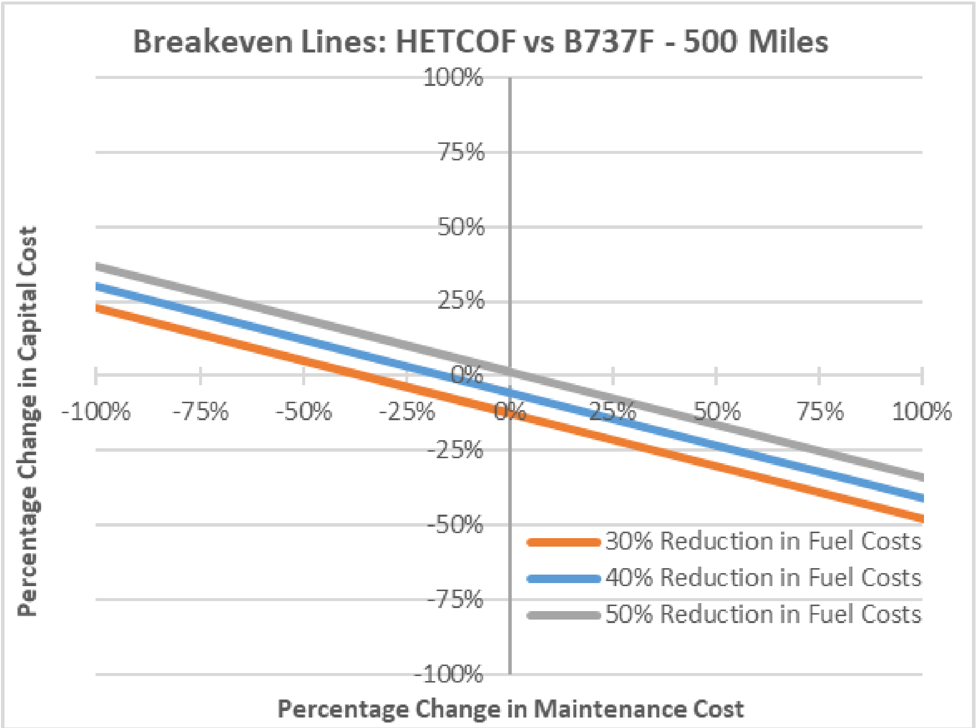


Fig. 5 Breakeven Rates at 500 Miles by Fuel Reduction Scenarios

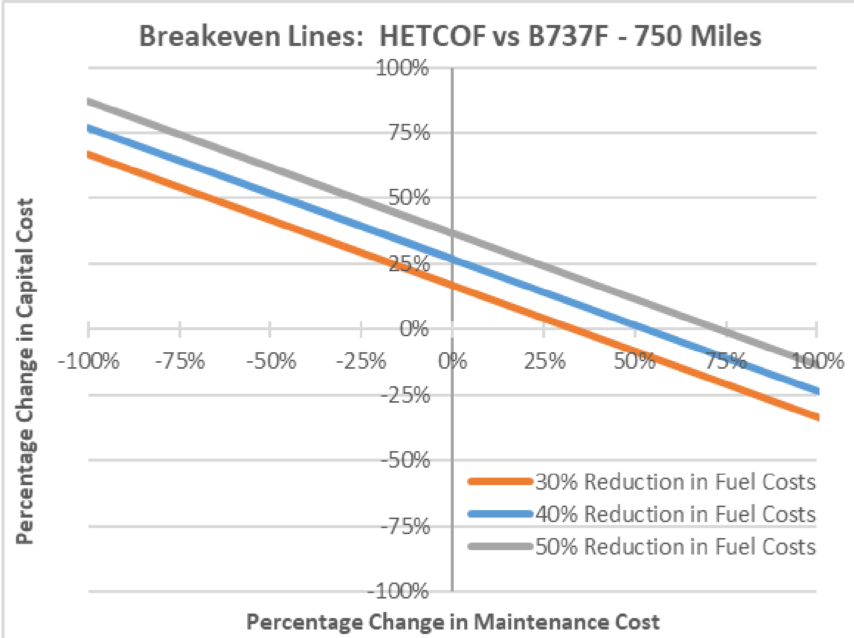


Fig. 6 Breakeven Rates at 750 Miles by Fuel Reduction Scenarios

To examine input assumptions for utilization rates and fuel price values in more detail, annual operations were increased from 700 to 1,110 and 1,500, and separately, fuel prices were increased from $2.18 to $5 per gallon to gauge the impacts on the breakeven analysis space. These results for the two separate scenarios are presented in Figure 7 and 8, both showing improved cost effectiveness with increases in utilization rates or fuel price levels. For the utilization rate test, an average distance range of 750 miles per operation and a 40% reduction in fuel is assumed, which pushes the breakeven line up and to the right, significantly increasing the range of potential cost increases for both capital and maintenance. The fuel price test assumes an average distance of 750 miles per operation at the three fuel reduction scenarios, also moving the breakeven lines up and to the right in parallel with each other, increasing the range of potential cost increases to still breakeven. These results are to be expected and suggest there is significant potential room for cost-effectiveness conditional on expected utilization rates of the HETCOF aircraft or higher future fuel prices.

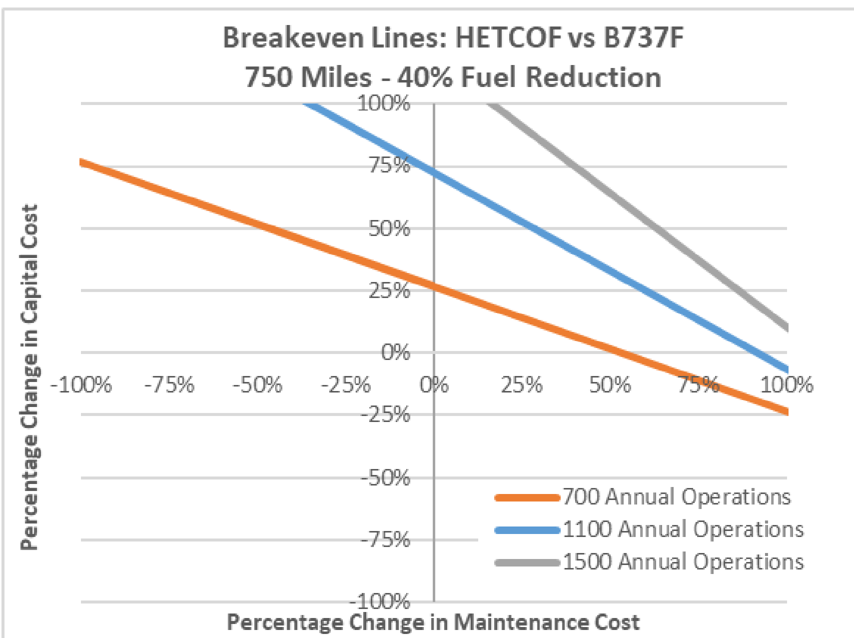


Fig. 7 Breakeven Rates by Alternative Annual Operation Levels

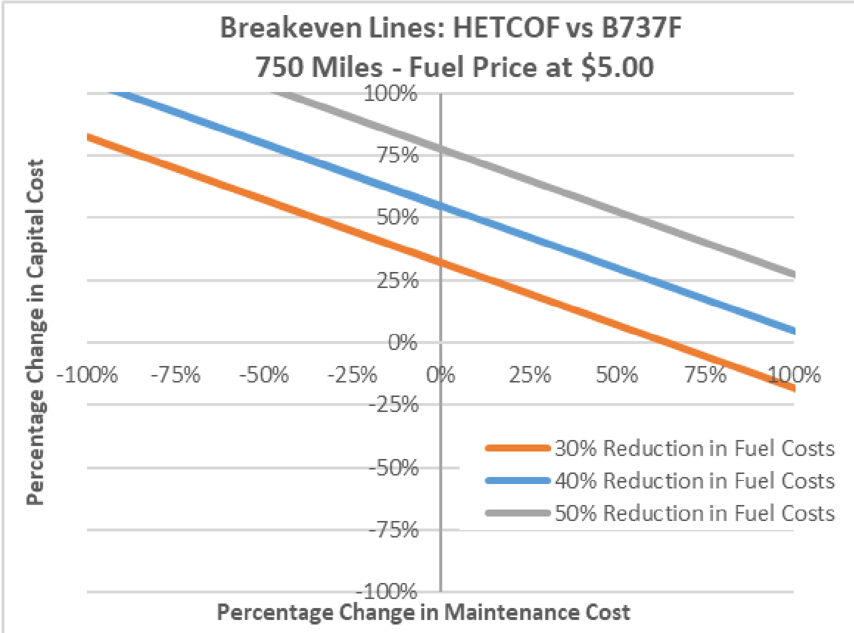


Fig. 8 Breakeven Rates by Alternative Fuel Price

IV. Acknowledgements

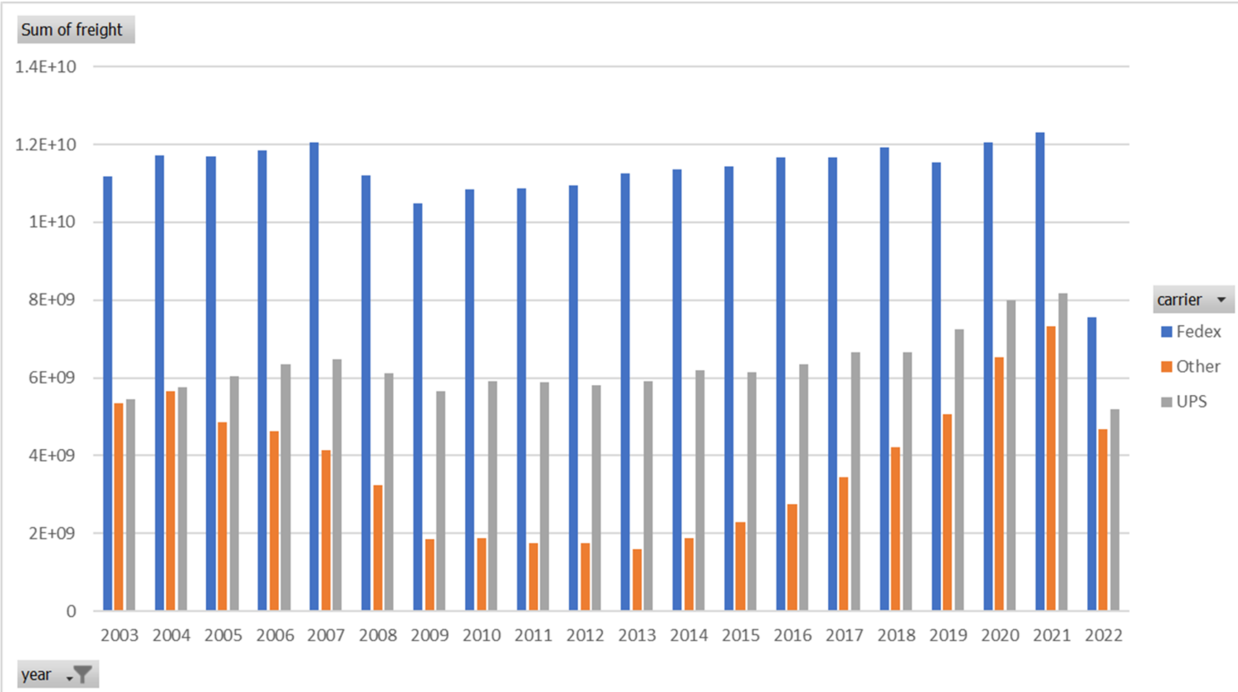
The authors would like to acknowledge the support and review by our colleagues at the US DOT Volpe Center and NASA Glenn and NASA Ames Research Centers, including David Pace, Seamus McGovern, Mary Reveley. Additional the authors would like to thank Dahlia Pham and the other authors on the related technical concept papers [4,5]. This work was funded by the Convergent Aeronautics Project Subsonic Single Aft Engine (SUSAN) activity.

V. Conclusion

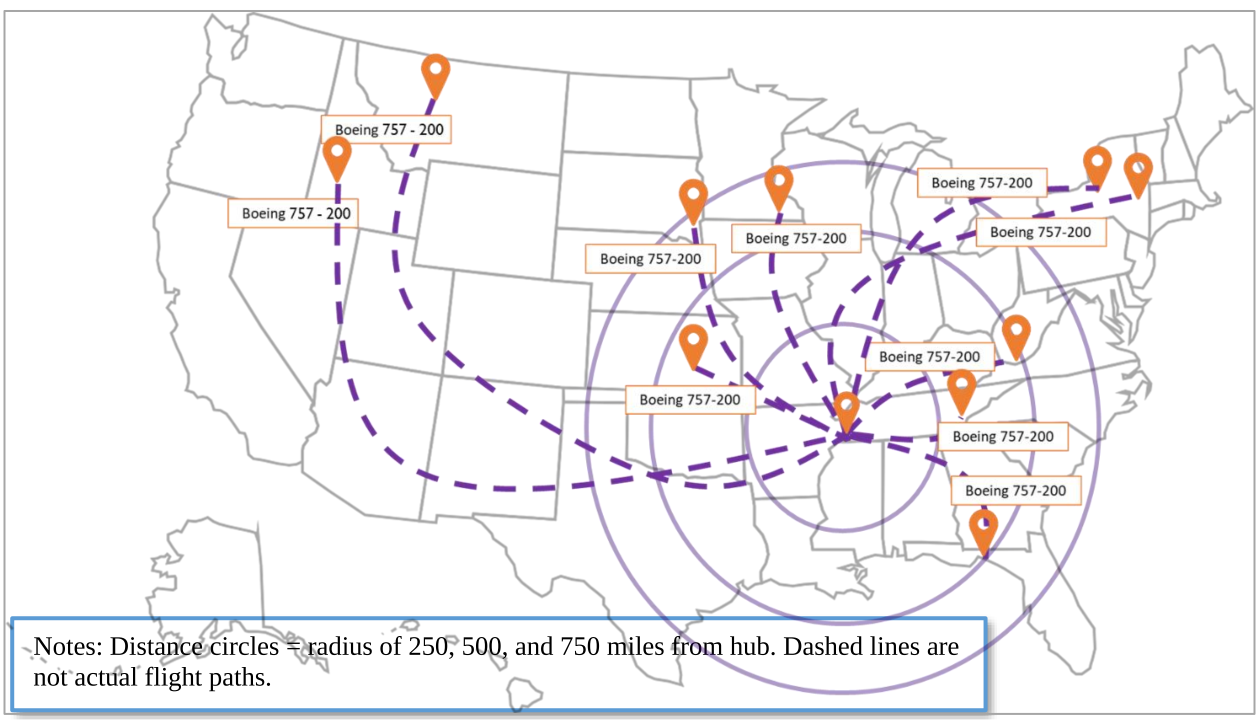
A significant market exists for the HETCOF if the performance and operational requirements can be achieved through technical and system integration advancements beyond the state of the art. The cost requirements are a challenge for initial market penetration; however, the analysis shows that under certain conditions the total cost of ownership and operation may be less than converted narrowbody aircraft that currently serve the market. Significant advancements would need to be made to reduce costs associated with the HETCOF in practice. The specific technical areas, system integration concepts, and operational concepts are being considered under other studies. Future work on market considerations should focus on second order issues for electrification and required airport infrastructure to support such an aircraft, similar to previous studies conducted by NREL [25].

Appendix

Fig. A1 US Domestic Air Cargo Freight Ton Miles by Carrier (BTS T-100, 2003-2022)



ig. A2 FedEx Network – Narrowbody Operations (2019-2022)



Notes: Distance circles = radius of 250, 500, and 750 miles from hub. Dashed lines are not actual flight paths.

Fig. A3 UPS Network – Narrowbody Operations (2019-2022)

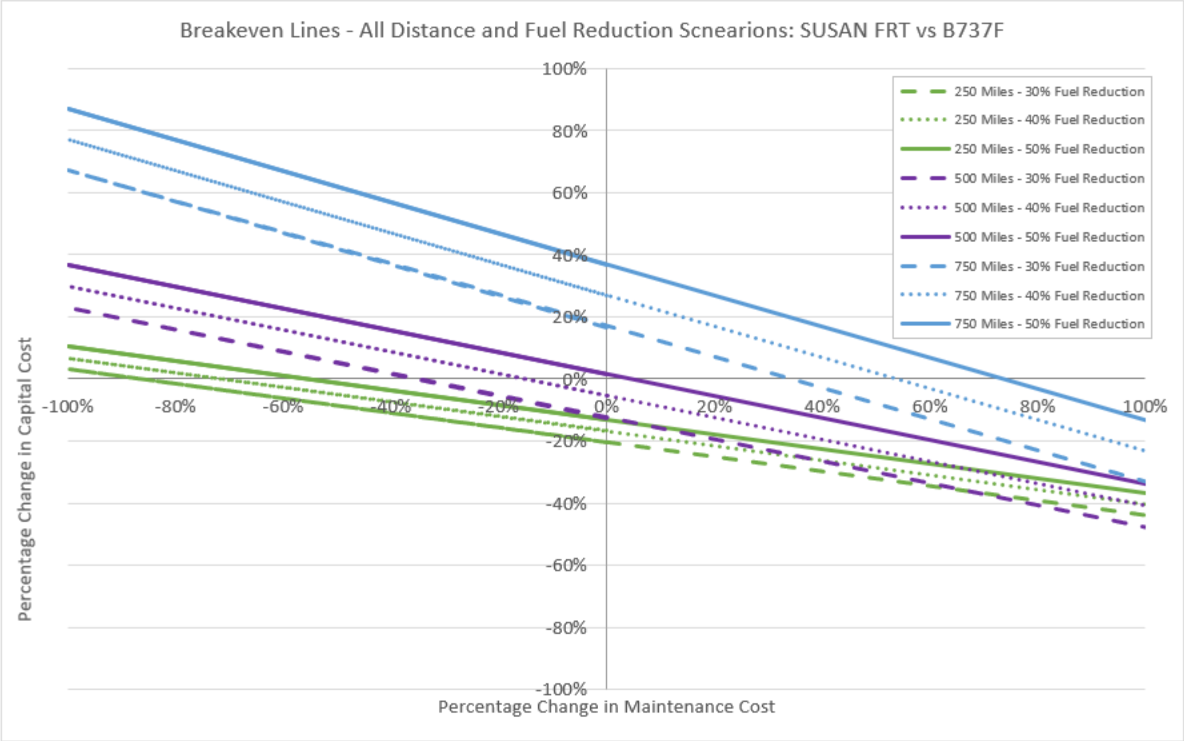


Fig. A4 Breakeven Lines for Combined Distance and Fuel Reduction Scenarios

References

[1] Wright Electric, Inc. “About Wright.” Available: https://www.weflywright.com/about

[2] Ampaire Inc. “Tailwind Aircraft”. Available: https://www.ampaire.com/vehicles/tailwind%E2%84%A2-aircraft

[3] magniX. “About Us.” Available: https://www.magnix.aero/about-us

[4] Pham, Dahlia D. V., Bowles, Jeffrey V., Zilliac, Gregory G., Go, Susie, and Listgarten, Noah S., Jansen, Ralph, H. "Parametric Modeling and Mission Performance Analysis of a True Parallel Hybrid Turboprop Aircraft for Freighter Operations," in AIAA Aviation Forum, Las Vegas, NV, 2024. https://doi.org/10.2514/6.2024-3581

[5] Pham, Dahlia D. V., Recine, Carl, Jansen, Ralph, H. “Sizing and Performance Analysis of a MW-Class Electrified Aircraft Propulsion (EAP) System for a Parallel Hybrid Turboprop Concept.” ICAS, Florence, Italy, 2024. https://ntrs.nasa.gov/citations/20240008318

[6] International Air Transportation Association. “The Value of Air Cargo.” IATA, Montreal, Canada, 2021. Available: https://www.iata.org/contentassets/62bae061c05b429ea508cb0c49907c4c/air-cargo-brochure.pdf

[7] International Air Transportation Association. “Air Cargo Market Analysis.” IATA, Montreal, Canada, December 2023. Available: https://www.iata.org/en/iata-repository/publications/economic-reports/air-cargo-market-analysis-december-2023/

[8] Schwieterman, J. P., Craig, C., Mader, A. “The Daily Double: Twice-a-day Flight Clusters at CVG Enhance Amazon Air’s Capability as Recession Looms.” The Chaddick Institute, DePaul University, Chicago Illinois, U.S.A., 2022. Available: https://las.depaul.edu/centers-and-institutes/chaddick-institute-for-metropolitan-development/research-and-publications/Documents/Daily%20Double%20Twice-a-day%20Flight%20Clusters%20at%20CVG%20Enhance%20Amazon%20Air's%20Capability%20as%20Recession%20Fears%20Loom.pdf

[9] The Boeing Company. “World Air Cargo Forecast 2022-2041.” Crystal City, Virginia, U.S.A, 2022. Available: https://www.boeing.com/content/dam/boeing/boeingdotcom/market/assets/downloads/Boeing_World_Air_Cargo_Forecast_2022.pdf

[10] The Boeing Company. Orders and Deliveries, updated monthly. Available: https://www.boeing.com/commercial#/orders-deliveries

[11] Lockheed Martin Corporation Annual Reports. Available: https://www.lockheedmartin.com/content/dam/lockheed-martin/eo/documents/annual-reports/lockheed-martin-annual-report-2021.pdf

[12] Wishart, Jacob, Mahavier, Kendall, Jansen, Ralph, H. “Market Analysis of the Subsonic Single Aft Engine (SUSAN) Transport Aircraft Concept.” AIAA SCITECH 2023 Forum, National Harbor, MD, 2023. https://arc.aiaa.org/doi/10.2514/6.2023-1941

[13] United States Federal Aviation Administration. Aviation Environmental Design Tool Available: https://aedt.faa.gov/

[14] United States Federal Aviation Administration. “FAA Airport Benefit-Cost Analysis Guidance.” FAA, Washington, DC., 2020. Available: https://www.faa.gov/regulations_policies/policy_guidance/benefit_cost

[15] Statista. “Average prices for Boeing aircraft as of March 2021, by type.” Statista, 2021. Available: https://www.statista.com/statistics/273941/prices-of-boeing-aircraft-by-type/

[16] Air Cargo News. “Conversions in Demand as All-Cargo Flights Continue to Soar.” Air Cargo News, 2021. Available: https://www.aircargonews.net/services/freighter-conversions-mro/conversions-in-demand-as-all-cargo-flights-continue-to-soar/#:~:text=Looking%20at%20conversion%20costs%2C%20IBA,m%20for%20the%20A330%2D300

[17] International Air Transport Association. “IATA Economics Chart of the Week.: IATA, June 2019. Available: https://www.iata.org/en/iata-repository/publications/economic-reports/why-it-matters-that-the-airline-industry-stays-value-creating-for-its-investors/

[18] Delta Air Lines, Inc. "Form 10-K." Securities and Exchange Commission, Washington, DC, December 2020. Available: https://d18rn0p25nwr6d.cloudfront.net/CIK-0000027904/4062dcf6-2f8c-4727-afc8-55f364c951f3.pdf

[19] American Airlines Group, Inc. 'Form 10-K." Securities and Exchange Commission, Washington, DC., December 2020. Available: https://americanairlines.gcs-web.com/static-files/8e328305-2df2-4726-910c-a7e44f091913

[20] jetBlue. "Annual Report 2020." jetBlue, 2020. Available: https://blueir.investproductions.com/~/media/Files/J/Jetblue-IR-V2/Annual-Reports/jblu017-jetblue-2020-annual-report-web.pdf

[21] Spirit Airlines, Inc. 'Form 10-K." Securities and Exchange Commission, Washington, DC., December 2020. Available: https://s24.q4cdn.com/507316502/files/doc_financials/2020/ar/c2a41aa1-7a65-44e3-86c4-6a7e7a917c1a.pdf

[22] United Airlines, Inc. 'Form 10-K." Securities and Exchange Commission, Washington, DC., December 2020. Available: https://ir.united.com/static-files/a30cf7ec-7b4a-4fd9-9ae3-2656e9d53f24

[23] Congress of the United States Congressional Budget Office. "Operating Costs of Aging Air Force Aircraft." Washington DC., September 2018.

[24] Dixon, M. "The Maintenance Cost of Aging Aircraft: Insights from Commercial Aviation." RAND Corporation, 2006.

[25] Cox, J., Harris, T., Krah, K., Morris, J., Li X., Cary, S. "Regional Air Mobility and Electrified Aircraft on Airport Electricity Infrastructure and Demand." CO: National Renewable Energy Laboratory. NREL/TP-5R00-84176. https://www.nrel.gov/docs/fy23osti/84176.pdf