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Short-Haul Revitalization Study Final Report

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May 2018

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Abstract

A feasibility study was performed for an advanced commercial short-haul aircraft to evaluate the potential for increased service for short-haul flights that operate out of regional and community airports. An analysis of potential origin-destination markets and trip distances resulted in a seat capacity selection of 48 passengers and a design range of 600 NM. A down-select of advanced technologies resulted in a hybrid-electric propulsion system being chosen as the primary enabling technology. A conceptual design of the advanced aircraft was developed, and a mission and sizing analysis was performed, comparing variants of the advanced aircraft with different levels of electrification. Fairly aggressive levels of electrification and battery specific energy are needed for the hybrid-electric architecture to realize any benefit in terms of total energy cost for the 600 NM design mission. The development and operational costs were estimated for the advanced aircraft and compared to the baseline. This analysis demonstrated the negative effect of the cost to develop the hybrid-electric technology on the eventual operating cost. A market analysis was performed to determine possible passenger demand for the advanced short-haul aircraft. According to the market analysis, there is potential demand for such an aircraft, but not necessarily in many of the smaller regional and community airports that were the intended beneficiaries of this new aircraft concept.

1. Introduction

NASA's Advanced Air Transport Technology Project (AATT), under the Advanced Air Vehicles Program (AAVP) funded a study called "Advanced Aircraft Concepts to Revitalize Short-Haul Air Transportation". This study explored the incorporation of advanced airframe and propulsion technologies into an advanced small transport aircraft concept with the objective of increasing short-haul transport safety, affordability, environmental compatibility, and customer acceptance. The aim of the study was to produce a vehicle concept with the potential to revitalize the demand for smaller commercial aircraft that operate out of regional and community airports.

2. Background

During the 1990's, the commercial aviation industry experienced a significant origin-destination (O-D) market growth in the National Airspace System (NAS), especially in the short-haul sector. The sudden increase in direct-to routes was the result of a number of factors. Fuel costs, economic conditions, and aggressive airline market share strategies were all important ingredients in creating the environment where this growth in connectivity could occur (ref. 1). From a technology perspective, the most important factor was the introduction of the regional jet. The Bombardier CRJ and Embraer ERJ regional jets represented an advance in technology that allowed jet aircraft to compete in terms of operational cost with turboprop aircraft on short-haul routes. In addition, these 50 seat regional jets had much better customer acceptance than the turboprops they began displacing. Airlines used these aircraft to add new scheduled service between regional airports, increasing passenger choice and reducing passenger travel times.

In the last decade many short-haul O-D markets have seen a dramatic decline in flights. There have been a number of factors, including the "great recession", higher fares, airport delays, and new technology for business meetings (ref. 2). Many of the smaller O-D markets are no longer economical, and airlines have either reduced or eliminated service. Airlines have been retiring their fleet of 50 seat regional jets in favor of larger aircraft with better cost per seat mile and higher customer acceptance (ref. 3). The focus has shifted from capturing O-D market share to consolidating operations in the most profitable routes. Airlines have also increased the average load factor of flights, resulting in fewer daily flights on many routes. This new airline operations paradigm has contributed to the significant loss of connectivity for many regional and community airports (ref. 4).

In the 38 years since airline deregulation, 51% of the top 300 U.S. commercial airports have experienced reductions in the number of daily flights and 25% of the top 300 commercial airports have experienced reductions in annual passenger enplanements. These statistics are reflective of airline service consolidation at fewer hub airports. After the merger of American and U.S. Airways, the top four U.S. mainline carriers control 70.3% of the seats in the domestic market (ref. 5). Consolidation has also occurred at the regional airline level. In 1980 there were 247 U.S. certificated regional carriers; today the number is 66 (ref. 6).

The above trends are also reflected in the declining number of airports in the U.S. that offer commercial service, as seen in Figure 1. The number of U.S. airports offering commercial service declined by about 11% between 1996 and 2002. Since then the number of commercial airports has fluctuated up and down without any significant recovery of that lost service. In 2014, there were 668 commercial airports in the U.S. that offered scheduled services (ref. 5). Of these, 219 are located in Alaska and Hawaii and are considered low volume airports (<10,000 passengers annually). The remaining 449 commercial airports are located in the continental U.S. If one considers that there are 112 Essential Air Service commercial airports, which are airports subsidized by Congress to offer minimum aviation connecting service to a hub airport, the number of commercial airports considered "viable" in the continental U.S. is just 337.

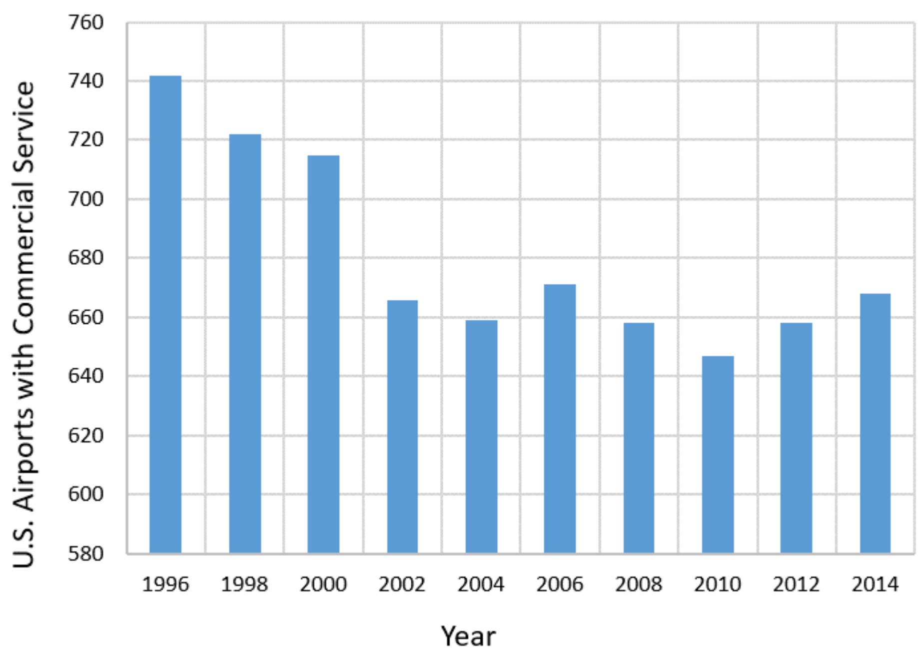

Figure 1. U.S. commercial airports by year. (Data from ref. 5.)

The purpose of this Short-Haul Revitalization Study was to investigate the potential for a new aircraft type to reverse the current decline in short-haul air transportation, through application of advanced technologies or advanced flight operations. If a small, short-haul aircraft could be operated economically compared to larger aircraft, it could potentially encourage airlines to open up new O-D markets, reestablish service at smaller airports, and increase mobility and connectivity for passengers.

NASA has a vested interest in promoting mobility for the flying public. Much of NASA’s aeronautics research portfolio takes guidance and direction from the National Aeronautics Research Plan (ref. 7). The 2010 National Aeronautics R&D Plan specifically calls out Mobility as a guiding research principal. In addition, NASA’s Aeronautics Research Mission Directorate has identified three overarching drivers to guide research planning in its Strategic Implementation Plan (SIP). The first “Mega-Driver” is “Global Growth in Demand for High Speed

Mobility" (ref. 8). An aircraft that contributes to increasing the number of commercial short-haul flights would both increase mobility and shorten travel times for the flying public.

3. Short-Haul Aircraft Characteristics

Before designing a new short-haul aircraft concept, it is important to study the current short-haul fleet and understand their operations. This section introduces various aircraft used in short-haul operations worldwide, focusing on aircraft flying regular commercial operations with a range of 500 statute miles or less. The information presented has been collected from various aircraft manufacturer documents and the Official Airline Guide (OAG) (ref. 5) - an airline schedule database.

3.1. Short-Haul Range Characteristics

To understand the need for short-haul services, consider that during the third week of July 2014 commercial airlines scheduled 43,900 daily flights with Great Circle Distances (GCD) less than 500 statute miles (ref. 5). This constitutes 47% of all the commercial flights scheduled in the typical day. A distribution of flight distances worldwide is shown in Figure 2. The figure shows that the number of flights scheduled peaks at a GCD distance of 500 statute mile.

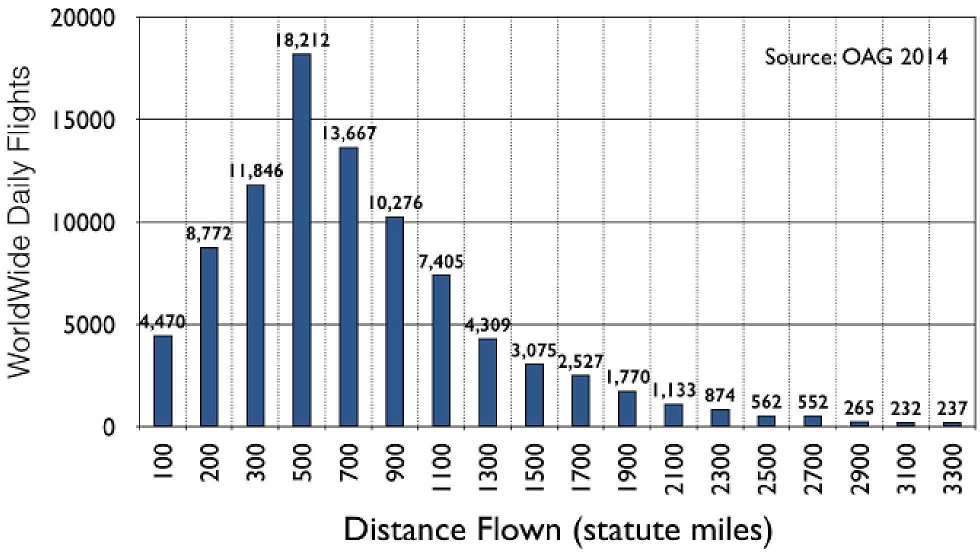

Figure 2. Distance distribution of daily flights worldwide. (Data from ref. 5.)

To understand what types of aircraft are used in short-haul O-D markets, refer to Figure 3. The data in the figure show two distinct trends in the use of aircraft: a) 91% of the O-D markets served with turboprop aircraft are less than 500 statute miles; and b) 59% of the O-D markets served with regional jets are less than 500 statute miles. Figure *3* also shows that 44% of the markets served with turboprop aircraft involve routes less than 200 statute miles.

A distribution of the O-D market distances flown by turboprop aircraft worldwide is shown in Figure 4. The figure includes historical trends of stage length flown over a period of 10 years (2004-2014). The smaller turboprop aircraft (i.e., less than 19 seats) have experienced a significant reduction (26%) in the average distance flown from 186 statute miles in 2004 to 137 statute miles in 2014. The successful introduction of the Cessna Caravans (C208), a 10 passenger aircraft capable of flying very short-haul segments economically, is likely responsible for some of this reduction by opening up new routes with very short ranges. There also may be a shift of some of the longer short-haul routes from the <19 seat turboprops to the 20-40 seat turboprops, which would explain the decrease in average distance flown for that seat category.

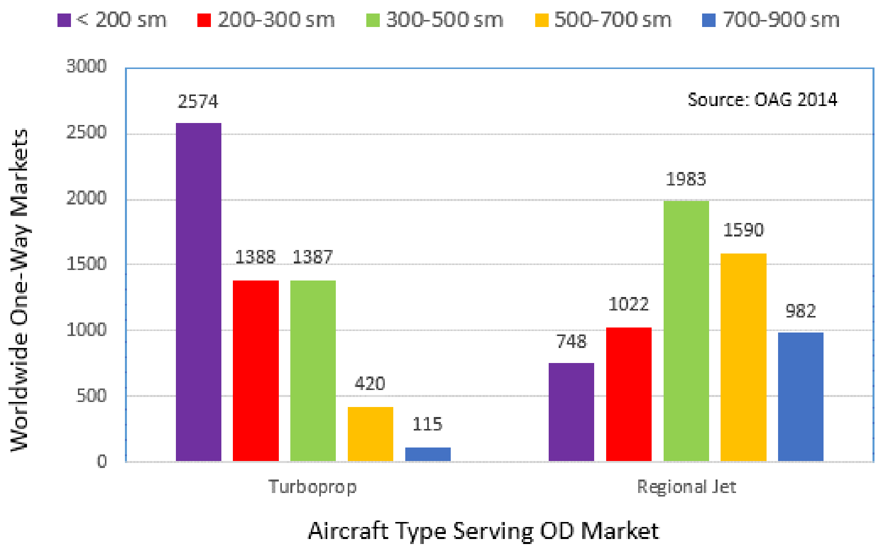

Figure 3. One-way origin-destination markets worldwide.

Figure 4 shows that turboprop aircraft with more than 60 seats are being used in longer O-D markets. The figure indicates a significant increase (29%) in the average stage length flown between years 2004 and 2014. This is statistically significant and can be explained by the introduction of Bombardier Q400 turboprops to commercial service in that time period. The Q400 is capable of cruise speeds of 360 knots (~60 knots faster than other large turboprops in the market), allowing airlines to fly turboprops on longer routes while maintaining block times similar to regional jets.

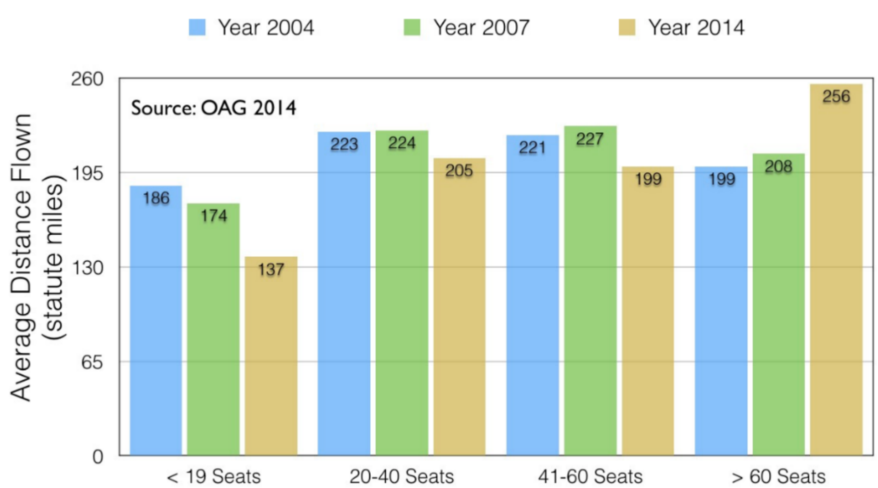

Figure 4. Great circle distance between origin-destination markets worldwide operated with turboprop aircraft.

3.2. Runway Length Characteristics for Short-Haul Transport Aircraft

Figure 5 shows the Federal Aviation Regulation (FAR) runway length requirements for two popular turboprop aircraft, the Bombardier DHC-8-300 and the Aerospatiale/Alenia ATR-72, and two regional jets, the Bombardier

CRJ-200 and Embraer E-175. The regional jets require between 22% and 85% greater runway length at sea level International Standard Atmospheric (ISA) conditions. As a result, turboprops are able to use a larger number of runways worldwide.

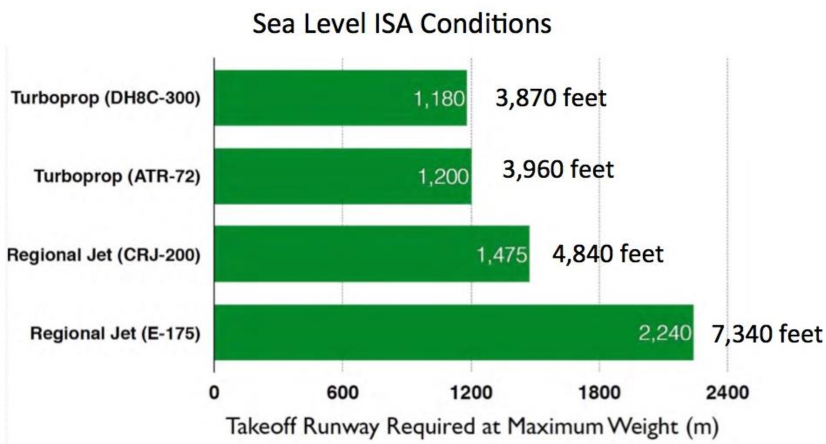

Figure 5. Typical runway length characteristics for short-haul aircraft.

Turboprop aircraft services operate in diverse climatic environments worldwide, from small airports serving northern towns in Greenland (e.g., Aasiaat) with extreme winter weather conditions to small commercial airports in the Cape Verde Islands (e.g., Praia) with short runways and tropical weather conditions. Turboprops operate side-by-side with regional jets and larger turbofan-powered aircraft at medium and large airports in the U.S. and in Europe. Figure 6 shows the distribution of runway lengths at airports where turboprop aircraft operate worldwide. The graph is constructed by taking the longest runway available at each airport where turboprop aircraft operate. Turboprops may actually operate from smaller runways available at the airports with more than one runway. However, it is not possible to assess how often these aircraft operate from such runways since no information on runway use is available worldwide. Figure 6 shows that 13.6% of all turboprops flights are operated from airports whose longest runway is shorter than 5,000 feet. Around 24% of the daily flights worldwide using turboprops are operated from airports where the longest runway is 6,000 feet or less. Few turboprops operate at airports with runways less than 4,000 feet in length. There are airports in Canada, Costa Rica, Philippines and Greenland with short runway lengths. However, the vast majority of turboprop operations occur at airports that have medium and long runways as shown in Figure 6. By comparison, most regional jet operations worldwide are limited to airports with runways longer than 6,000 feet.

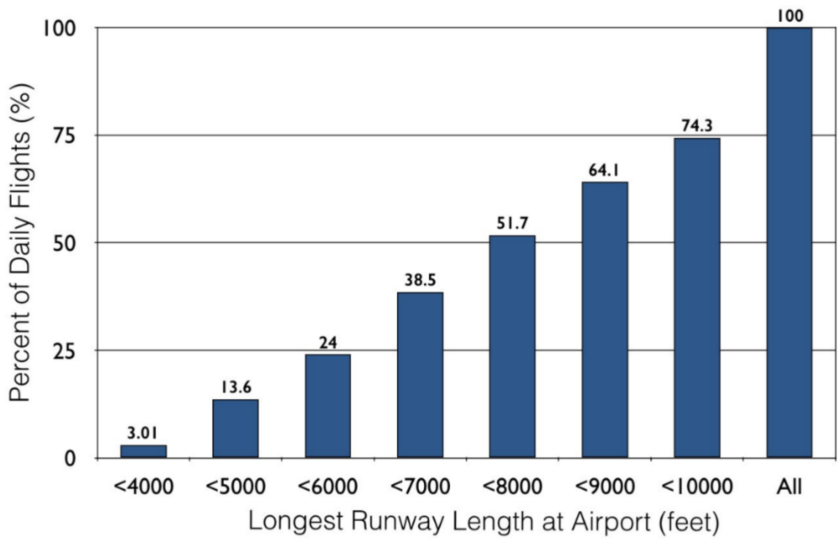

Figure 6. Longest runway available at worldwide airports where turboprops operate regular scheduled services as a percentage of daily flights. (Data from ref. 5.)

3.3. Fuel Efficiency of Short-Haul Transport Aircraft

The efficiencies of current turboprops and regional jets can be seen by examining fuel metrics for typical flights in the U.S. system. Figure 7 shows a composite plot of computer simulated Specific Air Range (SAR) for three regional aircraft types operating in the U.S. network: a) a 50 seat regional jet, b) a 50 seat turboprop, and c) an 86 seat regional jet. SAR is the distance an aircraft travels per unit of fuel consumed. The results presented were generated using a fuel consumption model of the 2010 U.S. airline network. The fuel metric calculations include typical terminal area detours and taxi-in and out times. Each point in the plot represents the SAR parameter for individual airport O-D pairs flown by each aircraft type. The 50 seat turboprop has a clear advantage in terms of SAR for ranges below 450 NM. The 50 seat regional jet consistently has higher SAR values than the 86 seat regional jet for all ranges. Figure 8 is a plot of the fuel consumption per passenger-mile for the same three aircraft types. As with SAR, the 50 seat turboprop outperforms the two regional jet types in terms of fuel burned per passenger-mile. However, for this metric the results are reversed for the regional jets. The 86 seat regional jet has consistently better fuel burn per passenger-mile when compared to the 50 seat regional jet for ranges below about 900 NM. These results are consistent with the industry trend of phasing out the older 50 seat regional jets and replacing them with the newer (and larger) 86 seat regional jets. This data also gives some indication of the fuel burn performance needed by a new short-haul aircraft in order to significantly outperform the existing short-haul fleet.

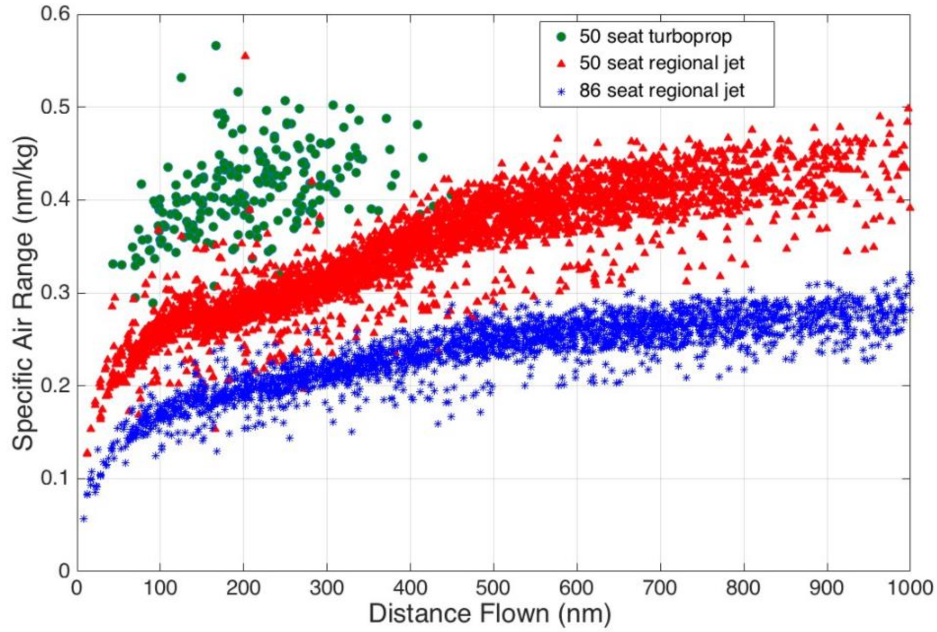

Figure 7. Specific air range for three regional aircraft types.

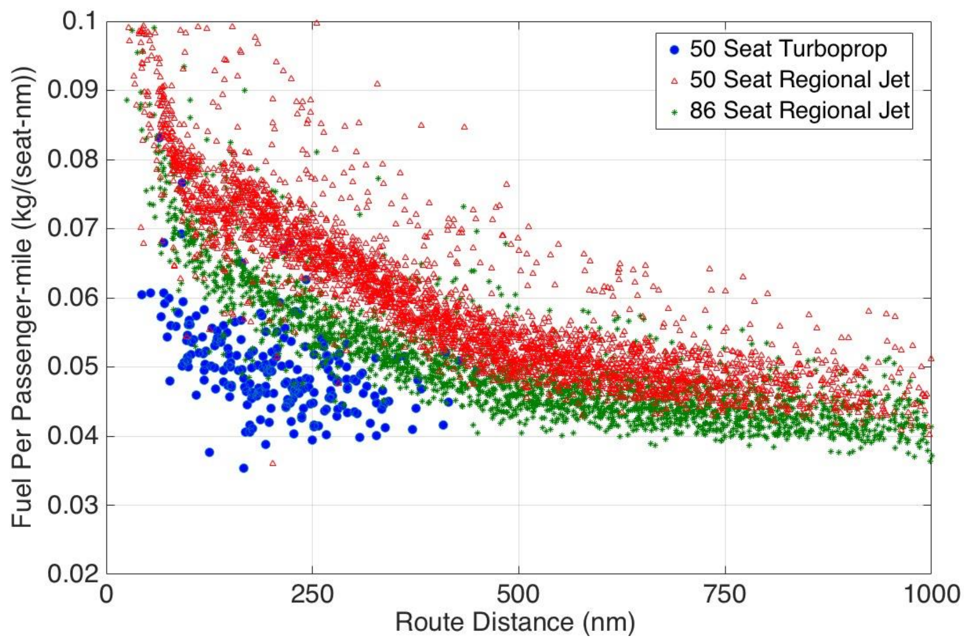

Figure 8. Fuel per passenger-nautical mile for three regional aircraft types.

3.4. Short-Haul Aircraft Inventory and Evolution

3.4.1. Turboprop Transports

In order to understand the turboprop aircraft market segment size worldwide it is important to first look at the current inventory of such aircraft. Table 1 shows the inventory of turboprop aircraft as of January 2014. The table also shows the number of weekly flights scheduled for each aircraft type according to the OAG. In January 2014 there were 4,881 turboprops active in commercial service. The largest fleets belong to the Bombardier DHC-8 and the Aerospatiale/Alenia aircraft families. The medium size turboprop aircraft with seating capacities ranging from 20-45 seats, represent the smallest turboprop portion of the fleet with 690 units. The largest turboprops with seating capacities above 45 represent the largest portion with 2455 units and the smallest turboprop aircraft with fewer than 20 seats have 1736 units.

Table 1. Worldwide inventory of turboprop aircraft

Aircraft	Fleet (Worldwide) January 2014	Weekly Flights (OAG 2014)	Average Seats
Aerospatiale ATR42	257	3080	44
Aerospatiale ATR72	709	17345	72
Antonov 140	20	104	52
Antonov 24	195	397	50
Bombardier DHC-6	444	2481	19
Bombardier DHC-8-100/200/300	567	16459	48
Bombardier Q400	421	15399	76
Cessna Caravan	494	5659	10
Dornier 228	81	161	19
Dornier 328	104	530	30
Embraer 120	156	2122	32
Fokker 50	165	1242	21
Jetstream 31/32	139	673	19
Jetstream 41	63	1073	32
Let L-410	185	56	21
Raytheon Beech 1900	393	5104	19
Saab 2000	41	866	48
Saab 340	264	4220	33
Xian MA-60	80	234	60
Xian Y-7	103	71	30

Over the last decade, turboprop aircraft use has evolved differently for various aircraft size categories. The low seating capacity turboprop aircraft segment experienced a recession cycle between 2004 and 2007, as shown in Figure 9. That segment recovered with the introduction of smaller capacity aircraft such as the Cessna Caravan (passenger version) after 2007. The number of daily flights offered worldwide using turboprops with 20-40 seats experienced a drastic reduction of 71% between 2004 and 2014. This dramatic drop is a consequence of aircraft retirements and the lack of new aircraft alternatives in that segment.

The trends for medium size turboprops are supported by recent actions by small airlines. In December 2014, Skywest announced a short-term plan to retire all its 33-seat Embraer E120 (ref. 9). Skywest Airlines was one of the largest operators of the E120 in the world with 45 E120s in its fleet. The airline is replacing the services flown by E120s with Embraer 175 regional jets. Air New Zealand recently completed the retirement of its fleet of 17 Beech 1900D (Eagle Airways). The airline now uses Aerospatiale/Alenia ATR 42 and ATR 72 aircraft.

It is clear from Figure 9 that the most successful turboprops today are larger sized turboprops. Success in this context is defined by the number of units deployed and the number of flights performed on a daily basis. The average daily flights worldwide for turboprop aircraft with 41-60 seats improved by 36% in the last decade. This number represents modest growth and was driven by new deliveries of Bombardier DHC-8-300 and improved versions of the Aerospatiale/Alenia ATR 42-600 and ATR 42-500 series. For turboprops with more than 60 seats, the number of average daily flights worldwide increased by 202% in the decade between 2004 and 2014. The Aerospatiale/Alenia ATR 72 and Bombardier Q400 aircraft are the best-selling turboprop aircraft in recent years and between them currently account for more than 42% of the total daily turboprop flights offered by airlines. Their success is tied to the better operational economics of larger capacity turboprop aircraft.

The medium and large turboprop commercial aircraft market segment is very fragmented. The U.S. has lost its leadership role in producing regional turboprop aircraft for nearly three decades, and many of the regional aircraft alternatives from Canada (Bombardier Q400 series aircraft) and Europe (Aerospatiale/Alenia ATR-42/72) are not optimized for today's small O-D markets. Between the years 2005 and 2014, roughly 1.7 million annual departures using 50-seat or less regional jets and turboprops were cut from the U.S. domestic system (ref. 10). The same analysis shows that only 0.63 million departures were replaced by 70-seat and larger regional aircraft. It is unclear whether or not the flight frequency loss could be recovered if more advanced turboprops were available today or in the near future.

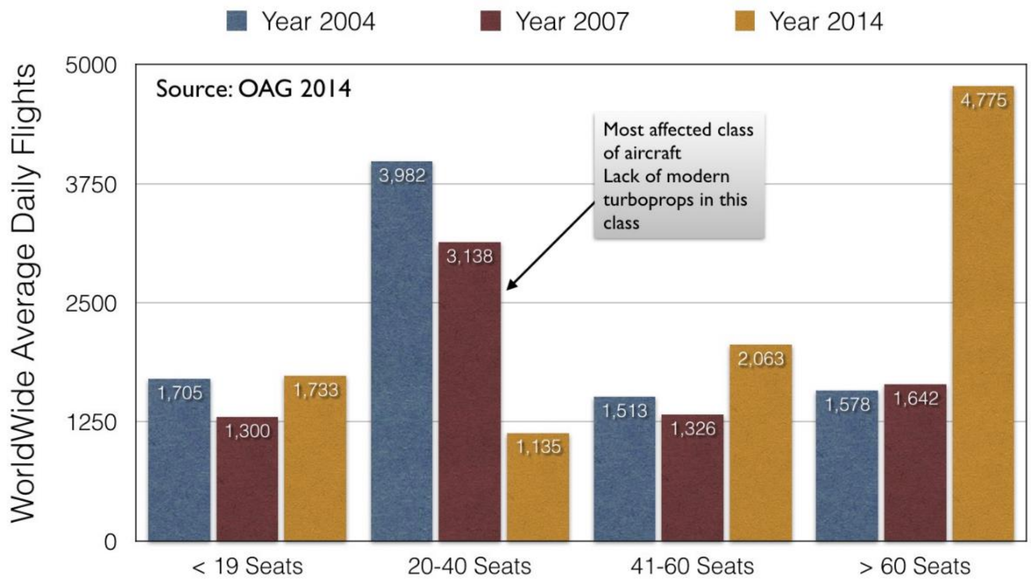

Figure 9. Distribution of daily flights performed by turboprop aircraft worldwide. (Data from ref. 5.)

3.4.2. Turboprop-Only Markets

Although turboprops operate side-by-side with regional jets and larger narrow body commercial aircraft in many O-D markets, it is instructive to study markets served exclusively with turboprop aircraft. These markets can be used as indicators of the unique capabilities of turboprop aircraft. The analysis presented in this section divides the turboprop segment into three categories based on different seating capacities: a) small turboprop aircraft with less than 20 seats, b) medium capacity turboprops with 20-45 seats, and c) large turboprops with more than 45 seats. This analysis focuses on markets that are served exclusively by one turboprop size category. For example, if a given O-D market is served by both small and medium capacity turboprops, it is not included in the analysis. This restriction helps ensure that the results for each size category are not skewed because of atypical operational scenarios. The analysis uses the OAG database; the third week of July of each year is used to make comparisons across years.

Figure 10 shows the number of distinct U.S. O-D markets served exclusively with turboprop aircraft spanning a decade (2004-2014). The figure shows that between 2004 and 2014, the number of O-D markets served by small turboprops with fewer than 20 seats decreased 55.6%. This change is five times the change experienced worldwide for the same turboprop group (see Appendix A). Similarly, in 2014 the number of weekly frequencies of operation using small turboprops decreased to 36% of their 2004 value in O-D markets served exclusively by such aircraft (see Figure 11). The number of weekly frequencies using turboprops in the medium size category (20-45 seats) decreased to nearly one fourth of its 2004 level by 2014. The only turboprop group to record a positive growth in O-D markets served exclusively by turboprop aircraft between 2004 and 2014 was the larger turboprop group with more than 45 seats. The number of U.S. markets served exclusively by this type of aircraft increased by more than 214% in the decade 2004-2014.

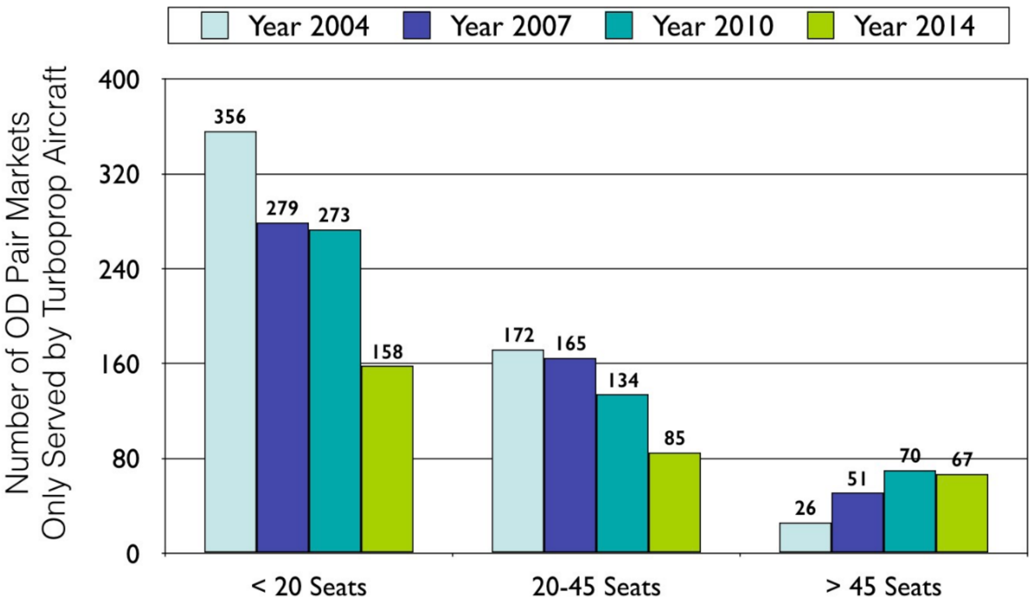

Figure 10. Number of origin-destination U.S. O-D markets served exclusively by turboprop aircraft.

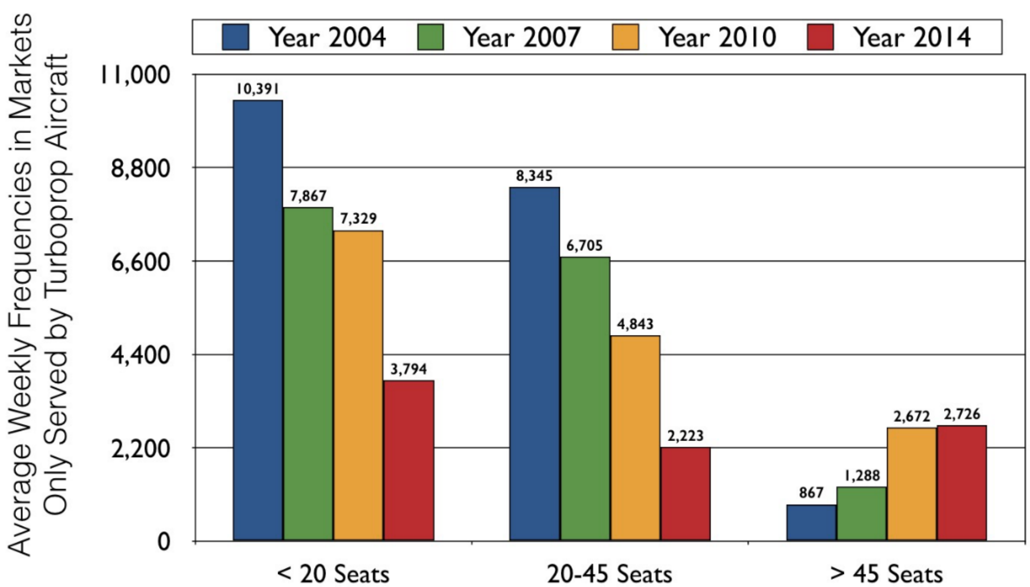

Figure 11. Number of weekly frequencies at U.S. O-D markets served exclusively by turboprop aircraft.

Figure 12 shows the number of weekly seats offered in the U.S. for the three turboprop aircraft categories. The figure shows a dramatic change (226%) in the number of weekly seats in the large turboprop category between 2004 and 2014. In the same graph we observe a drastic reduction (74%) in the number of seats for O-D markets served only by medium size turboprops.

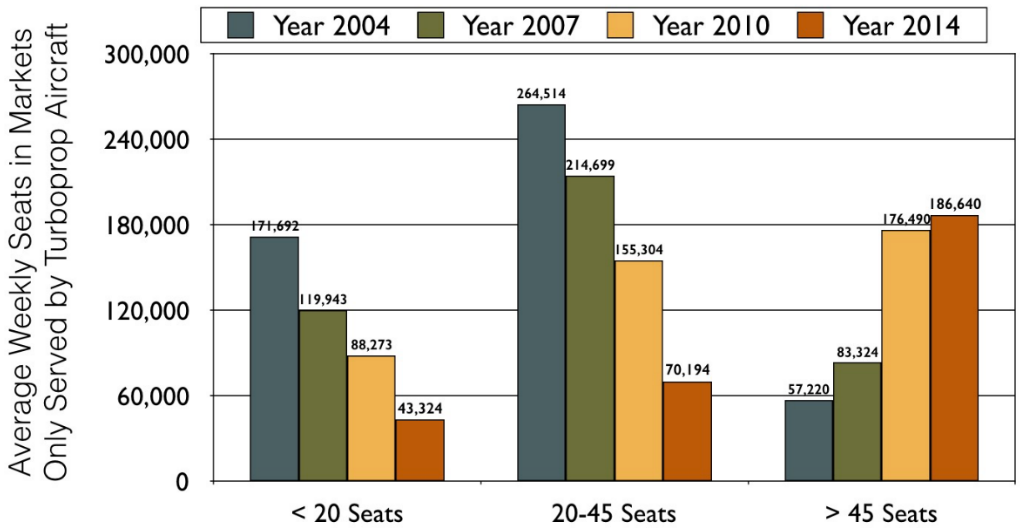

Figure 12. Number of weekly seats offered at U.S. O-D markets served exclusively by turboprop aircraft

Figure 13 shows the average number of seats per flight in U.S. O-D markets served exclusively by turboprop aircraft. In the figure we observe the fast reduction in the average seating capacity of the small turboprop aircraft. The average seating capacity in the small turboprop segment decreased from 16.4 seats in 2004 to 11.5 in the year 2014. The large turboprop segment (i.e., > 45 seats) gained 2 seats per flight on average in the period 2004-2014.

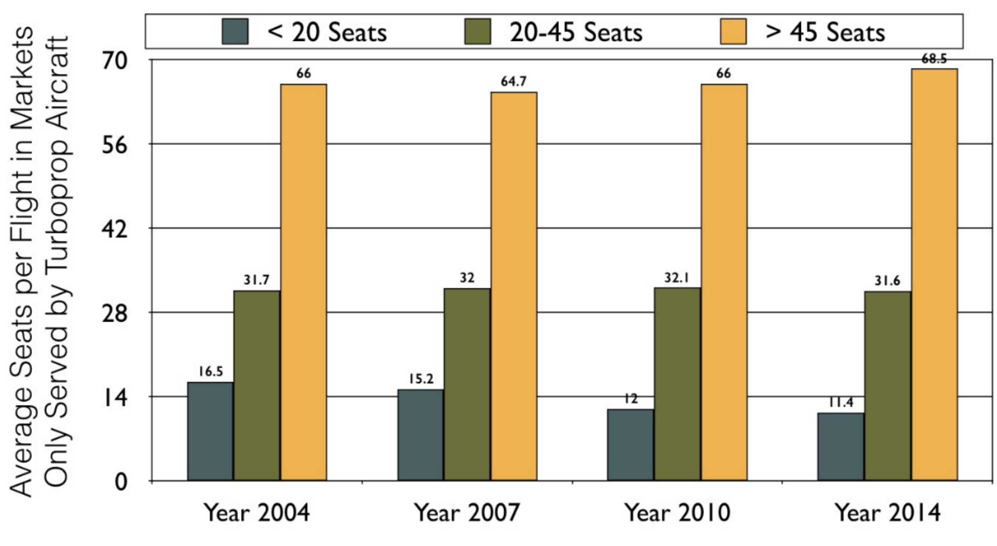

Figure 13. Average number of seats per flight at U.S. O-D markets served exclusively by turboprop aircraft.

Figure 14 shows the graphical distribution of U.S. O-D markets served exclusively using small turboprop aircraft in years 2004 and 2014. In 2014 about half of the O-D markets were located in Alaska. A decade ago, 86% (by frequency) of the exclusive markets were located in the continental U.S. Considering a seven-day week period, in 2014 the O-D markets served exclusively using small turboprops offered an average of 1.72 daily departures from each airport.

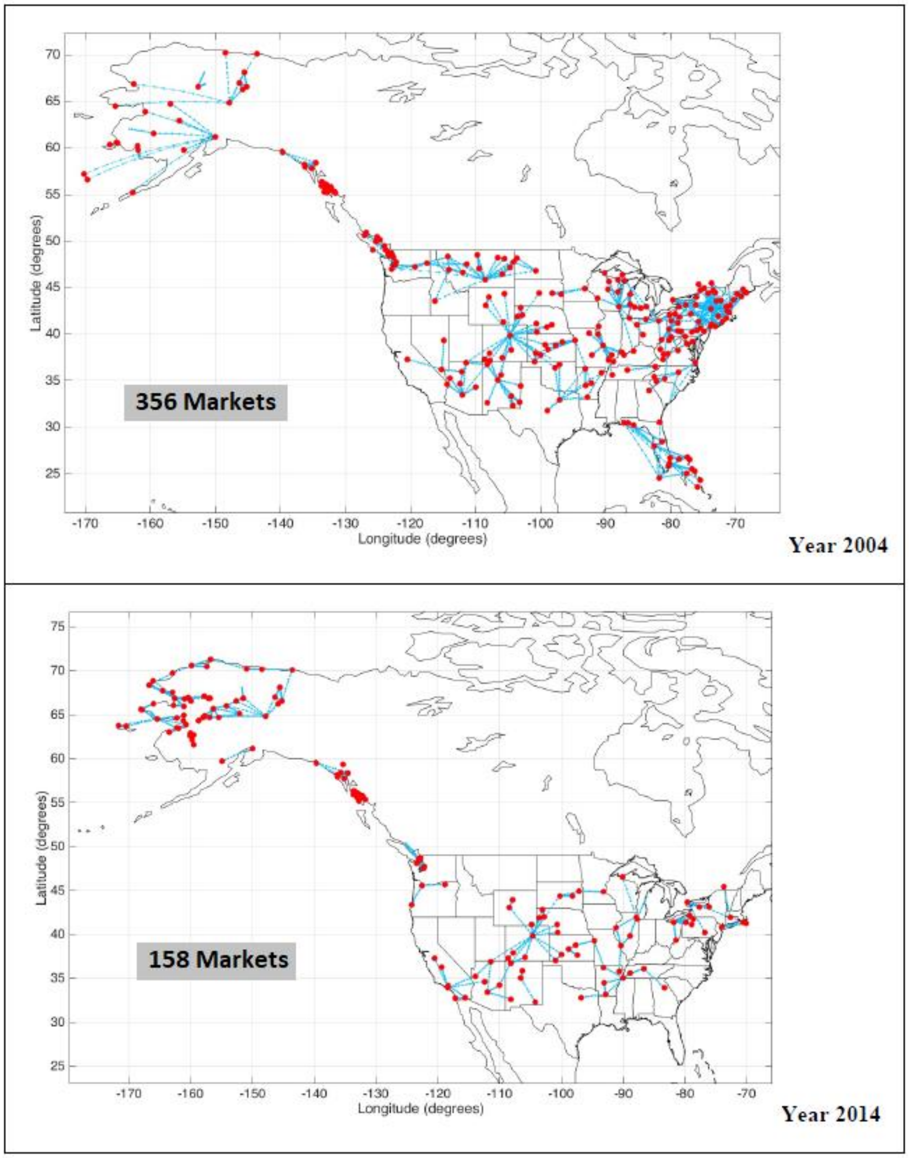

Figure 14. U.S. O-D markets served exclusively with small turboprop aircraft (< 20 seats). Top figure presents exclusive markets in 2004 (356). Bottom figure presents exclusive markets served in 2014 (158).

Figure 15 shows the graphical distribution of U.S. O-D markets served exclusively using medium turboprop aircraft in years 2004 and 2014. In 2014, 90% of the 85 O-D markets were located in the continental U.S. The results are localized to the airlines still operating Saab 340 and Embraer 120 aircraft in Florida and California. As of late 2015 many of the medium size turboprops were being retired from U.S. markets. In 2004, medium size turboprops were used more prominently in the continental U.S., including some international services to México. Considering a seven-day week period, in 2014 the O-D markets served exclusively using medium turboprop aircraft offered an average of 1.87 daily departures from each airport.

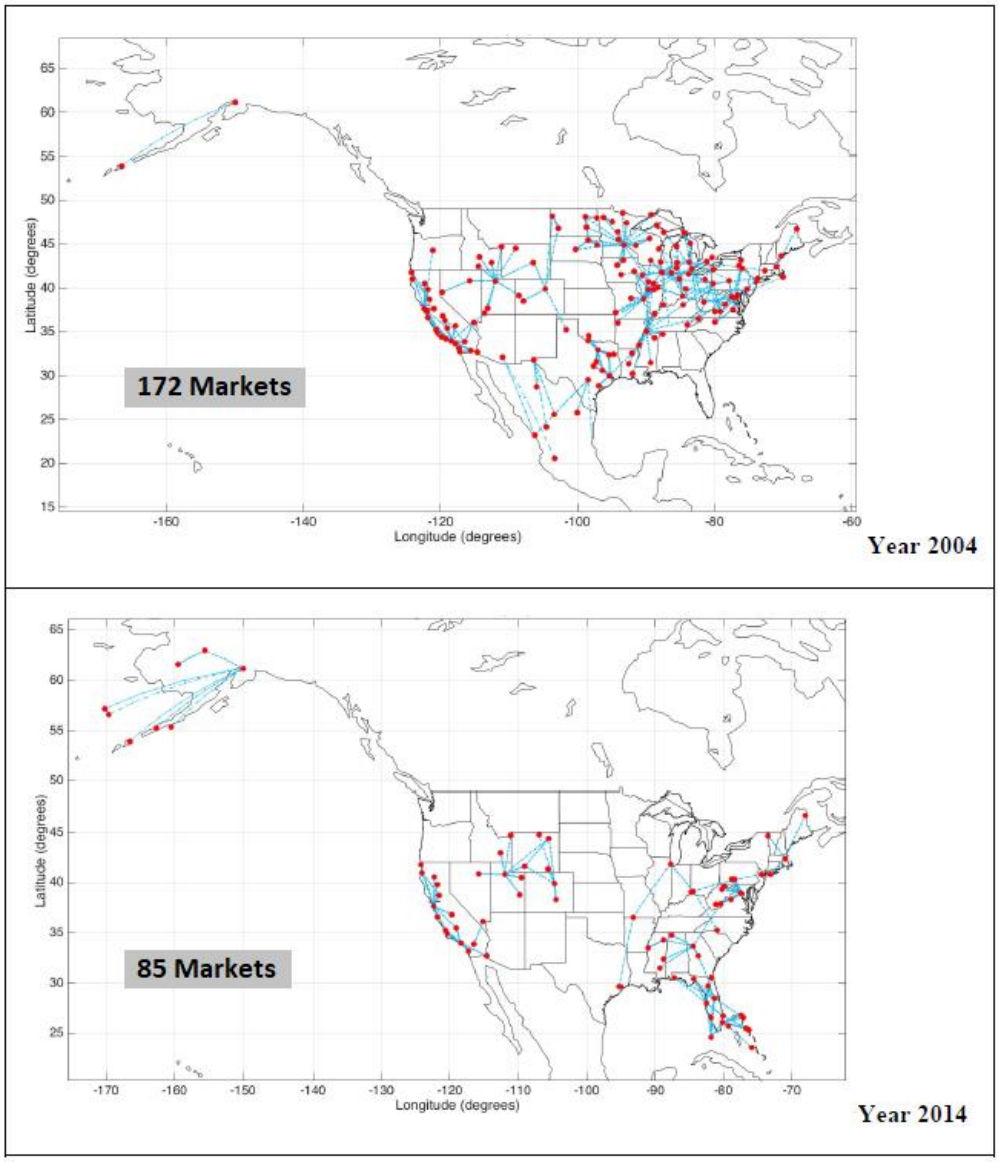

Figure 15. O-D markets served exclusively with medium turboprop aircraft (20-45 seats). Top figure presents exclusive markets in 2004 (172). Bottom figure presents exclusive markets served in 2014 (85).

Figure 16 shows the graphical distribution of U.S. markets served exclusively using large turboprop aircraft (> 45 seats) in years 2004 and 2014. In 2014, the O-D markets flown using large turboprops were localized and dominated by two airlines, Horizon Air operating services in the Pacific Northwest and what used to be U.S. Airways Express (now American Airlines) operating in the Northeastern states. A decade ago, exclusive O-D markets served by large turboprops were localized in the Pacific Northwest with a few more in Florida. Considering a seven-day week period, in 2014 the O-D markets served exclusively using large turboprop aircraft offered an average of 2.91 daily departures from each airport.

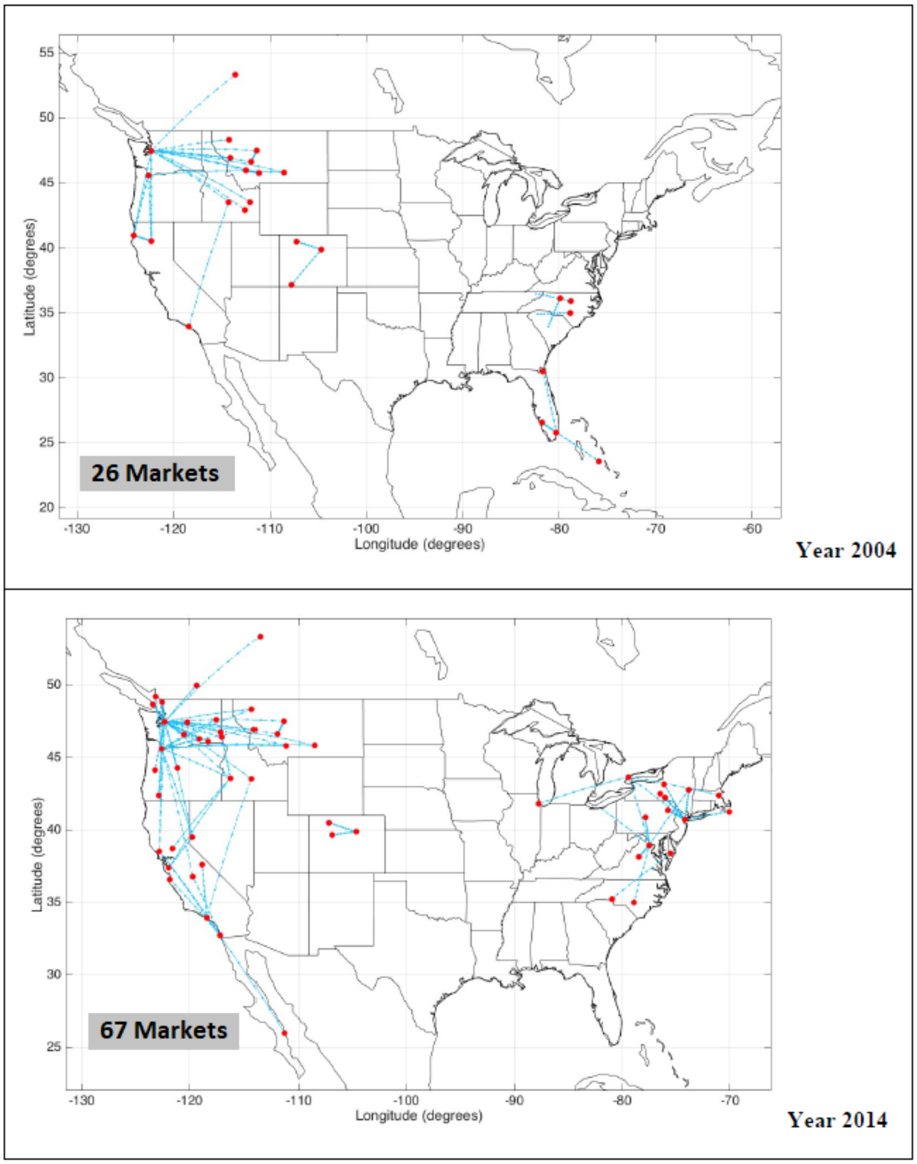

Figure 16. U.S. O-D markets served exclusively with large turboprop aircraft (>45 seats). Top figure presents exclusive markets in 2004 (26). Bottom figure presents exclusive markets served in 2014 (67).

This discussion has been focused on U.S. turboprop operations. A description of the evolution of turboprop markets worldwide is contained in Appendix A.

3.4.3. Regional Jet Transports

Table 2 shows the worldwide inventory of regional jet aircraft as of January 2014. The table also shows the number of weekly flights scheduled for each aircraft type according to the OAG. In January 2014 there were 4,469 regional jets active in commercial service, roughly equal to the number of active commercial turboprops. The largest fleets belong to the Embraer ERJ/E and the Bombardier CRJ aircraft families. Small regional jets (< 40 seats) represent the smallest portion of the fleet with 165 aircraft. Regional jets with 61-80 seats are the next largest category with 1358 units, followed by large regional jets with more than 80 seats with 1435 units. The largest regional jet group in 2014 was the 40-60 seat category, with 1511 units.

Examining the weekly flights for each group reveals similar trends. The <40 seat regional jets represent only a tiny fraction of the regional jet weekly flights, less than one percent. Next is the >80 seat category, representing about 27% of the weekly flights. The 61-80 seat category captures 31% of the weekly regional jet flights, and the 40-60 category represents 42% of the weekly flights. In 2014, the 40-60 seat jets were still dominant in terms of weekly operations worldwide, even though that category is shrinking and flights are being shifted to larger aircraft.

Table 2. Worldwide inventory of regional jet aircraft.

Aircraft	Fleet (Worldwide) January 2014	Weekly Flights (OAG 2014)	Average Seats
Antonov An-148/158	124	291	78
BAe 146 / Avro RJ	178	2771	95
Boeing 717	135	5659	117
Bombardier CRJ-100/200	758	27926	50
Bombardier CRJ-700	328	12855	68
Bombardier CRJ-900	296	11704	79
Bombardier CRJ-1000	57	1515	99
Dornier 328JET	41	182	32
Embraer ERJ-135/140/145	744	29185	49
Embraer E170/175	566	15880	75
Embraer E190/195	719	23092	104
Fokker F28	9	7	56
Fokker 70	44	1033	80
Fokker 100	165	2773	103
Sukhoi Superjet 100	131	500	94
Yakovlev Yak-40	124	20	26
Yakovlev Yak-42	50	151	104

Figure 17 shows the average number of daily operations worldwide for different regional jet classes from 2004 to 2014. This figure shows that the 40-60 seat regional jets were still the dominant class in 2014, even though the daily operations have declined during the previous decade. Average daily operations declined 24% for this class of regional jet from 2004 to 2014, driven mainly by the operational cost and customer acceptance issues previously mentioned. Operations for the <40 seat regional jets have virtually disappeared in that same time span. In general, operations declined for regional jet classes under 60 seats and daily operations increased for regional jet classes greater than 60 seats. The largest increase occurred in the medium-large category. The average number of daily operations increased by an impressive 421% over that ten-year span. Large regional jets experienced a much more modest increase of 18% in average daily operations.

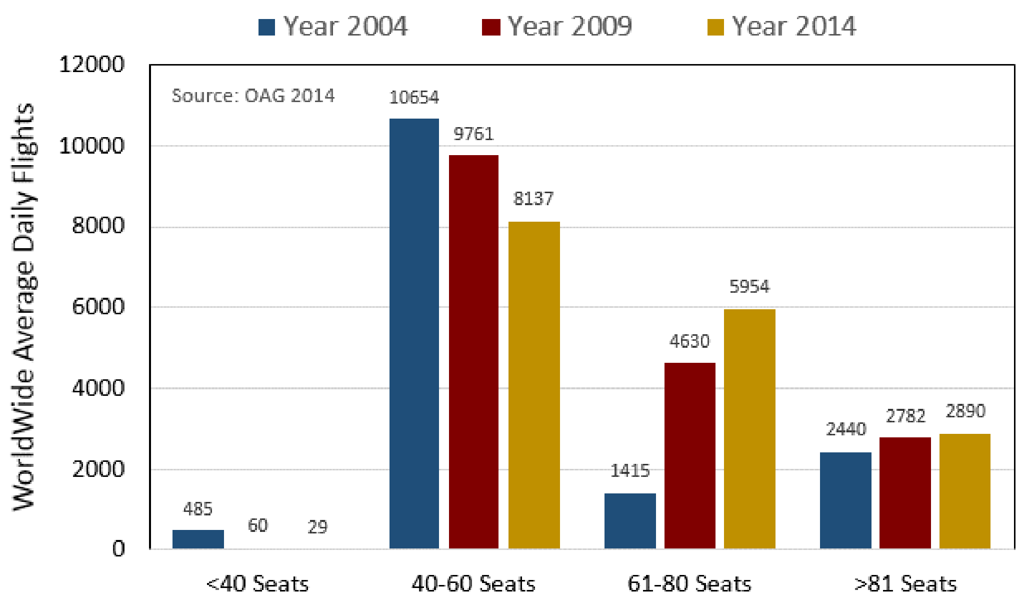

Figure 17. Distribution of daily flights performed by regional jet aircraft worldwide. (Data from ref. 5.)

Figure 18 shows the spatial distribution of U.S. O-D markets served exclusively by regional jets with less than 55 seats in 2004 and in 2014. Note that this is a slightly different seat categorization than discussed above. A decade ago, 657 O-D markets were flown exclusively with this <55 seat category. In the year 2014, there were 512 exclusive O-D markets in the U.S. operated with <55 seat regional jet aircraft. In 2014, these markets served exclusively by <55 seat regional jets represented a total of 942,112 weekly seats and 19,106 weekly flights (average seat capacity of 49.3). The average flight frequency among these markets was 2.7 departures per day (average of seven days).

As regional airlines continue to retire smaller regional jets in the future, the expectation is that not all the O-D markets served by these aircraft will become served by larger capacity regional aircraft. A study by Swelbar (ref.10) points out that more than 1.7 million departures using 50-seat regional jets and turboprops were lost in the last decade. The same study shows that only 37% of the departures were replaced by larger capacity regional jets. This gap could represent an opportunity for an advanced turboprop aircraft having the right operational economics.

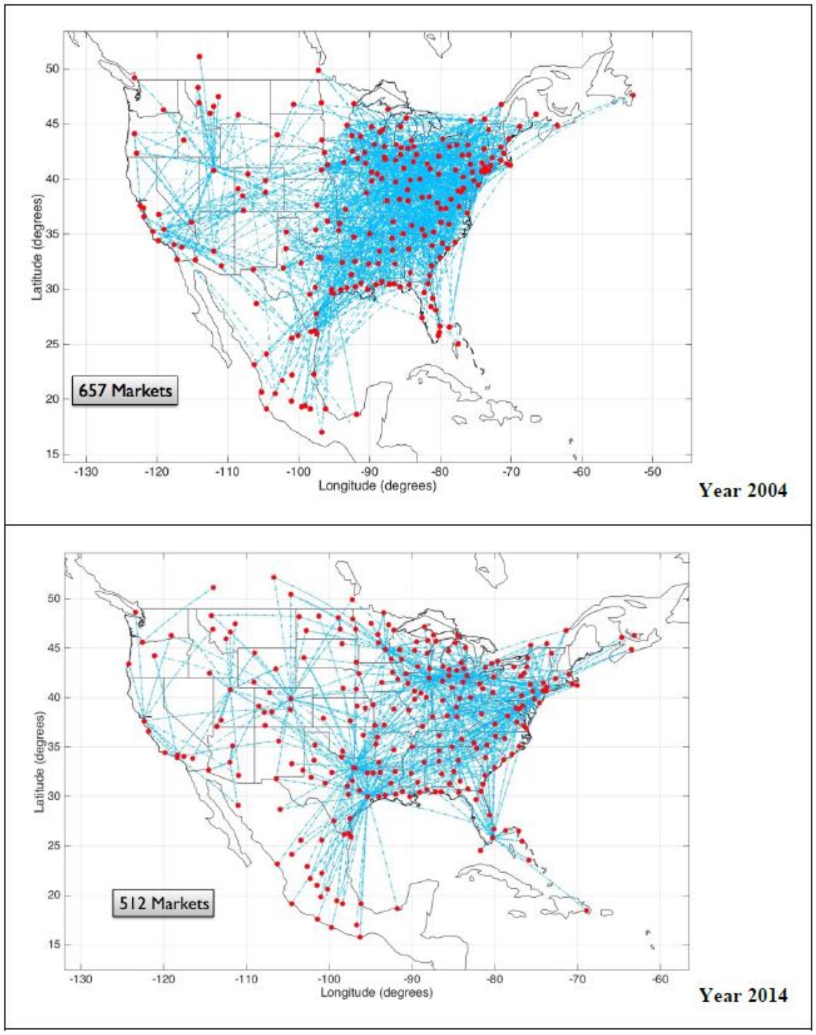

Figure 18. U.S. O-D markets served exclusively with <55 seat regional jet aircraft. Top figure presents exclusive markets in 2004 (657). Bottom figure presents exclusive markets served in 2014 (512).

Figure 19 shows the cumulative density function of Great Circle Distance (GCD) for all individual O-D markets flown exclusively by <55 seat regional jet aircraft in the U.S. According to the data presented in the figure, an advanced turboprop concept with a practical range of 600 statute miles could cover 67% of the O-D markets flown exclusively by regional jets today. If the practical range of the advanced turboprop concept is stretched to 900 miles, the coverage increases to 92%.

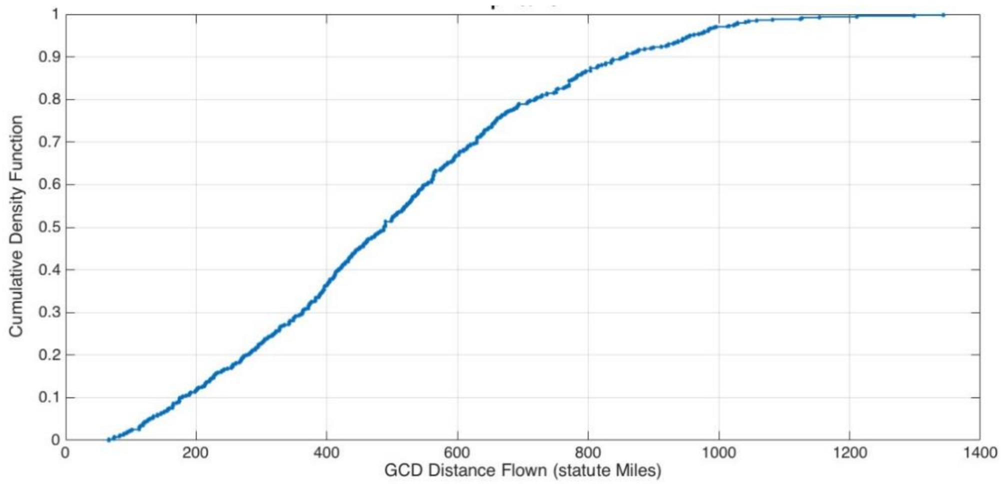

Figure 19. Cumulative density function of GCD distance flown for U.S. O-D markets served exclusively with <55 seat regional jet aircraft in 2014.

If a replacement strategy of advanced turboprops applies to the U.S., there could be further opportunities worldwide. Figure 20 presents the number of worldwide O-D markets operated exclusively by turboprops, small regional jets (<55 seats) and large regional jets (>= 55 seats) in the year 2014. Beyond the 512 O-D markets identified in the U.S. for that year, there are an additional 309 non-U.S. markets operated exclusively by <55 seat regional jets. Worldwide, there were 821 O-D markets operated exclusively by small regional jet aircraft.

Figure 21 illustrates the level of competition between turboprops and regional jets in common markets. In 2014 there were 249 O-D markets worldwide served only with flights using turboprops and <55 seat regional jets. Similarly, there were 375 O-D markets with services flown by turboprops and >55 seat regional jets. These statistics indicate that airlines can operate many of the same O-D markets profitably using turboprops and regional jets. Some airlines do that by choice, others are forced to by the uniqueness of their fleet (e.g., Horizon Air).

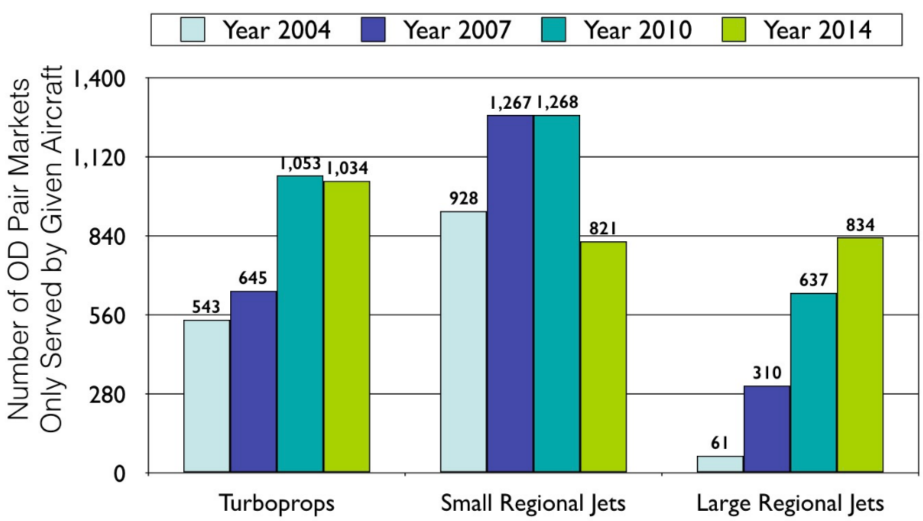

Figure 20. Worldwide O-D markets served exclusively with turboprops, small regional jet aircraft (<55 seats) and large regional jets (>= 55 seats). (Data from ref. 5.)

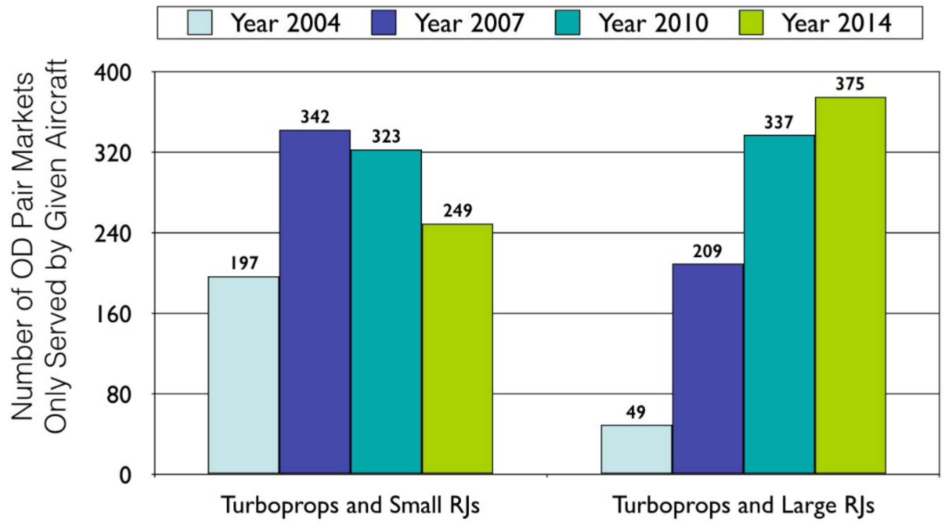

Figure 21. Worldwide O-D markets served with turboprops and regional jet aircraft simultaneously. (Data from ref. 5.)

4. Short-Haul Aircraft Requirements

4.1. Requirements Development

At the start of this study, the design space was completely open in terms of size, performance, cost, and operation. The design team had the responsibility of determining the set of requirements that would result in a successful short-haul aircraft design. The only guidance available was the original study goal, to develop a conceptual design of an advanced short-haul aircraft that could revitalize short-haul air transportation and improve mobility (i.e., the availability and convenience of flight service) for the general public. An additional guidepost for this study was the hypothesis that some advanced technologies and/or flight operations might be more successfully applied to a smaller aircraft than a larger aircraft. This could be due to the nature of the technology itself, the regulatory environment, or the natural progression of technology development favoring introduction of new technology on a smaller aircraft.

The design team made some initial assumptions that served as ground rules for this analysis. The year 2030 was chosen as the target for introduction of the advanced short-haul aircraft into the fleet. This would presumably give many new technologies currently under development time to mature. The aircraft would notionally be a turboprop and would travel at cruise speeds consistent with current turboprop aircraft. However, the propulsion system had not been selected at this point and all options were still under consideration.

4.1.1. Aircraft Seat Capacity Analysis

The survey of short-haul aircraft and operations in Section 3 shows the recent trend of shifting operations towards larger aircraft in order to minimize operating costs on a per-seat-mile basis. As this shift has occurred, the number of profitable O-D markets has shrunk because of the need to maintain high load factors for these larger aircraft. Selecting a seat capacity for the advanced short-haul aircraft based on this trend would likely result in an aircraft too large to provide a mobility benefit to the flying public. On the other hand, selecting a very small seat capacity based on mobility needs and ignoring market forces is equally unacceptable. Instead, a method was needed that would consider both market forces and the mobility goals of this study.

The approach chosen for determining the target seat capacity was to compare the potential O-D markets for a series of advanced short-haul aircraft of varying passenger capacities. Both passenger demand and airline profitability were considered in the analysis. The first step was to determine all the potential short-haul O-D markets with passenger demand, without regard for profitability. The important consideration in this step was the passenger choice to fly or select another travel mode, based on the airfare and travel time. The second step was to determine which of these potential short-haul O-D markets an airline might want to operate in, by comparing the operating cost against the potential passenger revenue. This same analysis was repeated for a number of aircraft capacities between 20 and 80 passengers, and the results were compared. The metrics examined were airline profitability in the short-haul O-D markets, the total number of annual trips serviced, and the total number of short-haul O-D markets served.

An airline's decision to operate a particular aircraft size or type in a given O-D market is influenced by a number of factors. The number of daily operations, operating costs, desired load factor, crew and aircraft scheduling, and a host of other considerations all weigh in this decision. Also, competition between airlines is a major factor that can affect airfares and services offered. Determining the behavior of different airlines based on their economics and competition strategies was beyond the scope of this study. Instead, a single airline was assumed to operate the advanced short-haul aircraft and compete with the regular commercial service flights in all feasible short-haul O-D markets. This notional airline would use a point-to-point operations model and operate only one aircraft type over all the short-haul routes in its network. The complex nature of a hub-and-spoke network and the difficulties of integrating such a network into the existing commercial airline network put that scenario beyond the reach of this quick-look analysis.

The Transportation Systems Analysis Model (TSAM) (ref. 11) was used to determine the passenger demand for short-haul flights in the U.S. It uses socio-economic and demographic data (refs. 12, 13) to forecast intercity travel behavior in the contiguous United States out to the year 2040. TSAM allows for different modes of travel (e.g., commercial air, automobile, and rail). It also supports any new mode of travel that the user can model with performance and cost data.

A four-step process taken from classic transportation theory was used to forecast air traffic demand:

1) Trip Generation
2) Trip Distribution
3) Mode Choice
4) Network Assignment

The Trip Generation step forecasts the number of trips generated-by and attracted-to each county. In the Trip Distribution step, TSAM connects the generated trips in each county to the attracted trips in other counties, using a distribution algorithm based on a gravity-type model. In the Mode Choice step, each trip is run through a utility function to determine which travel mode (auto, commercial air, etc.) the trip will use, based primarily on the mode cost and travel time. In the Network Assignment step, the air traffic trips are given origin and destination airports, and assigned routes on the network from origin to destination.

For this study, the advanced short-haul aircraft was modeled as its own independent travel mode, which competes for trips with the other modes. This means that the short-haul mode consisted solely of the flights utilizing the advanced short-haul aircraft. These flights compete directly against commercial air short-haul aircraft (e.g., single aisle jets, regional jets, turboprops, etc.) and also automobiles for trips between O-D city pairs of less than 900 NM. As previously mentioned, the short-haul mode utilized a direct point-to-point network between the O-D pairs, whereas the commercial air mode used the existing hub-and-spoke network. The advanced short-haul aircraft was assumed to be able to operate out of all current commercial airports with at least one paved runway of 4,000 ft or longer. Short-Haul flights were not allowed to make multiple hops between O-D pairs.

The Mode Choice step was used to determine how many passengers chose to travel via the short-haul mode versus automobile and regular commercial air modes. In order to calculate the passenger utility for the Mode Choice step, it was necessary to develop airfare models and travel time profiles for the short-haul travel mode. A speed profile (average ground speed vs. great circle distance) was developed for a representative turboprop aircraft. TSAM used this speed profile to determine the travel time for each short-haul trip. Short-Haul trip fares for both business and non-business trips were calculated using a method from Rama-Murthy (ref. 14). This fare model predicts airfares based on the great circle distance between airports.

The Trip Generation, Trip Distribution, and Mode Choice steps were run for the year 2030, with the short-haul mode competing with commercial air and automobile for trips between O-D pairs. Once the Mode Choice step had determined the number of overall trips that were captured by the short-haul mode, trip tables were generated. These tables contained all business and non-business short-haul trips for each O-D pair for the year 2030. The TSAM output tables contain the potential short-haul O-D pairs for the advanced short-haul aircraft based on passenger demand in those markets. A fare structure was assumed for all of these O-D markets, but no consideration was given in the TSAM analysis to the airline operational costs in each O-D market. Also, a large number of these O-D pairs have too little demand for an airline to consider operating in that market. A filtering procedure was needed to remove O-D markets that an airline would not want to operate in due to profitability and/or operational reasons.

An O-D Market Profitability Metric (MPM) was created to help determine the most profitable short-haul O-D markets. This metric consisted of the short-haul trip revenue, as determined by the short-haul fare model, minus the short-haul trip operating cost to the airline. Trip costs were calculated using a method for short-haul flights described by Swan and Adler (ref. 15). This method assumes trip cost is linear with trip distance and seat capacity. The operating cost includes pilot, cabin crew, fuel, airframe maintenance, engine maintenance, and ownership costs. It does not include any of the airline's other fixed costs.

For each O-D pair, business and non-business round trips were aggregated into daily flights based on an assumed seat capacity value. The MPM was calculated for the day's flights, subtracting the total trip costs for each flight from the total fares. O-D pairs where the MPM was negative (the total flight costs exceeded the total fare revenues) were filtered out, with the assumption that an airline would not choose to operate in an unprofitable market. In addition, the TSAM trip table outputs were filtered by setting limits on the minimum and maximum number of daily flights between O-D pairs. If there were only fractional daily round trip flights between an O-D pair, then that O-D pair was excluded from the analysis. The assumption was that an airline would not choose to operate in a market with less than one round trip flight per day. Conversely, if an O-D pair had more than five round trip flights per day, then it was assumed that an airline would choose to operate a larger aircraft for that market and that O-D pair was excluded from the analysis. Finally, the trip tables were filtered to ensure that all the O-D pair distances were under the advanced short-haul aircraft assumed maximum range (900 NM).

After all the filtering was completed, the total daily operations, costs, and fare revenues across all of the feasible O-D pairs was aggregated. These aggregated results represented the values for a single assumed aircraft seat capacity. The analysis was repeated for each aircraft seat capacity.

The above analysis was performed using the short-haul aircraft seat capacity as the independent variable with the expectation that a trend could be identified or an optimum value found for one of the metrics of interest. Fortunately, an optimum value was present for the MPM, as seen in Figure 22. As the short-haul aircraft seat capacity increases from 20 seats to 80 seats, the MPM increases and reaches a maximum at approximately 70 seats. With respect to the MPM, this represents the best seat capacity for a single aircraft type operating in all profitable O-D markets shorter than 900 NM, using a point-to-point operational model with current technology.

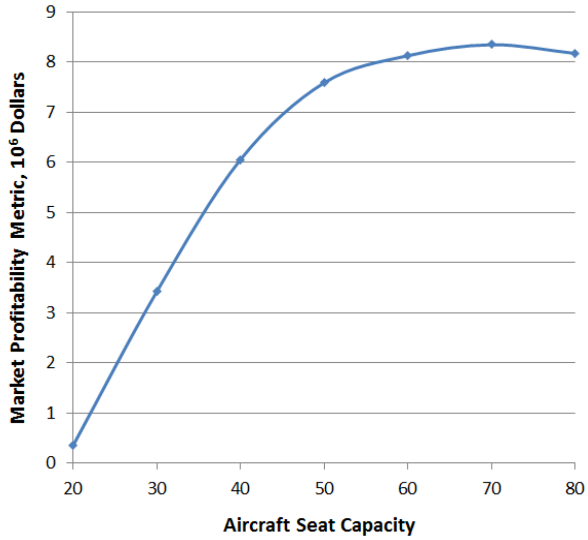

Figure 22. Best aircraft seat capacity in terms of O-D MPM.

Since the Short-Haul Revitalization Study was focused on ways to reduce the operating cost for an advanced short-haul aircraft, the next step in the analysis was to determine if the seat capacity for maximum MPM shifts when the aircraft operating costs are significantly lower than the baseline. Figure 23 shows the relationship between aircraft seat capacity and operating cost, in terms of dollars per available seat-mile (ASM), using the Swan and Adler method for a trip distance of 900 NM. It shows the significant effect seat capacity has on operating cost and how the curve begins to flatten out as seat capacities increase. Also shown is the effect of applying simple across-the-board cost reductions to the baseline cost curve.

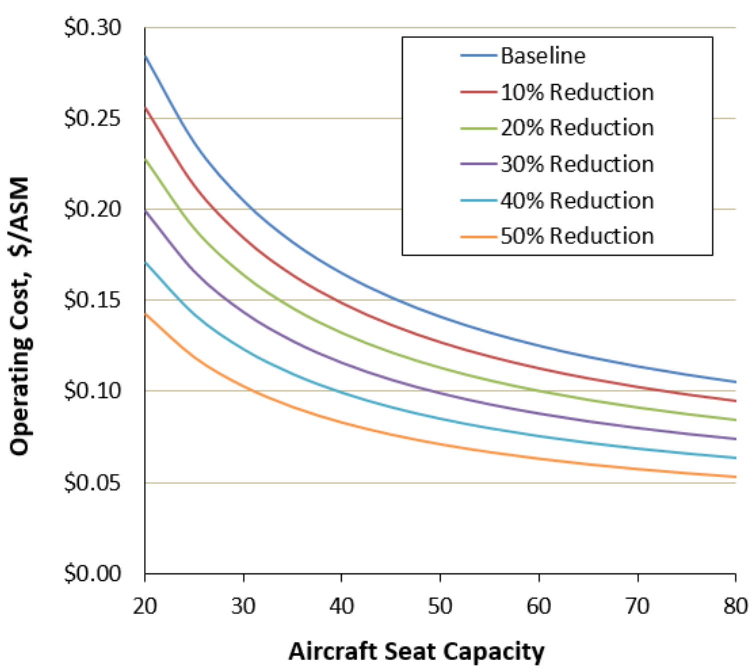

Figure 23. Relationship between aircraft seat capacity and operating cost.

Simple percentage reductions were applied to the trip costs in the previous analysis to determine if the optimum MPM would occur at a different seat capacity value. The results are shown in Figure 24, with the original baseline curve also shown. The aircraft seat capacity with the highest MPM shifts towards smaller values with increasing cost improvements. If it were possible to reduce the operating cost by 50%, the aircraft seat capacity with highest MPM would be about 35 passengers, compared to 70 for the baseline case. This effect is due to the smaller aircraft benefiting more from lower operating costs. As the operating costs go down, more O-D pairs become profitable. Recall that in this analysis, O-D pairs with a negative value for the airline profit metric are filtered out. As those O-D markets become profitable with lower operating costs, they are included back in the aggregated results. Smaller aircraft benefit more than larger aircraft because it is easier to fill up a smaller aircraft and achieve the minimum one round trip flight per day operational requirement for that O-D pair. Larger aircraft benefit from the cost reductions in the markets they already operate in, but they see fewer new O-D markets open up.

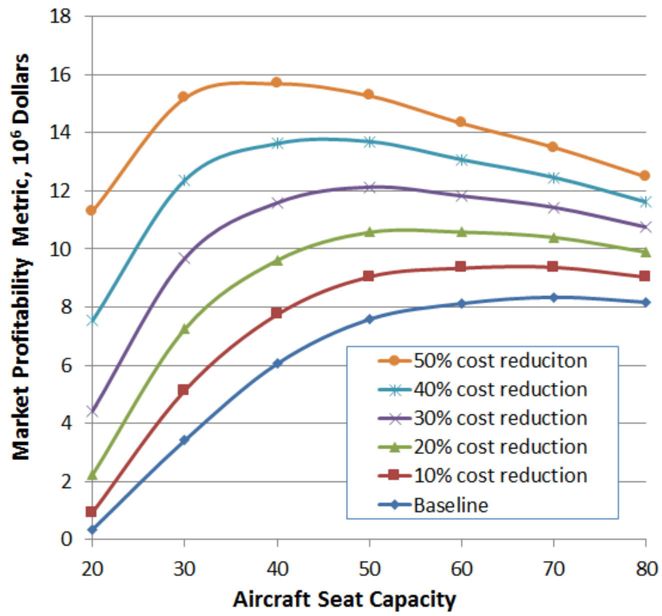

Figure 24. Effect of cost reduction on best seat capacity in terms of MPM.

Based strictly on the MPM, this analysis suggests that the target design seat capacity should be somewhere between 50 and 70 passengers, assuming an operating cost reduction between 0 and 25 percent for the advanced short-haul aircraft. As will be shown in Section 6.2, a 25% operating cost reduction is a reasonable projection for an advanced short-haul aircraft.

Although airline profitability is an important consideration in determining the target seat capacity for the advanced short-haul aircraft, increased mobility for the flying public is an important goal for NASA. NASA's Aeronautics Research Mission Directorate has identified three overarching drivers to guide research planning in its Strategic Implementation Plan (SIP). The first "Mega-Driver" is "Global Growth in Demand for High Speed Mobility." The analysis was therefore repeated using mobility metrics, instead of the MPM, to determine the best aircraft seat capacity. Two metrics were chosen to represent mobility for passengers: number of annual round trips and number of O-D pairs served.

The first metric used to represent mobility was the total number of annual round trips taken for the short-haul transportation mode. These trips represent person-trips, not aircraft flights. As previously described, the number of annual round trips is calculated for each O-D pair (after excluding the unprofitable O-D markets and O-D markets outside the operational limits previously described). The results can be seen in Figure 25. For the baseline case, the maximum number of annual round trips occurs with a seat capacity of approximately 44 passengers. As operational cost reductions are assumed, the maximum point in the curve shifts towards smaller seat capacities. This is the same effect seen for the MPM in Figure 24. The same reasoning applies; the smaller aircraft benefit more than the larger aircraft because more new O-D markets open up to smaller aircraft as operating cost is reduced.

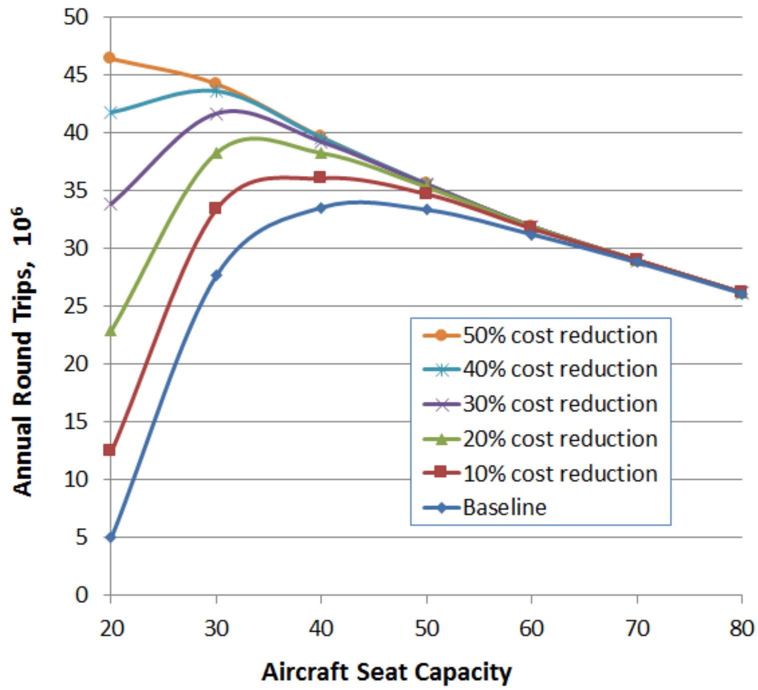

Figure 25. Effect of cost reduction on best seat capacity in terms of annual round trips.

The second mobility metric examined in this analysis was the total number of O-D pairs served by the short-haul travel mode. More O-D pairs served implies more passenger choice and greater mobility. Figure 26 shows the number of short-haul O-D pairs as a function of the aircraft seat capacity for the baseline and the cost reduction cases. Using this metric, the best seat capacity for the baseline case is between 35 and 40 passengers, even lower than for the annual round trip metric. As seen with the other metrics, the best seat capacity shifts towards smaller values as operating costs are reduced. Aircraft larger than about 60 seats see little-to-no benefit in terms of O-D pairs served because they are too large to serve the thousands of thin markets that open up.

It is interesting to note that for cost reductions of 40% or more, the seat capacity with the maximum O-D pairs served is driven towards very small values, into the realm of general aviation or possibly personal air vehicles (PAVs). Perhaps one day very small, fully automated aircraft may be feasible and operate economically enough to represent a mobility solution for the NAS.

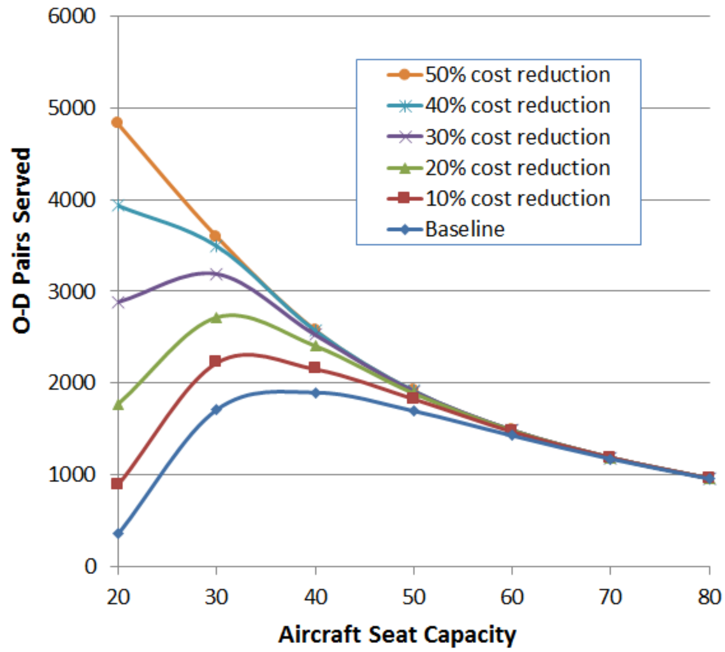

Figure 26. Effect of cost reduction on best seat capacity in terms of O-D pairs served.

The design team was ultimately left with a range of aircraft seat capacities to consider. The team had to weigh the relative importance of airline profitability versus mobility for the public and consider the possible reductions in operating cost for the advanced short-haul aircraft. There were also other considerations outside the scope of this analysis, such as the Federal Aviation Regulations (FAR) requirement for an additional flight attendant if the seat capacity is 50 or more. Ultimately, the design team chose a design seat capacity of 48 for the advanced short-haul aircraft. This aircraft size was a good compromise for achieving the study goals. Also, this seat capacity is the same as the ATR 42-500, which allowed a direct comparison of the advanced short-haul aircraft to a current technology aircraft that performs a similar mission.

4.1.2. Cruise Speed and Maximum Range Sensitivities

A sensitivity analysis of MPM was performed for cruise speed and maximum trip length, using a 48 passenger capacity for the advanced short-haul aircraft. The previous analysis assumed a maximum trip length of 900 NM. Routes requiring a stop for refueling were not allowed. The sensitivity analysis placed an upper limit on the trip length, from 300 NM to 900 NM, to determine the sensitivity of demand to maximum trip length. Cruise speeds were also varied between 210 mph and 290 mph in this sensitivity analysis. The cruise speeds are important in the TSAM Mode Choice step because they affect the trip times, which can make the short-haul mode either more or less attractive compared to the other travel modes. The TSAM demand analysis was performed for each trip length and cruise speed combination using the same methodology previously described.

The effect of varying maximum trip length on the MPM for different cruise speeds is shown in Figure 27. The biggest increase in MPM occurs between 300 NM and 400 NM. For the 210 mph cruise speed, the MPM no longer increases as the maximum trip length goes beyond 600 NM. For the 290 mph cruise speed, the MPM continues to grow even beyond the 900 NM maximum trip length. As expected, the spread between the curves increases with increasing maximum trip length. So, for short maximum trip length, the trip length is a moderate factor and cruise speed is a minimal factor in determining MPM. As the maximum trip length is increased, cruise speed becomes more important and an incremental increase in maximum trip length becomes less important.

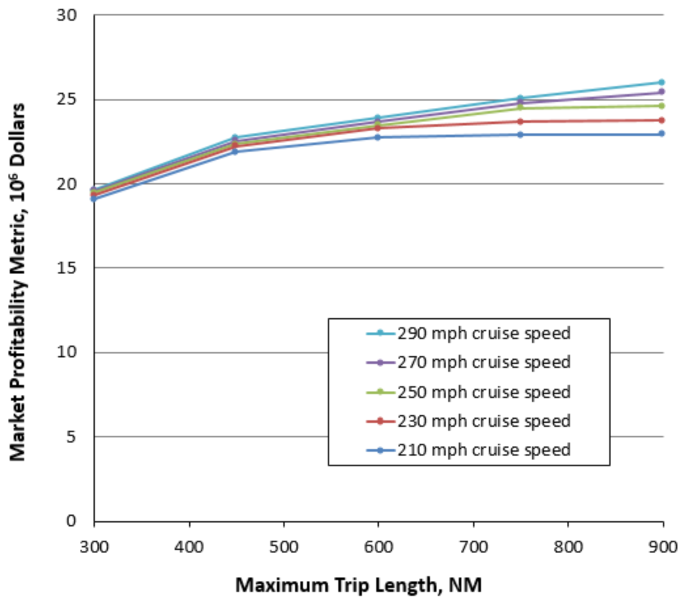

Figure 27. Sensitivity of MPM to maximum trip length for various cruise speeds.

The effect of varying the cruise speed for various maximum trip lengths is shown in Figure 28. The MPM is not very sensitive to the cruise speed for any of the trip lengths under 900 NM, although the slope of the MPM curve increases with increasing maximum trip length. As the maximum trip length is increased to above 600 NM, the MPM curves begin to overlap, indicating there is little or no advantage to operating at longer trip lengths for the given speed range. The reason is that there are few new O-D markets opening up where the MPM is positive for these longer trip lengths. The speed sensitivity results support the initial assumption of cruise speeds consistent with a turboprop, especially if the trip length will typically be less than 600 NM. There is a benefit in terms of MPM for higher cruise speeds, but it appears to be small for short-haul ranges.

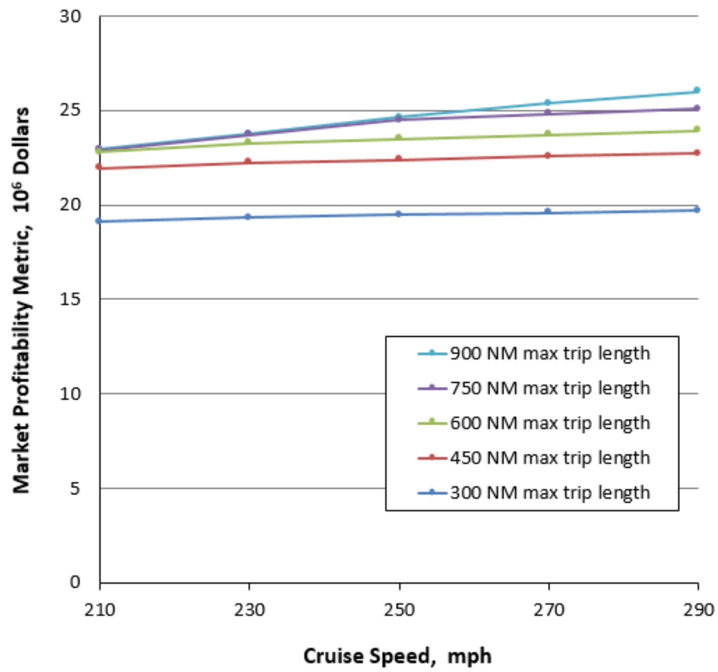

Figure 28. Sensitivity of MPM to cruise speed for various maximum trip lengths.

4.1.3. Short-Haul Aircraft Technical Requirements

The design team selected the following requirements after surveying the existing short-haul aircraft and operations and conducting the seat capacity analysis:

Design Range
The aircraft shall have a design range of 600 NM. This design range was chosen based on the results from the cruise speed and maximum range sensitivity studies using TSAM. This range is consistent with the operational distances being flown by current aircraft, previously shown in Figure 2.

Payload
The aircraft shall carry 48 passengers. This payload is based on the discussion in Section 4.1.1.

Cruise Speed
The aircraft shall have a cruise speed greater than 200 kts, with a goal of 300 kts. The TSAM sensitivity studies showed that the cruise speed had little effect on the demand metrics for typical short-haul ranges. However, higher cruise speeds are generally desirable and give more operational flexibility.

Balanced Field Length
The balanced field length for takeoff and landing shall not exceed 4,000 feet. This requirement is based on a survey of existing runways at commercial airports, previously shown in Figure 5.

Reserve Segment
The aircraft shall meet IFR reserve requirements at best endurance speed.

5. Short-Haul Aircraft Design

5.1. Technology Selection

The design team conducted a technology down-select exercise considering technologies that could be available in the 2030 timeframe. These technologies had to be applicable to a smaller aircraft, and they ideally might initially be applied more successfully on a smaller aircraft than a larger aircraft. Electric propulsion was identified as a potential enabling technology, as it has historically been applied only to small aircraft due to the experimental nature of the technology. It is reasonable to expect that the first intercity commercial aircraft to use electric propulsion will be a regional or commuter aircraft. Although electric propulsion has advantages in terms of efficiency, major disadvantages include the low specific power, specific energy, and power densities of current batteries, motors, and power electronics. Even with optimistic projections for these electric systems, an all-electric aircraft introduced in the 2030 timeframe would be unlikely to have enough range capability to be competitive with conventional aircraft, even for a regional, short-haul mission. With this in mind, a hybrid-electric propulsion system was proposed as an alternative to an all-electric system. There are currently a number of NASA activities related to hybrid-electric aircraft propulsion that could enable such a propulsion system in the future. A hybrid-electric system would have many of the advantages of an all-electric propulsion system, yet could take advantage of the superior energy density of jet fuel to overcome some of the disadvantages, such as limited range. Although a hybrid-electric system would not be able to match the efficiencies of an all-electric propulsion system, it might enable the operating costs of a small regional aircraft to be competitive with much larger aircraft using conventional propulsion systems.

Once hybrid-electric propulsion was identified as the primary enabling technology for the advanced short-haul aircraft, other technologies were considered in the areas of aerodynamics, structures, systems, power and propulsion, and controls. The goal was to select compatible technologies that complemented the propulsion system selection. Since the hybrid-electric system itself is a high risk item, especially when considering battery technologies, the other technologies selected tended to be lower risk in comparison. The following technologies were selected for the advanced short-haul aircraft:

Aerodynamics:	Natural Laminar Flow
Structures/Systems:	Advanced Composites (Damage Arresting, Advanced Sandwich, Metal Matrix, Ceramic Matrix), Lightweight Electrical Systems, Lightweight Cabin Furnishings
Propulsion:	Hybrid-Electric Propulsion System (Advanced Batteries, Advanced Turbine Engine)

Noise reduction technologies (e.g., shielding, acoustic liners, undercarriage fairings, etc.) were not considered explicitly, although some noise reduction is implicit in the technologies associated with an advanced turbine engine. There was no plan to perform noise modeling for this study and therefore no basis for evaluating any benefits from adding noise reduction technologies.

5.2. Hybrid-Electric Architecture

As the primary enabling technology, hybrid-electric propulsion was chosen to meet the study objectives of increasing safety, affordability, environmental compatibility, and customer acceptance of short-haul aircraft. The parallel hybrid-electric propulsion architecture presented in this study consists of a turbine engine driving a propeller, with additional power provided by an electric motor attached to the turbine shaft. A battery provides electrical power to the motor. A methodology is presented for the sizing and mission performance analysis of the parallel architecture hybrid-electric regional aircraft. Multiple trade studies are presented later in this report that examine the effect of battery specific energy (BSE), mission range, projected energy costs, and propulsion electrification (the shaft power provided by the electric motor as opposed to the shaft power provided by the turbine) on aircraft sizing, performance, and total energy cost.

5.3. Mission and Sizing Assumptions

The study mission profile includes takeoff at sea-level, climb to optimum altitude for specific range, cruise at 300 kts, descent, and landing. Additional fuel and battery energy for a reserve mission are also included. The reserve mission consists of 5% reserve fuel as a fraction of total trip fuel, an 87 nautical mile diversion, and a 45 minute continued cruise. This requirement is based on the ATR 42-500 reserve mission requirements for comparison purposes (ref. 16).

The advanced short-haul aircraft was analyzed with four levels of electrification, 0% electric with 100% conventional, 25% electric with 75% conventional, 50% electric with 50% conventional, and 75% electric with 25% conventional. Each of the four aircraft were designed to minimize the takeoff gross weight (TOGW) on the design mission by varying wing area and maximum takeoff thrust. Design constraints were used to bound the design space and limit the designs to feasible or useful products. The results for these different designs are compared to determine the tradeoffs available for a conventional/hybrid-electric powered regional class aircraft.

Several assumptions were made in order to keep the study manageable without missing any significant factors. The design variables were limited to the wing area and maximum takeoff thrust. Consequently, the fuselage geometry was essentially fixed for each configuration and the tails were resized based on the use of a constant tail volume coefficient. Current technology level was assumed for the baseline aircraft. In other words, the baseline aircraft was calibrated to published ATR 42-500 data and no additional technology factors or adjustments were made. The advanced aircraft, including the motor, battery, and electric system, was based on technologies projected to be available in the year 2030. A fixed mission that is consistent with existing capabilities for a 48 passenger short-haul transport aircraft was assumed for all of the aircraft. A propulsion system performance deck with a total shaft power of 2400 horsepower was scaled as necessary for each design. This total shaft power was split between the conventional and electric components based on the percent electric desired, impacting the fuel flow and battery discharge rate of the system.

5.4. Engine Model Development

Engine models were developed to represent current turboprop engine performance and projected future performance with advanced technology. The basis for the engine modeling was the PW 100 series of engines, which are three shaft, two spool turboprop engines (ref. 17). A representative model of the PW 127E turboprop engine, minus the propeller, was assembled in the NPSS (Numerical Propulsion System Simulation) code for cycle analysis (refs.18, 19, 20). NPSS is a component-based, object-oriented engine cycle simulator in which a model is assembled from a collection of interconnected engine components and controlled through the implementation of an appropriate solution algorithm. The PW 127E uses two stages of centrifugal compression providing an overall pressure ratio (OPR) of 14.7. Each compression stage is powered by a single stage turbine, one low pressure and one high pressure. A two stage power turbine provides shaft power to the propeller through a reduction gearbox (2400 shaft horsepower (shp) at static takeoff conditions). The remainder of the fluid momentum provides jet thrust (289 lb at static takeoff conditions). The specific fuel consumption (SFC) is 0.474 lbm/hr/hp at maximum power (refs. 21, 22, 23, 24). Once an engine model representative of current performance was completed, individual components were then upgraded to predict the overall performance of an advanced version of the engine that could be available in the year 2030.

The NPSS turboprop models were run through the FLOPS (ref. 25) engine module to add the propeller performance. FLOPS uses the Hamilton Standard method to estimate the propeller performance. Publically available engine and propeller data was used as input to FLOPS (refs. 20, 21, 26).

Component efficiencies (η) for the NPSS model of a PW 127E-like engine were estimated using representative values for component performance corresponding to the state-of-art (SOA) period in the evolution of engine technology (ref. 27). These values are listed in Table 3. The SOA turbine inlet temperature (T4) for a cooled turbine was estimated to be 2860°R and typical compressor bleed flow rates for turbine cooling were assumed. For example, there is 5% bleed from the high pressure compressor to the inlet guide vane (HPC-IGV), 2.5% bleed from the high pressure compressor to the high pressure turbine (HPC-HPT), and 3.5% bleed from the low pressure compressor to the low pressure turbine (LPC-LPT). These estimates combine in the NPSS model to provide the takeoff (T/O) performance given in Table 4, which matches the published OPR of 14.7 and SFC of 0.474 lbm/hr/hp at 2400 shp with a jet thrust of 287 lbf. The performance of this engine model was predicted over the flight envelope of altitude (0-30,000 ft), Mach number (0-0.6) and throttle setting (100-10%). Results are presented in Table 4 for static takeoff, rolling takeoff, top of climb, start of cruise, and average cruise.

Component efficiencies (η) for the NPSS model of an advanced turboprop engine were estimated using envisioned values for component performance corresponding to an advanced evolution of engine technology (ref. 26). These values are listed in Table 3. The turbine inlet temperature was left the same as the SOA, but the cooling flow to the inlet guide vanes is zero assuming that they are made of ceramic matrix composites (CMC). The advanced engine model created in NPSS has the same static takeoff OPR, shaft power, and jet thrust as the baseline model as noted in Table 4. Basically, the advanced engine has 9.8% lower SFC and has 12.3% lower inlet mass flow at sea level static conditions. The performance of this engine model was predicted over the flight envelope of altitude (0-30,000 ft), Mach number (0-0.6) and throttle setting (100-10%). Results are presented in Table 4 for static takeoff, rolling takeoff, top of climb, start of cruise, and average cruise.

Reduced thrust versions of the advanced engine model at 1800 shp (25% electric), 1200 shp (50% electric), and 600 shp (75% electric) were developed for the hybrid-electric propulsion system. These versions have the same OPR and SFC characteristics as the advanced 2400 shp model. This result is dictated by the fact that the PW 100 series engines used as the basis for the cycle modeling are three shaft engines with a separate power turbine shaft driving the propeller gearbox. Since the NPSS models are 1-D and the component efficiencies are assumed the same for the reduced power versions, even though smaller versions would likely see some performance penalty, the output of this power turbine shaft is directly proportional to mass flow. The inlet to exit pressure ratio was also kept the same in the model, setting the exit Mach number to be the same as the 2400 shp model and resulting in a jet thrust proportional to mass flow as well.

Table 3. Current (SOA) and advanced engine component performance.

	SOA	**Advanced**
Diffuser	0.975	0.975
LPC	0.86	0.88
HPC	0.86	0.88
HPC-IGV Cooling (%)	5.0	0
HPC-HPT Cooling (%)	2.5	2.5
LPC-LPT Cooling (%)	3.5	3.5
Burner	0.95	0.98
Burner Pressure Loss (%)	7.0	7.0
T4 (°R)	2860	2860
HPT	0.85	0.88
LPT	0.85	0.88
PT	0.85	0.88
Nozzle	0.975	0.985

Table 4. Engine performance estimates for SOA and advanced engine technology levels

	Units	Static T/O	Rolling T/O	Top of Climb	Start of Cruise	Average Cruise
MN		0	0.2	0.5	0.5	0.5
Altitude	ft	0	0	20,000	20,000	20,000
Throttle	%	100	100	100	90	80
SOA						
Power	hp	2,400 (2400*)	2,452	1,696	1,527	1,357
Jet Thrust	lbf	287 (289*)	294	230	206	181
SFC	lbm/hr/hp	0.474 (0.474*)	0.469	0.430	0.432	0.433
Mass Flow	lbm/s	12.15	12.33	7.59	7.32	7.01
OPR		14.7 (14.7*)	14.5	16.8	15.9	14.9
Advanced						
Power	hp	2,400	2,462	1,604	1,443	1,283
Jet Thrust	lbf	287	297	218	194	170
SFC	lbm/hr/hp	0.427	0.423	0.398	0.394	0.391
Mass Flow	lbm/s	10.65	10.85	6.47	6.26	6.01
OPR		14.7	14.6	16.4	15.4	14.4

*Published manufacturer values

Following the engine cycle model development, estimates of the engine weights and flowpath dimensions were developed. A NASA software tool, WATE++ (Weight Analysis of Turbine Engines) (ref. 28), was used to create engine architectures that could achieve the engine thermodynamic cycles produced by the NPSS models. The cycle data required for WATE execution, such as air mass flow, temperatures, pressures, pressure ratios, etc., were derived from the NPSS cycle model output. Both the ADP (aerodynamic design point) and off-design cases were used to encompass the maximum performance level (i.e., temperature and pressure) required to size each engine component. The cycle data, the material properties, and design rules for geometric, stress, and turbo-machinery stage-loading limits were used to determine an acceptable engine flowpath. For the advanced engines, ceramic-matrix composite HPT inlet guide vanes were assumed, versus nickel-based alloys used for the SOA engine. An empirical correlation was used to calculate the weight of the gearbox and lubrication system as shown in Figure 29, where *hp* represents horsepower and RPM represents revolutions per minute. The correlation is a function of maximum delivered output power and gear ratio. It was developed at NASA based on actual gearbox weight data from over fifty rotorcraft, tilt rotor, and turboprop aircraft (ref. 29).

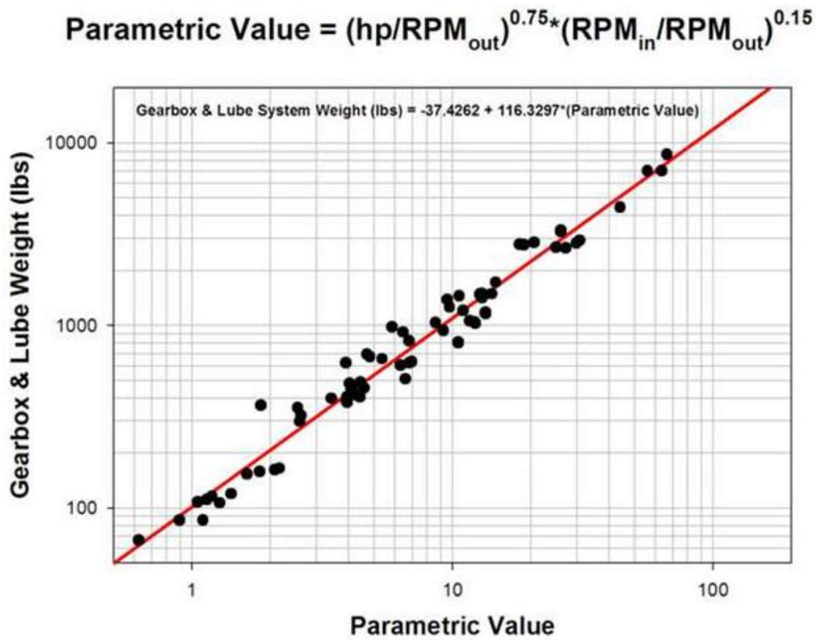

Figure 29. Transmission and lubrication system weight correlation.

For the propeller systems, a rotor weight correlation was used that is a function of maximum power delivered to the rotor, propeller tip-speed, and propeller diameter. A weight reduction factor of 20 percent was applied to account for the use of current (SOA) materials. The propeller system includes blades, disks, spinner, and pitch-changing mechanism. For the hybrid-electric systems, a projected power density of 8 hp/lb was assumed for the motors, and 10 hp/lb was assumed for the power electronics. For the current study, it was assumed that the thermal management system would be incorporated into the motor casing by using multifunctional structures (ref. 30).

Table 5 gives a summary of the major weights and dimensions of the engines developed for this study. The propeller diameter for all the engines in this study is about 12.8 feet and the nacelle diameter stays constant (about 3.3 feet). For the hybrid-electric engines, it was assumed that the electric motor systems are installed within the engine pods.

Table 5. Principle turboprop engine flowpath parameters.

Mechanical Design Parameter	**SOA Turboprop 2400 SHP**	**Advanced Turboprop 2400 SHP**	**Advanced Hybrid-Electric Turboprop** Gas Turbine + Electric Motor		
			1800 + 600 SHP	**1200 + 1200 SHP**	**600 + 1800 SHP**
Turbine engine + Gearbox weight (lb)	1054	1010	819	626	410
Propeller system + Nacelle weight (lb)	782	781	766	752	737
Electrical system weight (lb)	-	-	135	270	405
Total engine weight (lb)	1836	1791	1720	1648	1552
Engine pod length (ft)	7.0	7.0	6.1	5.3	4.2
Maximum Propeller Diameter (ft)	12.8	12.8	12.8	12.8	12.8
Nacelle Diameter (ft)	3.3	3.3	3.3	3.3	3.3

5.5. Aircraft Model Development

5.5.1. Baseline Technology Model

The basis for the aircraft modeling was the ATR 42-500, a twin-turboprop powered, high wing, t-tail configuration. Both baseline technology and advanced technology aircraft models were created in FLOPS (ref. 24). First, the baseline technology model was created and calibrated to known data. Then, technology factors were applied to the baseline model to create the advanced technology aircraft model. ATR 42-500 data was used to calibrate the baseline model (refs.16, 31, 32, 33). The technology factors for the advanced model were based on previous NASA projects (ref. 34, 35). Both aircraft were simulated flying the study mission to enable a direct performance comparison.

An Open Vehicle Sketch Pad (OpenVSP) model (ref. 36) was created based on publically available geometry data for the ATR 42-500 (see Figure 30). This model was used to calibrate the wetted area estimates in FLOPS. The initial FLOPS estimate for operating empty weight (OEW) was higher than the published data. Since multiple components of the ATR 42-500 are made of composite materials, adjustments to account for composite construction were made to the FLOPS weight estimates for these components to calibrate the FLOPS OEW to the published data. The FLOPS estimated performance was calibrated using the published payload-range diagram. The engine fuel flow, lift-independent drag, and lift-dependent drag factors were used as calibration parameters. No source was found for the cruise altitudes and velocities used to generate the published payload-range diagram; therefore, they were also allowed to vary during the calibration. The calibration process resulted in the baseline aircraft shown in Table 6. The results of both the ATR 42-500 baseline calibration mission (840 NM) and the baseline study mission (600 NM) are shown in this table.

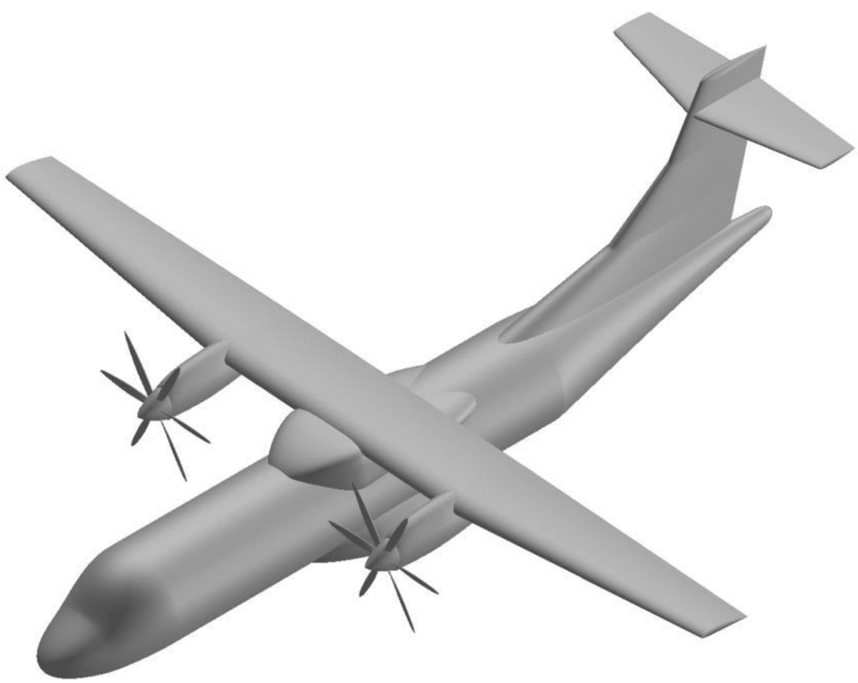

Figure 30. OpenVSP model of baseline aircraft.

5.5.2. Advanced Technology Model

As previously discussed, advanced aerodynamic, structural, systems, and propulsion technologies were added to the baseline aircraft to create the advanced technology model. The aircraft weight reduction technologies were applied as reduction factors in FLOPS. The electric aircraft architectures were assumed to replace most or all of the hydraulic systems. No overall weight savings was assumed for the "Lightweight Electrical Systems" technology used to replace the hydraulic systems. This conservative assumption was used due to a lack of weight data on the electrical systems replacing the hydraulics. A weight reduction in cabin furnishings was estimated using information from an ATR marketing brochure (ref. 37). NASA Ames Research Center 12 ft wind tunnel test data was used to estimate the extent of natural laminar flow on the wing and tail surfaces (ref. 38). The performance of the advanced aircraft flying the design mission (600 NM) is shown in Table 6.

Table 6. Baseline and advanced aircraft characteristics and mission performance.

	Units	Baseline Calibrated Model	Baseline Technology Model	Advanced Technology Model
Mission Parameters				
TOGW	lb	41,000	40,700	36,000
OEW	lb	24,800	24,800	21,800
Payload	lb	10,100	10,800	10,800
Number of Passengers		48	48	48
Design Range	NM	840	600	600
Total Mission Fuel	lb	6,200	5,100	3,360
Block Fuel	lb	4,600	3,700	2,220
Aircraft Parameters				
Wing Area	ft^2	590	590	520
Wing Span	ft	81	81	76
AR		11	11	11
Wing Loading, W/S	lb/ft^2	70	70	70
Cruise Velocity	kts	295	300	300
Start of Cruise L/D		13	11	15
Start of Cruise CL		0.377	0.307	0.502
Start of Cruise CD		0.0290	0.0272	0.0326
Start of Cruise Altitude	ft	15,000	9,500	24,900
Thrust per Engine (SLS)	lb	8,400	8,400	7,300
Start of Cruise TSFC	lb/hr/lb	0.507	0.526	0.423

5.6. Multi-Disciplinary Optimization Framework

A new analysis framework was created specifically for this study. A low-order, multi-disciplinary optimization (MDO) environment was created to capture the unique features of parallel hybrid-electric aircraft. FLOPS is utilized to develop aerodynamic, weight, propulsion, geometry, and performance data for the vehicles (ref. 25). ModelCenter (ref. 39) is used as a platform to connect FLOPS with engine deck files created within Excel as well as battery energy and weight calculations. The MDO framework does not capture the detailed coupling and interactions among different disciplines such as aerodynamics and structures to save computational time. For this effort, there was a focus on low computational time to enable analysis in minutes rather than hours or weeks.

5.6.1. Hybrid-Electric Aircraft Sizing Procedure

The use of two sources of energy introduces additional complications in aircraft sizing. Aircraft sizing typically involves determining the takeoff weight, wing area, and engine thrust required to perform the design mission while meeting necessary performance requirements such as minimum rate-of-climb and maximum approach speed. For a conventional aircraft, the fuel weight required to complete the mission drives the aircraft sizing. For a hybrid-electric aircraft, the energy storage system (e.g., battery) becomes an additional weight that is also a function of the mission and aircraft characteristics. The FLOPS aircraft synthesis code includes a basic capability for analysis of electric and hybrid-electric aircraft. FLOPS allows two different propulsion systems with different types of energy sources to be defined, resulting in a hybrid aircraft. But, only one propulsion system can be operating during any given segment of the mission. In other words, it is not possible to have both a battery and fuel providing propulsive energy at the same time as is the case in a parallel hybrid propulsion system. Therefore, hybrid-electric propulsion, such as the parallel hybrid system considered here, cannot be directly analyzed in FLOPS. Because of this limitation, the electric propulsion capabilities of FLOPS were not used in this study. Instead, FLOPS was used as a mission analysis core with external analyses providing the necessary inputs to perform the complete aircraft sizing.

Figure 31 shows the overall process flow for the aircraft sizing procedure. Necessary inputs include: gas turbine performance (shaft power, nozzle thrust, and fuel flow vs. Mach, altitude, and throttle setting) and weight data; propeller performance (thrust vs. power, Mach, altitude) and weight data; overall electric system efficiency (from energy storage to shaft power) and weight data; energy storage specific energy; level of electrification; and a FLOPS model of the basic non-hybrid aircraft. Three key simplifying assumptions are made for the analysis in this study. First, the level of electrification (% of shaft power provided by the electric system) is constant throughout the mission. In other words, “50% electric” means that the electric motor is providing 50% of the total shaft power at all times. This limitation is inherent in the approach used. Given this simplifying assumption, it is not possible to use this process to size vehicles with a more varied concept of operations, such as using electric power only in certain phases of the flight or optimizing the power split at different points in the mission. The second key simplification is that the gas turbine performance (i.e., specific fuel consumption) is independent of its rated output. In reality, it is expected that as more of the power is provided by the electric system and the size of the gas turbine decreases, the gas turbine performance will degrade. Appropriate performance scaling laws were not available for the class of turbine engines used in the study and therefore specific fuel consumption was held constant with size. The sizing procedure in Figure 31 does not, however, preclude the inclusion of such degradation in the methodology. The final key simplification is that the efficiency of the electric power system (93%) is invariant with the power output. In reality, the efficiencies of the electric system components will be a function of the electrical load.

The gas turbine performance input in Figure 31 is for the all-turbine, zero electric power case. For a given level of electrification, this information is used to create a new propulsion performance deck for input to FLOPS. In generating the hybrid engine deck, the shaft power is held the same as the all-turbine case at all conditions independent of level of electrification, as the electric motor plus gas turbine is assumed to generate the same total shaft power as the all-turbine case. The level of electrification does impact the fuel flow and nozzle thrust at each condition, however. For example, for a 25% electric system, the original fuel flow and nozzle thrust values are multiplied by 0.75 since the gas turbine is sized to only provide 75% of the power. (The fuel flow factor could be adjusted further to account for gas turbine scaling effects as discussed above.) Although fuel flow is reduced by the addition of electric power, it is necessary to track the amount of electric energy being used in order to size the electric energy storage appropriately. Fortunately, there is another input in the FLOPS engine deck besides fuel flow that is integrated over the course of the mission analysis. Typically this input is used to track NO_X emissions during the mission. However, in this case the electric system “energy flow” for each condition, that is, power output of the electric energy storage system, is placed in the NO_X input field. The energy storage system power output is calculated from the electric shaft power output at each condition and the user provided overall electric efficiency. For example, consider a case in which the total shaft power output of the propulsion system is 1000 kW, the electrification is 25%, and the overall electric efficiency is 90%. The energy storage system power output would be 0.25*1000/0.9 = 278 kW. Stated another way, the rate of energy use from the storage system would be 278 kWh per hour. The hybrid propulsion system performance is provided to FLOPS as a “thrust deck” (thrust, fuel flow, and energy flow vs. Mach, altitude, and throttle setting) by using the propeller performance data to determine propeller thrust and adding the gas turbine nozzle thrust. Reference 40 provides more details on the process for creating a thrust deck using shaft power and nozzle thrust data. In the MDO framework, the hybrid engine deck is generated in a spreadsheet and provided to the FLOPS analysis.

When the energy flow from the hybrid propulsion thrust deck is integrated over the entire mission by FLOPS, the result is the total electric energy used during the primary mission. Unfortunately, since FLOPS does not integrate the NO_X emissions input field for the reserve mission segments, the method used to calculate the total energy for the primary mission cannot be used for the reserve segments. Reserve energy requirements are instead estimated from the correlation between mission and reserve fuel for the conventional (0% electric) case. Another consideration for electric energy storage is the maximum depth-of-discharge. In the case of batteries, for example, there is a limit to how much of the stored energy can be used without damaging the battery. It was assumed for the current study that 80% of the energy storage system capacity could be discharged routinely without damage based on current state-of-the-art lithium-ion batteries (ref. 41). The energy storage system is sized, therefore, such that the primary mission energy and a majority of the reserve mission energy is within this 80% constraint. However, to avoid oversizing the re-useable portion of the energy storage for rare, emergency situations (for example, a flight at the maximum design range which also expends all of its fuel/energy reserves), a portion of the reserve mission energy is allocated beyond the 80% depth-of-discharge constraint. Use of this emergency reserve energy would have a negative impact on the future battery performance and life. The required mission and reserve energy combined with the constraint on depth-of-discharge results in a required energy storage capacity in kWh. The user provided electric storage specific energy combined with the required capacity provides an estimate of the energy storage weight. In the FLOPS analysis this weight is simply input as cargo. (This assumes the energy storage system has a fixed weight throughout the mission. Storage systems that increase or decrease in weight as they are discharged cannot be modeled with this approach.) As shown in Figure 31, FLOPS is executed in an iterative loop until the storage weight assumed is equal to the storage weight required. During each of the iterations, FLOPS is internally performing an iteration on the required fuel load to meet the mission requirements. In other words, for a given energy storage weight input, FLOPS is sizing the takeoff and fuel weights and providing an output of the electric energy use, which is then used to update the storage system weight estimate. Once converged, the weight allocated for electric energy storage on-board the aircraft is consistent with the electric energy requirements for the mission.

The Design Explorer optimization tool in ModelCenter is used to size the wing area and propulsion system to meet a series of performance constraints. As the required thrust/power of the propulsion system changes during the optimization, the FLOPS internal propulsion system scaling is used. Since FLOPS has been provided a hybrid engine deck and hybrid propulsion system weight, this means that the entire propulsion system is scaled together and the level of electrification (split in total shaft power between turbine and electric motor) remains constant during the sizing.

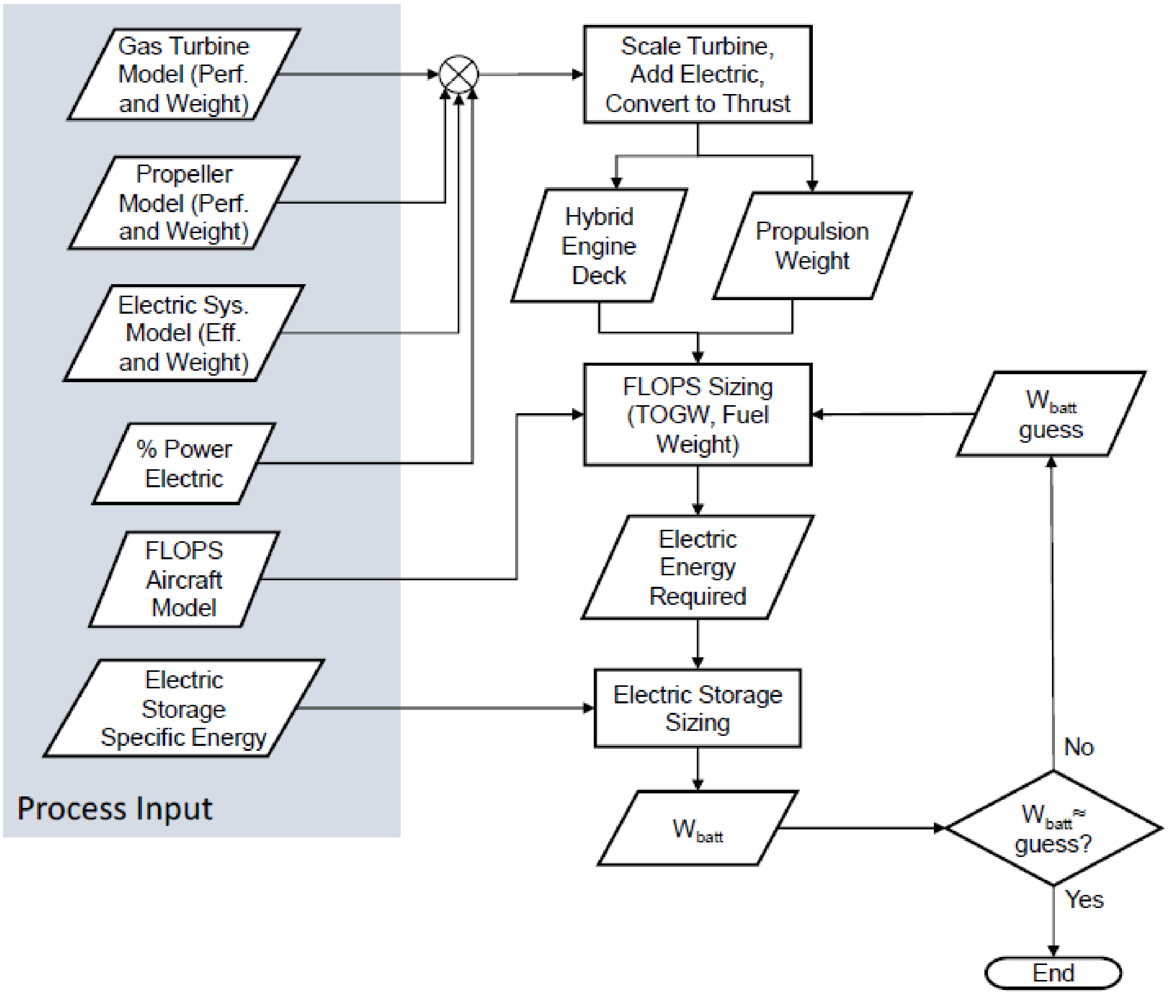

Figure 31. Hybrid-electric aircraft sizing process integrated into ModelCenter.

The design objectives drive the multi-disciplinary design and optimization (MDO). Given enough freedom in constraints and design variables, completely different aircraft can result from a MDO with a different design objective. The design objective chosen for the study was minimum Takeoff Gross Weight (TOGW).

The design variables used in this study are limited to the wing area and maximum takeoff thrust. Variation in these two parameters is necessary to meet performance constraints such as maximum approach speed and takeoff field length as the TOGW of the designs vary. The horizontal and vertical tail areas are allowed to scale with the wing area using a tail volume coefficient method.

The design constraints bound the problem and are used in this study to ensure adequate aircraft performance. In addition to the aircraft design requirements listed in Section 4.1.3 of this report, the design constraints are as follows:

1) Balanced Field Length: The balanced field length must not exceed 4,000 feet.
2) Missed Approach: The excess thrust available during a missed approach with one engine inoperative must be greater than zero.
3) Second Segment Climb: The excess thrust available during the second segment climb with one engine inoperative must be greater than zero.

4) Excess Fuel Capacity: The wing must have enough fuel volume to carry the required mission fuel plus reserves. The excess fuel capacity must be greater than zero.
5) Instantaneous Rate of Climb for Climb Ceiling: The instantaneous rate of climb for the climb ceiling must be greater than or equal to 300 ft/min.
6) Reserve Segment: The aircraft must carry an additional 5% reserve fuel as a fraction of total trip fuel and be capable of flying an 87 nautical mile range diversion and a 45-minute cruise segment after the design mission missed approach. This requirement is based on the ATR 42-500 reserve mission assumptions for comparison purposes (ref. 16).

5.7. Sizing Results

Both level of electrification and BSE were varied to observe their effect on the aircraft system. Twelve different aircraft designs were created and analyzed encompassing 0, 25%, 50%, and 75% electric with BSE values of 500, 750, and 1000 Wh/kg. Full tabular results including the variation in aircraft weights, fuel consumption, energy consumption, and projected energy cost are provided in Appendix B.

Figure 32 displays the effect of BSE and percent electric on the battery, fuel, and total energy consumption of the system. A few observations can be made:

- The battery energy and fuel energy are equal at ~76% electric. Recall that the percent electric is based on shaft power, not energy used.
- As the level of electrification increases, total energy used by the system is approximately constant for a BSE of 500 Wh/kg. However, for 750 and 1000 Wh/kg, the total energy decreases significantly. This decrease in total energy occurs because of the higher efficiency (93%) of the electric propulsion even though the weight of the aircraft is increasing.

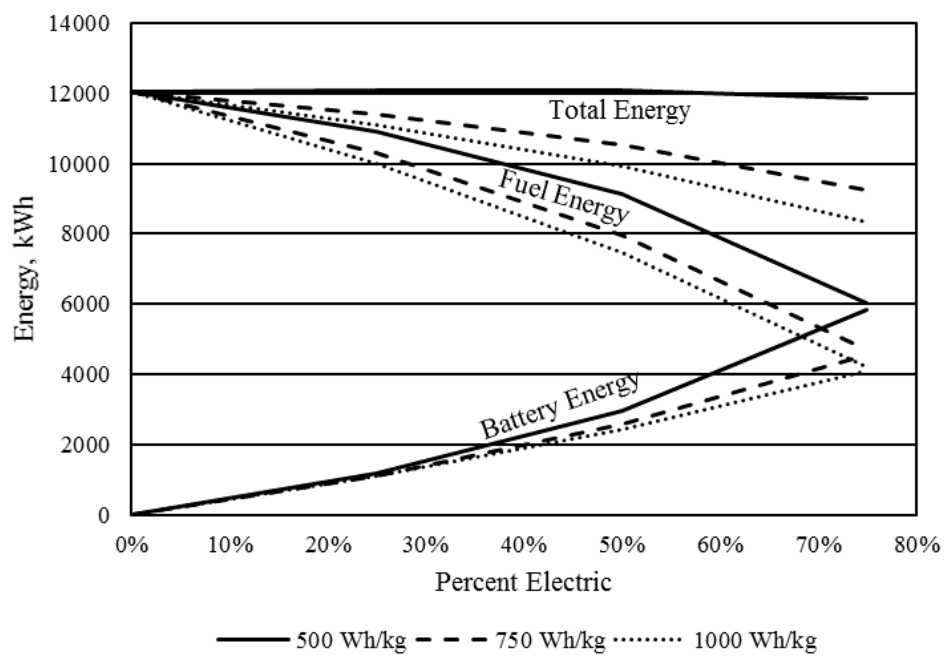

Figure 32. Battery energy, fuel energy, and total energy.

Figure 33 displays the effect of BSE and level of electrification on the takeoff gross weight (TOGW) and operating empty weight (OEW). Historically, the total life-cycle cost of an aircraft has had a strong correlation with the takeoff gross weight and the acquisition cost with the operating empty weight. A few observations can be made:

- Assuming a BSE of 500 Wh/kg, a 75% hybrid-electric aircraft would be 2.3 times heavier than a 0% electric advanced turboprop.
- Assuming a BSE of 750 Wh/kg, a 75% hybrid-electric aircraft would be 63 percent heavier than a 0% electric advanced turboprop.
- Assuming a BSE of 1000 Wh/kg, a 75% hybrid-electric aircraft would be 39 percent heavier than a 0% electric advanced turboprop.
- The operating empty weight of the aircraft is not as significantly influenced by the increase in electrification as TOGW is. The higher takeoff gross weights are primarily a result of the weight of the energy storage system, which is not included in OEW.

Figure 34 displays the effect of BSE and level of electrification on the projected total energy cost in the year 2030. The projections for the price of Jet-A fuel and electricity were calculated as an average of multiple projections for the year 2030 (ref. 42). These average prices were $3.33 per gallon for Jet-A fuel and $0.11 per kWh for electricity. The Jet-A price was converted to $0.09 per kWh using a conversion factor of 36.3 kWh/gallon. A few observations can be made from the following results:

- Assuming a BSE of 500 Wh/kg, energy costs for a 75% hybrid-electric aircraft would be 10 percent more than for a 0% electric advanced turboprop.
- Assuming a BSE of 750 Wh/kg, energy costs for a 75% hybrid-electric aircraft would be 14 percent less than for a 0% electric advanced turboprop.
- Assuming a BSE of 1000 Wh/kg, energy costs for a 75% hybrid-electric aircraft would be 23 percent less than for a 0% electric advanced turboprop.

These energy cost results are highly dependent on the prices assumed for electricity and jet fuel. There are other forecast scenarios that result in the relative energy costs of the hybrid-electric aircraft being more or less favorable.

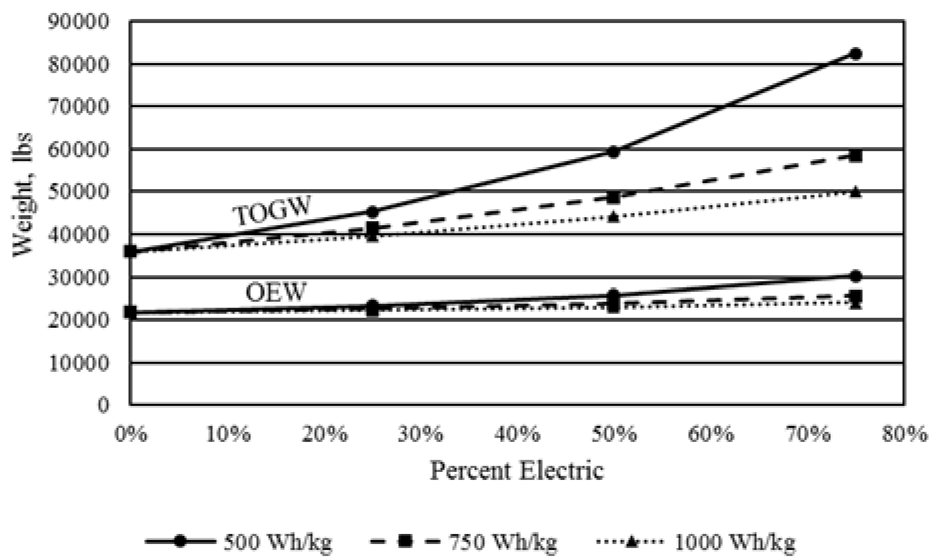

Figure 33. Takeoff and operating empty weight.

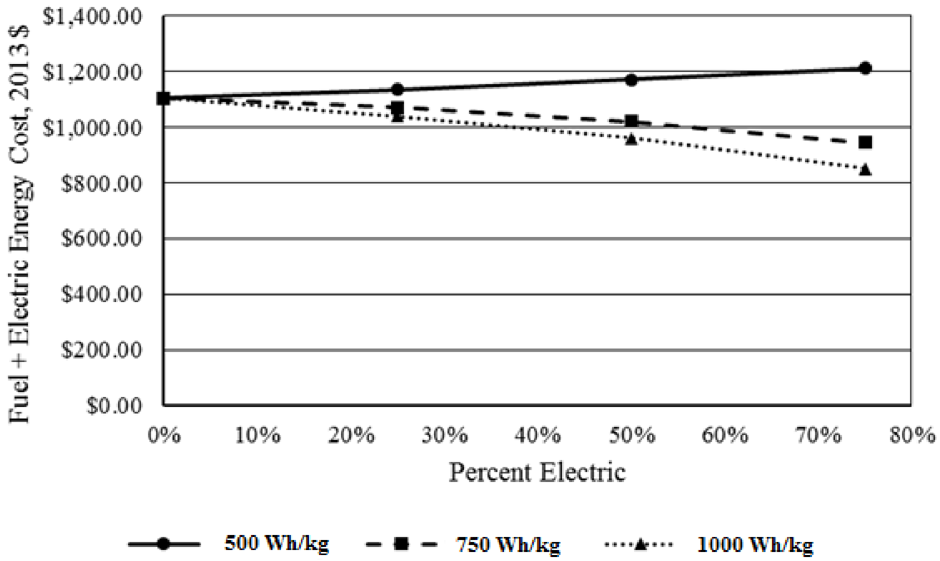

Figure 34. Total (fuel + electric) energy cost based on projections for 2030.

5.7.1. Energy Specific Air Range of the Hybrid-Electric Concept

In Section 3.3 the specific air range, or SAR, was examined as a possible figure of merit for evaluating the performance improvement associated with an advanced short-haul aircraft. However, SAR is not an appropriate metric to use with a hybrid-electric aircraft concept because it represents the distance traveled per unit of fuel consumed. It does not account for the energy supplied by the batteries. Instead, a more generalized figure of merit must be used. The Energy Specific Air Range (ESAR) (ref. 43) is given by:

$$ESAR = dR/dE$$

Where dR/dE represents the change of aircraft range per change of energy in the system. ESAR allows flight efficiency comparisons between a conventional and hybrid-electric aircraft. The average ESAR over the entire 600 NM design mission was calculated for the Baseline Technology aircraft and for the Advanced Concept Aircraft with 0%, 25%, 50%, and 75% electrification. Table 7 shows the improvements in the ESAR metric for the Advanced Aircraft compared to the Baseline Technology aircraft.

Table 7. Improvements in mission average ESAR for the advanced hybrid-electric aircraft.

Battery Specific Energy	**% Improvement in Average ESAR Compared to the Baseline Technology Aircraft**			
	0% Electric	**25% Electric**	**50% Electric**	**75% Electric**
500 Wh/kg	66.6%	66.4%	66.5%	69.2%
750 Wh/kg	66.6%	76.5%	91.3%	117.0%
1000 Wh/kg	66.6%	81.5%	104.0%	142.5%

The 0% Electric aircraft shows a significant improvement in ESAR compared to the baseline aircraft, due to the aerodynamic, propulsion, and structural technology improvements for the year 2030 aircraft. If a 500 Wh/kg BSE is assumed, the hybrid-electric technology gains very little in terms of overall aircraft efficiency as the level of electrification is increased. The higher efficiency of the electric propulsion is offset by extra power needed because of the energy storage system weight. Addition of hybrid-electric propulsion technology does not break even in terms of ESAR until the electrification level is over 50%. However, for the higher BSE values of 750 and 1000 Wh/kg, higher levels of electrification result in significant improvements in ESAR. The 75% Electric aircraft with 1000 Wh/kg battery specific energy results in a 142.5% improvement in ESAR compared to the Baseline Technology Aircraft.

5.7.2. Additional Sensitivities

As noted previously, high electric energy storage system weight is a significant factor in the overall characteristics of the hybrid-electric aircraft. Designing for a shorter range can mitigate the energy storage weight penalty. Table 8 displays the sensitivity of the 0% Electric aircraft and 75% Electric aircraft to a 50% reduction in design range from 600 NM to 300 NM. A few observations can be made:

- For the 75% Electric aircraft, a 50% reduction in design range results in greater than a 60% reduction in total battery weight, total energy, and total energy cost.
- For the 0% Electric aircraft, a 50% reduction in design range results in less than a 50% reduction in total fuel weight, total energy, and total energy cost.
- Reducing design range 50% reduces takeoff gross weight of the 75% Electric aircraft by 46,500 lb (44%) and takeoff gross weight of the 0% Electric aircraft by only 1400 lb (4%).

When increasing from 0% to 75% Electric with a 500 Wh/kg battery, the following observations can be made:

- For 600 NM, there is a 39% increase in OEW. For 300 NM, there is a 14% increase.
- For 600 NM, there is a 130% increase in gross weight. For 300 NM, there is a 48% increase.
- For 600 NM, there is a 9% increase in total energy cost. For 300 NM, there is a 21% decrease.

Table 8. Design range sensitivity (500 Wh/kg).

Electrification	**Units**	**0%**	**75%**	**0%**	**75%**
Design Range		**300 NM**		**600 NM**	
Operating Empty Weight	lb	21,380	24,190	21,800	30,330
Payload Weight	lb	10,800	10,800	10,800	10,800
Total Fuel Weight	lb	2,300	850	3,360	1,720
Block Fuel Weight	lb	1,220	440	2,220	1,110
Total Battery Weight	lb	0	15,270	0	39,590
Takeoff Gross Weight	lb	34,500	51,110	36,000	82,430
Wing Area	ft^2	480	690	520	1,100
Thrust per Engine	SLS, lb	7,120	10,350	7,300	14,710
Max Electric Power per Engine	kW	0	1,660	0	2,360
Fuel Energy	kWh	6,670	2,420	12,020	6,010
Battery Energy	kWh	0	2,250	0	5,830
Total Energy	kWh	6,670	4,670	12,020	11,840
Electric Energy Cost	$	$0	$254	$0	$659
Fuel Energy Cost	$	$608	$222	$1,100	$551
Total Energy Cost	$	$608	$476	$1,100	$1,210

Figure 35 displays the sensitivity of the energy cost benefits of the 75% Electric aircraft to the projected electricity and fuel costs. The projections for the price of Jet-A fuel and electricity used in the earlier energy cost analysis were $3.33 per gallon for Jet-A fuel and $0.11 per kWh for electricity (ref. 42). However, from 2005 to 2014 the industrial rate for electricity was an average of $0.03 per kWh less than the average electricity price (ref. 44). This would result in a price of $0.08 per kWh as the projected industrial rate for 2030. This lower electricity price results in a 14% decrease in total energy cost for a 600 NM mission as compared to the original 9% increase in total energy cost for the 500 Wh/kg battery scenario. The break-even cost (where the energy cost of the 0% and 75% electric are equal) for the 500, 750, and 1000 Wh/kg cases are displayed in Figure 35 as well as the two price projections mentioned previously. Cost combinations to the right of the lines lead to higher energy costs for the 75% electric compared to the 0% electric vehicle, whereas combinations to the left of the line result in energy cost savings from electrification.

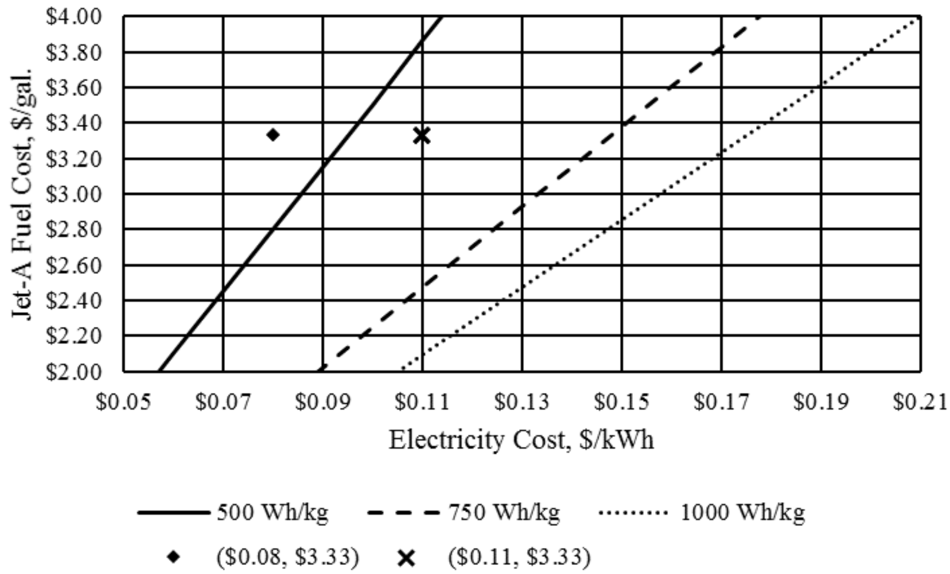

Figure 35. Break-even energy cost for the 75 percent electric advanced turboprop.

5.8. Sizing Conclusions

For a parallel hybrid architecture applied with conventional propulsion-airframe integration to a 48 passenger turboprop class vehicle, the following conclusions can be drawn:

a) At a design range of 600 NM, the BSE must be greater than 500 Wh/kg for the total energy to be less than that of conventional propulsion. The required BSE for energy consumption parity is less than 500 Wh/kg for a 300 NM design range.
b) The energy costs of the parallel hybrid vehicles (assuming $0.11 per kWh electricity and $3.33 per gallon fuel) are less attractive than the conventional advanced turboprop at a design range of 600 NM and a BSE of 500 Wh/kg, due to higher empty weight and higher gross weight. The energy cost of the hybrid vehicles become more favorable as BSE increases, design range decreases, or the ratio of electricity cost to fuel cost decreases.
c) With an electricity cost of $0.11 per kWh, fuel cost of $3.33 per gallon, and the 600 NM design range, the 75% Electric aircraft needs a minimum BSE of approximately 600 Wh/kg to result in energy cost parity with an advanced conventional propulsion vehicle.

It is important to view these results in the proper context. The relative size and energy costs of hybrid-electric vehicles compared to conventional turboprops is very sensitive to the design mission (range and other assumptions such as reserve requirements) and the relative cost of electricity and fuel in the future. (Future fluctuations in fuel costs are especially unpredictable due to the effect of global political instability on the price of oil). The propulsion system architecture and propulsion-airframe integration approach also greatly influence the potential benefits of hybrid-electric aircraft. In the current study no changes were made to the propulsion-airframe integration to take advantage of the additional flexibilities offered by electric propulsion. In addition, the optimum airframe design parameters (such as wing aspect ratio) will change with the different characteristics of the propulsion system. In this initial study, the airframe was not re-optimized for the new propulsion architecture. Finally, the hybrid-electric aircraft has potential benefits not considered in this study, such as the potential for a reduced carbon footprint when the energy storage system is charged from renewable sources.

6. Short-Haul Aircraft Cost Analysis

Although no specific cost requirements were enforced during the design of the advanced short-haul aircraft, both development and operational costs were important factors in the minds of the design team. The projected operating cost of the aircraft was of particular concern, as reducing the operating cost was viewed as a key element of revitalizing the demand for short-haul aircraft. Low operating cost would allow aircraft operators to offer service in O-D markets where demand is low, or to potentially pass some of the savings on to passengers in the form of lower fares. An initial passenger fare target of $0.15 per seat-mile was discussed, implying that the operating cost would have to be less than this value. However, there was no requirement enforced for this cost target during the design because of the lack of tools to design to a specific cost and the lack of time to iterate the design cycle to reach a cost goal. There also was no development cost target during the design. However, the team was cognizant that high development cost would increase the purchase price and make the aircraft unattractive to operators, unless that was balanced by low operating cost. This realization influenced the advanced technology down-select. The cost analysis was done at the end of the design cycle to determine how close the estimated operating cost was to the target and how much the development cost increased due to the advanced technologies selected. Any airport infrastructure costs associated with operation of a hybrid-electric aircraft were beyond the scope of this study and were not considered.

6.1. Short-Haul Aircraft Development and Production Costs

The aircraft development and production (D&P) costs were estimated using the Process-Based Economic Analysis Tool (P-BEAT), an engineering-focused economic analysis code. This tool, developed at NASA Glenn Research Center, uses a process rollup-based methodology to calculate product complexity and its impact on cost (ref. 45). P-BEAT has the following capabilities:

- cost estimates can be generated irrespective of function or performance measures;
- cost estimates can be generated during any phase of the product life cycle;
- capable of estimating hardware, electronics, and software cost estimates; and
- capable of estimating cost at assembly, subassembly, as well as component level.

The Cost Estimation Relationships (CERs) used in P-BEAT are process-based. A large historical database of effort and schedule was used to develop the cost estimating algorithms. Effort was categorized by the Work Breakdown Structure (WBS) category and by the type of process. P-BEAT contains models of 55 different development processes and about 400 different manufacturing processes. Users can identify the type of WBS element and the function (i.e., mechanical, structural, hydraulic, electrical, and software), and P-BEAT will use an appropriate set of CERs to generate a cost estimate.

P-BEAT can also be used to estimate the cost of new technologies. The user must assess the degree of complexity and the processes by which the hardware or software will be designed and built in order to generate an initial estimate of effort. The user must also assess the design maturity and the technology readiness level (TRL) of the new technology at the start of the development effort. These factors are used to scale the initial effort estimate and calculate a final cost estimate for the new technology. The design maturity and TRL metrics used in P-BEAT are somewhat subjective and require a good understanding of both the new technologies and the modeling techniques used in P-BEAT.

For the short-haul aircraft D&P cost estimates, the appropriate WBS processes and vehicle components were identified and modeled using P-BEAT. The design maturity and TRL of any new technologies were also represented in the model. Many of the inputs for the P-BEAT model were provided by FLOPS, the aircraft sizing and synthesis tool. FLOPS outputs help define the WBS levels to be modeled and provide physical and performance characteristics useful in characterizing the P-BEAT inputs. The D&P cost of many of the aircraft components correlates closely with the component weight, which can be obtained from the FLOPS output.

A D&P cost estimate for the ATR 42-500-like baseline was generated using P-BEAT in order to calibrate and validate the model, and to provide a cost comparison for the advanced technology aircraft. Each major aircraft component was analyzed separately and then the values were rolled up to get a total development and production cost, assuming a production run of 403 aircraft (400 production aircraft plus 3 certification aircraft). This production run is similar to the production run of the actual ATR 42 aircraft. P-BEAT input parameters were varied using a Latin hypercube sampling to generate a distribution of cost estimates for each major component. The results are shown in Table 9. These costs are presented in year 2015 dollars. This table contains the aircraft component descriptions, the development costs, and Average Unit Production Costs (AUPC) in terms of likelihood not to exceed values (1%, 50%, and 99%). The total development cost and total AUPC for each component are also shown. These values are calculated by assuming a probability distribution for the cost (a modified beta distribution was used), and then calculating the mean cost value for each component. These mean cost values are calculated using the equation:

$$\mu = \frac{\text{xmin} + \text{xmax} + \lambda\text{xmode}}{(\lambda + 2)}$$

where:

xmin is the minumum cost value (1% cost);
xmax is the maximum cost value (99% cost);
xmode is the most likely cost value (50% cost); and
λ is a parameter that scales the height of the distribution, the default value is 4.

The Development Cost and AUPC for each component are summed to get a total development cost and a total AUPC. For the engine cost, the 1%, 50%, and 99% AUPC values shown in Table 9 are for a single engine. The mean AUPC for the engine is multiplied by two to get the Average Unit Production engine cost for a twin engine aircraft. The estimated total development cost for the baseline aircraft is approximately $1.79 billion dollars. If the total development cost is amortized for a production run of 403 aircraft, the development cost per aircraft is $4.43 million. The total AUPC per aircraft is approximately $18.2 million. Adding the amortized development cost per aircraft and the AUPC per aircraft represents the manufacturer's "break-even" price to recover the D&P costs (this does not include other costs to the manufacturer, such as aircraft certification and marketing costs). The minimum sales price per aircraft would have to be approximately $22.6 million in order for the manufacturer to break even.

Table 9. D&P cost estimate for the baseline aircraft (2015 dollars).

Description	Dev 1% (millions)	Dev 50% (millions)	Dev 99% (millions)	Development (millions)	AUPC 1% (thousands)	AUPC 50% (thousands)	AUPC 99% (thousands)	Avg. Unit Prod (thousands)
AIR CONDITIONING	$17.5	$19.2	$20.8	$19.2	$46	$94	$207	$101
Aircraft Integration	$148.4	$153.6	$158.3	$153.6	$672	$1,564	$3,316	$1,663
ANTI-ICING	$16.4	$17.9	$19.3	$17.9	$22	$43	$90	$46
AUXILIARY POWER	$68.6	$70.2	$71.9	$70.2	$82	$162	$352	$174
AVIONICS	$70.9	$74.4	$78.3	$74.5	$261	$538	$1,056	$566
ELECTRICAL	$128.7	$137.2	$152.5	$138.0	$296	$599	$1,310	$645
ENGINES	$399.2	$487.5	$604.3	$487.5	$773	$1,334	$2,213	$1,371
FUEL SYSTEM-TANKS AND PLUMBING	$52.6	$54.8	$57.3	$54.8	$53	$105	$237	$114
FURNISHINGS AND EQUIPMENT	$200.0	$203.7	$207.6	$203.7	$1,456	$3,179	$7,376	$3,457
FUSELAGE	$233.3	$245.4	$262.7	$246.0	$1,968	$3,010	$4,591	$3,073
HORIZONTAL TAIL	$45.6	$48.5	$51.2	$48.4	$350	$516	$740	$523
HYDRAULICS	$23.7	$25.1	$26.4	$25.1	$55	$115	$255	$124
INSTRUMENTS	$43.9	$46.0	$48.0	$46.0	$33	$66	$138	$71
LANDING GEAR	$38.0	$40.0	$42.1	$40.0	$263	$533	$1,215	$579
SURFACE CONTROLS	$18.0	$20.2	$22.3	$20.2	$53	$105	$228	$113
VERTICAL TAIL	$30.3	$32.1	$34.3	$32.1	$277	$381	$549	$389
WING	$105.0	$109.1	$113.2	$109.1	$2,466	$3,716	$5,753	$3,808
		Total Dev Cost Estimate		$1,786,319,903		AUPC (403 units)		$18,188,133
		Amortized Cost Per Unit		$4,432,556		AUPC + Dev		**$22,620,689**

P-BEAT was also used to create a D&P cost model for the advanced short-haul aircraft. The D&P costs were estimated for the 0% Electric aircraft and the 75% Electric aircraft. Recall that the 0% Electric aircraft is an advanced conventional aircraft with no hybrid-electric propulsion technologies, and the 75% Electric aircraft takes advantage of all the advanced technologies, including hybrid-electric propulsion. A 75% electrification level with a BSE of 750 Wh/kg was chosen based on the previous analysis of aircraft energy costs. For both advanced short-haul aircraft, a production run of 803 aircraft (800 production aircraft plus 3 certification aircraft) was assumed, approximately double the production run of the baseline aircraft. It was surmised that the advanced short-haul aircraft would require at least double the production of the baseline to meet the goal of revitalizing the short-haul aircraft market. It is important to keep the production run differences in mind when comparing the baseline APUC to the advanced aircraft. In addition to the production run assumption, the cost differences between the baseline and advanced short-haul aircraft are mainly due to different component weights and the D&P costs of the new technologies associated with the advanced aircraft. The list of new technologies was described previously in Section 5.5.2.

The largest potential source of error in the D&P cost estimation for the 75% Electric aircraft is the battery cost. The battery weight and specific energy estimates used in the sizing calculations are based on projected advances in technology. However, the actual battery composition and construction for these 2030 batteries is very speculative at this point. There are a number of competing battery technologies that may potentially be selected for this application. Battery composition could have a significant impact on cost. Also, the cost of achieving a BSE target of 750 Wh/kg is difficult to determine. That could have a huge impact on the D&P cost if the technology is not ready in the necessary timeframe. Lithium Ion battery technology was selected as the representative battery technology for the P-BEAT calculations.

The D&P costs for the 0% Electric and the 75% Electric advanced short-haul aircraft are shown in Table 10 and Table 11. As in Table 9, these costs are in constant year 2015 dollars. The 0% Electric aircraft has a total estimated development cost of $1.93 billion. Compared to the baseline aircraft, the development cost increased over $100 million due to the inclusion of advanced technologies. The AUPC for the 0% Electric aircraft is $14.7 million, assuming a production run of 803 aircraft. On a per unit basis, production costs are primarily impacted by the component weights, and the 0% Electric aircraft is smaller and lighter than the baseline aircraft. The result is a break-even price of $17.2 million for the 0% Electric aircraft.

The total estimated development cost for the 75% Electric aircraft is $2.43 billion. The increase in total development cost over the 0% Electric aircraft is due mainly to additional development cost for the engine, electrical system and the battery. The AUPC of $20.4 million is significantly higher than the 0% Electric aircraft, due mainly to the much higher weight of the 75% Electric aircraft. The break-even sales price of the 75% Electric aircraft is $23.4 million per aircraft. This would represent a 3.5% increase in minimum price per unit compared to the baseline aircraft and a 36.7% increase compared to the 0% Electric aircraft.

Table 10. D&P cost estimate for the 0% Electric advanced aircraft (2015 dollars).

Description	Dev 1% (millions)	Dev 50% (millions)	Dev 99% (millions)	Development (millions)	AUPC 1% (thousands)	AUPC 50% (thousands)	AUPC 99% (thousands)	Avg. Unit Prod (thousands)
AIR CONDITIONING	$21.7	$23.6	$25.6	$23.6	$39	$82	$181	$88
Aircraft Integration	$156.8	$168.0	$180.4	$168.1	$519	$1,126	$2,314	$1,193
ANTI-ICING	$15.7	$16.9	$18.2	$16.9	$16	$31	$68	$33
AUXILIARY POWER	$69.1	$70.8	$72.5	$70.8	$66	$129	$291	$140
AVIONICS	$83.7	$87.1	$91.3	$87.2	$230	$457	$978	$490
ELECTRICAL	$158.6	$172.8	$185.9	$172.7	$318	$616	$1,305	$660
ENGINES	$446.8	$551.6	$672.6	$551.6	$880	$1,529	$2,539	$1,571
FUEL SYSTEM-TANKS AND PLUMBING	$66.9	$69.6	$72.2	$69.6	$44	$84	$172	$89
FURNISHINGS AND EQUIPMENT	$200.2	$203.9	$207.7	$203.9	$1,199	$2,739	$6,423	$2,981
FUSELAGE	$218.9	$229.7	$247.7	$230.5	$1,421	$2,167	$3,241	$2,205
HORIZONTAL TAIL	$59.7	$62.1	$64.4	$62.1	$307	$436	$634	$444
HYDRAULICS	$24.3	$25.6	$27.0	$25.6	$41	$78	$169	$84
INSTRUMENTS	$45.0	$47.0	$48.9	$47.0	$27	$54	$110	$57
LANDING GEAR	$38.2	$40.2	$42.3	$40.2	$179	$369	$807	$397
SURFACE CONTROLS	$20.1	$22.3	$24.5	$22.3	$40	$79	$168	$84
VERTICAL TAIL	$30.9	$32.7	$34.8	$32.8	$243	$344	$483	$349
WING	$100.3	$104.7	$109.4	$104.7	$1,498	$2,279	$3,332	$2,311
		Total Dev Cost Estimate		$1,929,592,172		AUPC (803 units)		$14,748,207
		Amortized Cost Per Unit		$2,402,979		AUPC + Dev		**$17,151,186**

Table 11. D&P cost estimate for the 75% Electric advanced aircraft (2015 dollars).

Description	Dev 1% (millions)	Dev 50% (millions)	Dev 99% (millions)	Development (millions)	AUPC 1% (thousands)	AUPC 50% (thousands)	AUPC 99% (thousands)	Avg. Unit Prod (thousands)
AIR CONDITIONING	$21.5	$23.6	$25.7	$23.6	$42	$81	$170	$86
Aircraft Integration	$199.7	$199.7	$199.7	$199.7	$1,340	$1,340	$1,340	$1,340
ANTI-ICING	$15.7	$16.9	$18.2	$16.9	$18	$36	$74	$39
AUXILIARY POWER	$69.2	$70.8	$72.6	$70.8	$63	$132	$286	$141
AVIONICS	$83.8	$87.5	$91.6	$87.6	$232	$469	$998	$502
BATTERY PACK	$113.6	$124.7	$138.0	$124.9	$1,536	$2,305	$4,396	$2,451
ELECTRICAL	$278.3	$298.1	$415.7	$298.1	$343	$658	$1,430	$709
ENGINES	$585.2	$721.7	$883.0	$721.7	$1,219	$2,111	$3,490	$2,169
FUEL SYSTEM-TANKS AND PLUMBING	$67.1	$69.9	$72.5	$69.8	$53	$105	$236	$114
FURNISHINGS AND EQUIPMENT	$203.9	$203.9	$203.9	$203.9	$2,750	$2,750	$2,750	$2,750
FUSELAGE	$229.4	$229.4	$229.4	$229.4	$2,151	$2,151	$2,151	$2,151
HORIZONTAL TAIL	$60.0	$62.2	$64.5	$62.2	$334	$480	$705	$489
HYDRAULICS	$24.3	$25.7	$26.9	$25.6	$42	$82	$180	$88
INSTRUMENTS	$44.8	$47.0	$49.0	$46.9	$28	$54	$113	$57
LANDING GEAR	$38.9	$41.0	$43.0	$41.0	$267	$557	$1,291	$606
SURFACE CONTROLS	$20.4	$22.5	$24.5	$22.5	$57	$109	$239	$118
VERTICAL TAIL	$43.4	$47.5	$52.4	$47.6	$286	$397	$550	$402
WING	$125.2	$133.0	$143.1	$133.2	$2,757	$3,967	$5,816	$4,042
		Total Dev Cost Estimate		$2,425,656,130		AUPC (803 units)		$20,423,668
		Amortized Cost Per Unit		$3,020,742		AUPC + Dev		**$23,444,410**

6.2. Short-Haul Aircraft Operating & Support Costs

The analysis of aircraft energy costs in Section 5.7 focused on one component in the overall aircraft operating and support (O&S) costs. O&S includes other costs to the aircraft operator, such as the cost of labor, maintenance, lease or ownership, training, insurance, etc. Figure 36 shows all the different cost categories included in the baseline aircraft O&S costs. Some of these costs are essentially fixed for a given aircraft utilization, whereas others can be significantly affected by the introduction of new technology. It is important to calculate the O&S costs to establish if the advanced short-haul aircraft provides any financial benefit to the operator compared to the baseline aircraft.

The O&S costs for the baseline ATR 42-500-like aircraft and the advanced short-haul concept aircraft were calculated using a spreadsheet tool developed using the Conklin & de Decker Aviation Cost Evaluator (ref.46) to quickly assess realistic operating and ownership costs for numerous aircraft types. Conklin & de Decker draws on a database of more than 585 jets, turboprops, helicopters, and piston aircraft. Since the Conklin & de Decker cost numbers are geared towards corporate flight operations, adjustments had to be made regarding aircraft utilization, passenger counts, fuel costs, maintenance costs, and crew costs. As shown in Figure 36, the two largest contributors towards the O&S cost of the baseline aircraft are fuel and depreciation (cost of ownership). This cost model assumes the aircraft is purchased instead of leased, and that the period of depreciation is 18 years. However, if the aircraft were leased, then the depreciation costs would be reflected in the lease payment. The next largest contributors towards O&S costs are aircraft parts and engine restoration, followed by labor and crew costs.

The O&S costs for the 0% Electric and the 75% Electric advanced aircraft are shown in Figure 37 and Figure 38. The 0% Electric aircraft and the baseline ATR 42-500-like aircraft have a similar cost breakdown. The main differences are the reduced fuel and depreciation costs for the 0% Electric aircraft. The 75% Electric aircraft has a significantly different cost profile than the other aircraft. First, the depreciation cost is the dominant component of the O&S cost, due to the substantially higher purchase price of the hybrid-electric aircraft. The higher purchase price of the 75% Electric aircraft is driven by increases in both the development and production costs, due to the additional systems and heavier design weight. The 75% Electric aircraft includes a new O&S cost category – electricity cost. Electricity cost is the second largest contributor towards O&S cost, assuming a price of $0.11 per kWh. Parts cost is the third largest contributor, and fuel cost is the fourth largest contributor, assuming a price of $3.33 per gallon. These electricity and fuel prices are consistent with the previous energy cost analysis in Section 5.7.

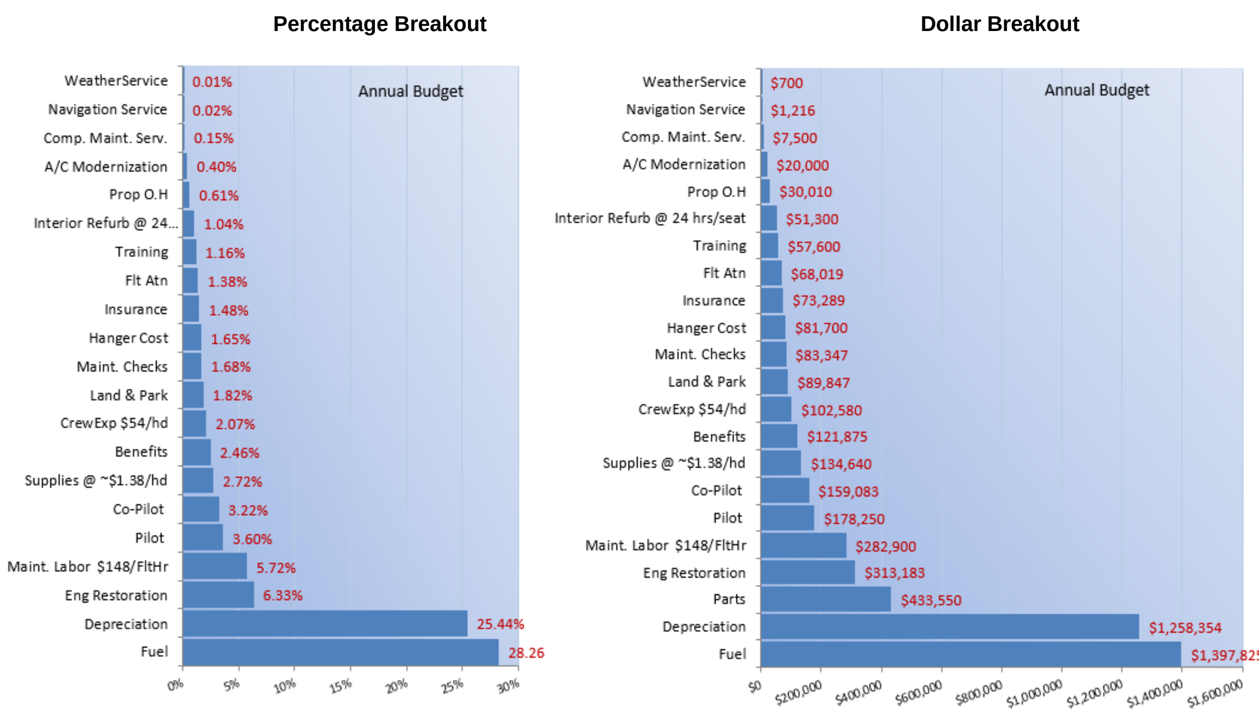

Figure 36. Annual baseline aircraft operating & support cost breakdown.

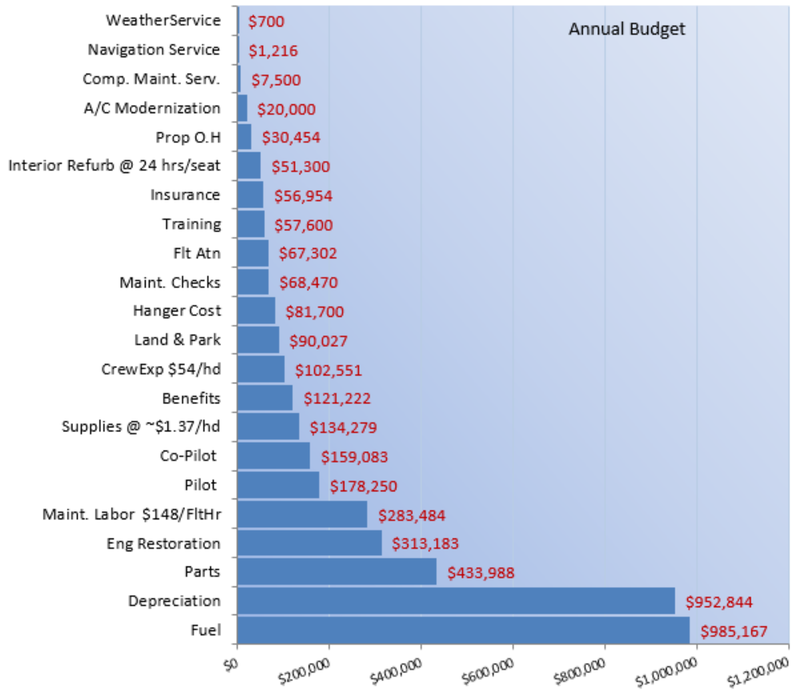

Figure 37. Annual O&S cost breakdown for the 0% Electric Advanced Aircraft.

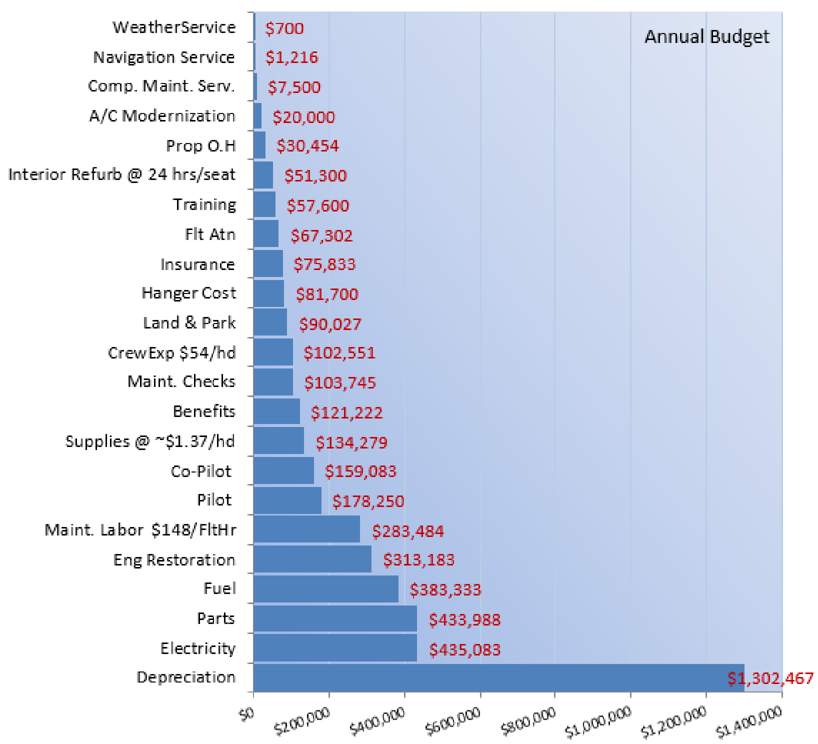

Figure 38. Annual O&S cost breakdown for the 75% Electric Advanced Aircraft (750 kWh/kg).

A comparison of O&S costs between the baseline ATR 42-500-like aircraft and the advanced aircraft versions is shown in Table 12. The calculated O&S cost for the baseline ATR 42-500-like aircraft is $0.179 per ASM. For the 0% Electric aircraft, the O&S cost is estimated to be $0.152 per ASM, a 15% reduction compared to the baseline. The 75% Electric aircraft (750 Wh/kg BSE) has an O&S cost of $0.161 per ASM, which is a 10.1% reduction compared to the baseline. The addition of hybrid-electric technology to the advanced aircraft results a 5.9% increase in O&S cost. The result is attributable, in large part, to higher depreciation costs (driven by higher D&P costs) negating the energy cost savings for the hybrid-electric aircraft. The earlier energy cost analysis suggested that a 75% Electric aircraft with a BSE of 750 Wh/kg would have a significant advantage over the 0% Electric aircraft. However, when the entire O&S cost is calculated, all of the energy cost advantage for the 75% Electric aircraft disappears. On a positive note, the 0% Electric aircraft nearly meets the target operating cost of less than $0.15 per ASM that was discussed during the requirements phase.

Table 12. Comparison of O&S costs between the baseline and advanced aircraft

	Baseline	Advanced Aircraft	
		0% Electric	75% Electric (750 Wh/kg)
O&S Cost ($/ASM)	$0.179	$0.152	$0.161
Total Annual O&S Cost	$4,947,000	$4,197,000	$4,434,000

6.3. Short-Haul Costs Conclusion

The development costs of the 0% Electric and the 75% Electric advanced aircraft both increased compared to the baseline aircraft due to the addition of the new technologies. For the 75% Electric aircraft, the new hybrid-electric propulsion system significantly increased the development costs over the other aircraft. The production cost per unit of the 0% Electric and 75% Electric aircraft each benefited by increasing the number of units produced compared to the baseline aircraft. The 0% Electric aircraft also benefited from lower empty weight than the baseline. The empty weight of the 75% Electric aircraft was much higher than the other aircraft, resulting in higher production costs per unit. The break-even sales price of the 0% Electric decreased by 24.2% compared to the baseline, while the 75% Electric break-even sales price increased by 3.6%.

The addition of new aerodynamic, propulsion, and structural technologies had a positive effect on O&S costs. A 15% reduction compared to the baseline aircraft was realized by the 0% Electric advanced aircraft. The addition of hybrid-electric technology on the 75% Electric aircraft actually increased the O&S cost an additional 5.9% above the 0% Electric cost. The sum of the fuel and electricity cost for 75% Electric aircraft was less than the fuel cost of the 0% Electric, but this savings was offset by increases in depreciation cost due to the higher development and production costs of the 75% Electric aircraft.

There are a number of sources of uncertainty in the cost analysis. The O&S cost is very sensitive to the assumptions about fuel and energy cost. The largest source of uncertainty for the cost analysis is the development of the hybrid electric system, especially the battery development cost. This uncertainty affects not only the D&P costs, but it also affects the O&S costs because of the depreciation associated with the purchase price. Battery technologies must mature significantly before this uncertainty can be reduced.

This O&S cost analysis does not seem to support incurring the risk of developing hybrid-electric propulsion, at least not for a 600 NM mission. However, application of hybrid-electric propulsion to shorter design ranges may make sense in terms of operating cost, as suggested in the mission performance analysis. Also, different assumptions about the relative cost of fuel and electricity may make the advanced hybrid-electric aircraft more or less attractive. As previously noted, there is a great deal of uncertainty regarding the D&P costs. If the D&P cost analysis is too conservative for the 75% Electric aircraft, then the O&S cost is also negatively affected. The key will be for the energy cost benefits to outweigh the technology development cost impacts on overall O&S cost.

7. Short-Haul Market Analysis

A market analysis was conducted to determine the impact of an advanced aircraft on the short-haul segment. This analysis used a quantitative transportation systems modeling approach to calculate the potential passenger demand for the aircraft, and qualitative approach for evaluating how the aircraft might fit into existing O-D markets. The analysis was conducted in parallel with the aircraft design cycle; therefore, the exact speed profile and operating cost estimates for the advanced short-haul aircraft were not used. Instead, these values were estimated based on target values.

7.1. TSAM Analysis of Short-Haul Operations

TSAM was used to model the potential passenger demand for the 48 passenger Short-Haul Advanced Aircraft. This effort was similar to the seat capacity selection analysis performed during the requirements phase of the study. However, this TSAM modeling effort addressed some of the shortcomings of that quick-look analysis. Most importantly, the short-haul O-D markets were modeled as part of the commercial air network instead of a separate transportation mode.

7.1.1. Scope and Framework

In order to study the potential application of a short-haul transportation vehicle the following steps were used in TSAM. These steps are illustrated in Figure 39 and described below:

Step 1: Determine the cost per seat-mile for the short-haul aircraft. Based on this cost, determine a relationship between the passenger airfare and the distance traveled. This airfare is used by the TSAM mode choice module when assigning a travel mode to each trip.

Step 2: Conduct a series of exploratory TSAM run(s). This involves making runs using a large airport set in TSAM to quantify if new O-D markets could exist beyond the commercial airport set in TSAM (~450 airports).

Step 3: Identify candidate O-D pairs produced in Step 2. This step identifies an expanded network of airports (outcome of Step 2) whose low volume of traffic preclude them from having commercial service but that are candidates for short-haul applications.

Step 4: Consolidate the short-haul network and the commercial airline network. This is done so that the TSAM mode choice module integrates the expanded airport set and traveler's choices consider the added connectivity of an expanded set of airports in the network. This assumes the short-haul network will feed the regular commercial service network in place.

Step 5: Run TSAM with the expanded network of airports. Confirm that all the input airports have sufficient passenger demand in the TSAM output.

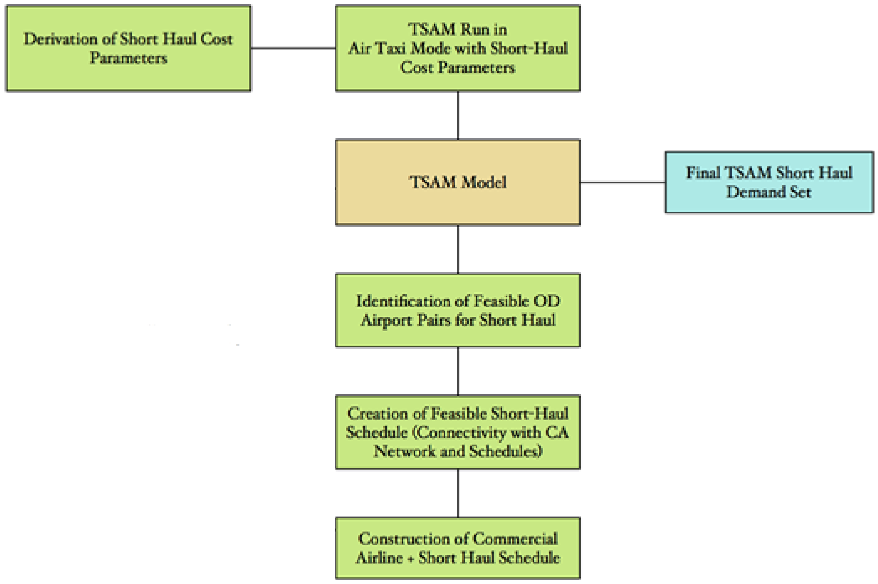

Figure 39. Flowchart of TSAM procedure to evaluate a short-haul concept.

7.1.2. Market Study Approaches using TSAM

Two separate approaches were adopted to identify airports and routes in the new O-D markets created by the advanced short-haul aircraft. Both approaches use the same basic analysis steps outlined above. The main differences in the approaches are in the short-haul airport set assumptions and consolidation of the short-haul and commercial airport sets, steps 3-5. In the first approach, all public access airports with a runway of at least 4000 ft were included in the analysis and TSAM was used to identify the airports and O-D markets that have the largest demand for an advanced short-haul aircraft. In the second approach, the short-haul network was restricted to smaller airports *without* current commercial service connecting to larger hubs. This method forces TSAM to only consider new O-D markets in areas where there is no current service to see if passenger demand exists in those markets.

7.1.2.1. Unrestricted Markets Approach:

The main advantage of this method is that it allows for point-to-point short-haul service between smaller airports if passenger demand supports it. This method of estimating the demand for the advanced short-haul aircraft has similarities to the method used to determine the optimum seat capacity for the aircraft. TSAM trip demand is calculated for the air taxi mode (a surrogate for the advanced short-haul aircraft fleet) while considering all public access airports with a runway of at least 4000 ft. This demand is then trimmed to only include feasible O-D pairs that could support a minimum number of daily flights. The airports and O-D markets identified in this process are then added to the commercial aircraft network. The TSAM mode choice is run again for the new commercial airline network and schedule, with only automobile and commercial air competing for trips (no air taxi mode). It is important to understand that the TSAM air taxi assumptions do not all apply to short-haul transport aircraft. However, these runs provide useful information on potential O-D markets that need to be further studied.

The assumptions about the flights rules used in the TSAM model to calculate integrated short-haul demand are shown in Table 13. The table shows the number of passengers (minimum and maximum) as a function of flights added to each additional short-haul airport. In order to integrate short-haul services it was necessary to create and assign departure times for the flights added to the commercial network and re-build the complete commercial airline flight schedules.

Table 13. Flight generation rules used in the TSAM analysis to model short-haul operations.

Define the demand breaks and number of daily flights								
Number of Seats	48							
Minimum Load Factor	0.5							
Maximum Load Factor	0.85							
Minimum Weekly Flights	5							
Number Of Weeks	52							
Minimum Daily Flights	2	3	4	5	6	7	8	9
Minimum Passengers	12,480	18,720	24,960	31,200	37,440	43,680	49,920	56,160
Maximum Passengers	21,216	31,824	42,432	53,040	63,648	74,256	84,864	95,472

The TSAM mode choice utility function can be based on two different logistic regression models, the C-Logit and Box-Cox Logit. The Box-Cox Logit is a newer method than the C-Logit and has been viewed as superior in certain applications (ref. 47). The TSAM air taxi mode requires the C-Logit calibration; however, if the air taxi mode is not used, either regression model can be used. To understand the changes produced in mode choice after short-haul services are introduced, TSAM was executed using both models.

A number of different scenarios were run using the Unrestricted Markets approach. All the scenarios used socio-economic conditions expected to be present in 2030. Two baseline cases were run using the usual travel modes (auto, commercial air, and train), one baseline using the C-Logit model and the other baseline using the Box-Cox model. As mentioned previously, an exploratory run was performed using the air taxi mode as a surrogate for the advanced short-haul aircraft. The feasible O-D pairs were identified from the results of this run, and then an additional run was done using the air taxi mode with the trimmed airport set. For the final runs, the trimmed airport set was incorporated into the commercial network and schedule (i.e., new airports were added to the commercial network), and TSAM was run using both the C-Logit and Box-Cox regression models for the mode choice. The TSAM run scenarios are listed in Table 14 with the number of round trips generated in the commercial air network for each scenario. In addition, three air fare cost levels associated with the short-haul service were examined – the baseline fare, a 7.5% reduction from the baseline, and a 15% reduction from the baseline.

Table 14. Year 2030 Unrestricted Markets scenarios developed in TSAM to model short-haul services.

Case	Mode Choice Type	New Short-Haul Airports	Short-Haul (as Air Taxi) Person Round Trips (Millions)	Commercial Air Person Round Trips (Millions)
Baseline Fleet	C-Logit	0	0	294.3
Baseline Fleet	Box-Cox	0	0	270.9
Short-Haul Initial Set	C-Logit	1253	85.3	250.5
Short-Haul Trimmed Set	C-Logit	346	78.6	251.5
Short-Haul combined with Commercial Air Network	C-Logit	166	0	313.2
Short-Haul combined with Commercial Air Network	Box-Cox	166	0	279.8

Modeling short-haul services as a surrogate air taxi mode (using the C-Logit model) produced potential demand for short-haul services in excess of 85 million person-trips per year. Demand for short-haul services came at the expense of automobile and commercial air modes. Demand for short-haul dropped to 78.6 million person-trips after trimming the short-haul airport set from an initial value of 1,253 to 346 short-haul airports. Based on extensive experience with TSAM and numerous other transportation system studies, the TSAM modeling team felt that the number of short-haul person-trips predicted was higher than expected and possibly not realistic.

The trimmed short-haul airport set was then incorporated into the commercial airline model, which allows the short-haul network to code-share with all of the airlines that make up the commercial network schedule. TSAM has an airfare model based on flight distance that was used as a baseline for the new short-haul O-D pairs. The total number of commercial airline trips increased by almost 19 million trips, compared to the C-Logit baseline case. The Box-Cox regression model was run for the same scenario. The Box-Cox results are presented in Table 14. The results indicate that an additional 8.9 million person-trips would be generated, when compared to the Box-Cox baseline case. For both regression models, an additional 166 airports were added to the commercial airline network for short-haul services. The sensitivity of the TSAM model with respect to air fare was almost negligible, as seen in Figure 40. This figure shows the baseline 2030 commercial fleet with no advanced short-haul aircraft compared to the fleet with an advanced short-haul with air fare reductions of 0%, 7.5%, and 15%. Reducing the air fare by 15% for the short-services produced a meager 0.5 million additional person-trips in the year 2030.

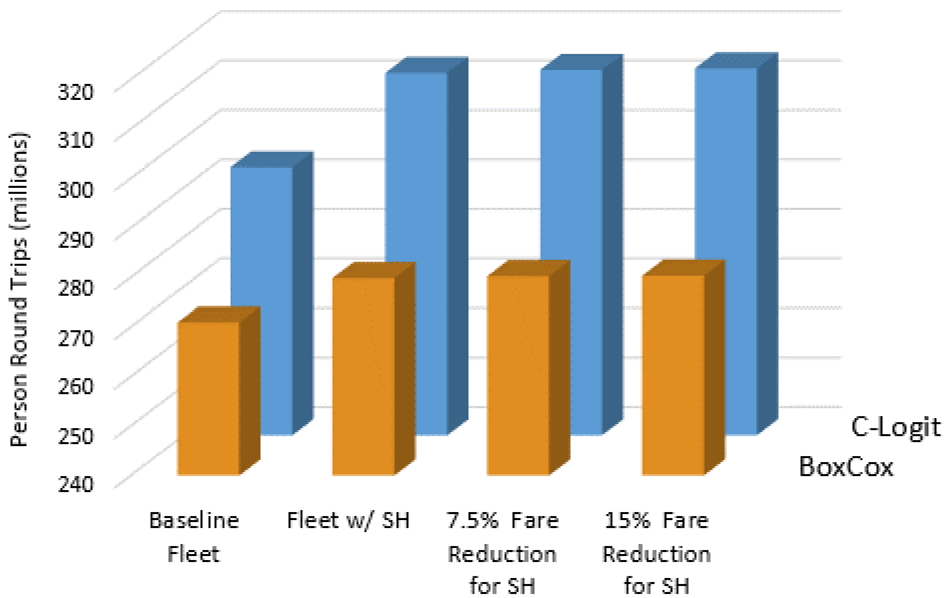

Figure 40. Effect of airfare for short-haul aircraft for different scenarios in 2030

7.1.2.2. Restricted Markets Approach:

The Restricted Markets approach uses a different strategy to identify airports where short-haul service could be made available. The underlying assumption is that demand exists at many small airports with no connection to a hub airport and introduction of a new low cost short-haul aircraft could capture this demand. Forcing TSAM to only consider these smaller underutilized airports is another way to gauge the feasibility and mobility advantages of an advanced short-haul aircraft. The TSAM airport-to-airport distance tables were used to identify a set of airports that currently have no scheduled air service and are located 50 statute miles or more from an airport with scheduled service. Demand for air travel was assessed with the TSAM air taxi model. The air taxi analysis resulted in 137 airports as candidates for short-haul type service. These 137 airports were added to the TSAM commercial airport network with flights to the closest Operation Evolution Partnership (OEP) airport and the demand calculated. OEP airports are large hub airports that serve major metropolitan areas. This method does not support point-to-point connections between these 137 airports. The baseline runs with the model included the normal 395 commercial airports in TSAM. The expanded airport set included all 532 commercial airports (including the 137 additional short-haul airports).

The results are presented in Table 15. The C-Logit runs produced an increase of about one percent in commercial airline trips with the addition of the new airports with short-haul service. The baseline C-Logit run produced 264.7 million round trips for the combined short-haul and commercial airline network. The C-Logit run with the additional 137 user defined airports produced 266.4 million trips. For the Box-Cox runs, a small decrease in commercial airline trips was seen when comparing the baseline to the expanded commercial network case. Although it seems counter-intuitive that adding airports to the system would cause a drop in trips, the resulting changes in the commercial air network, combined with the way TSAM selects routes and origin airports, did result in a very small drop in commercial air trips. This may be an artifact of the mode choice calculations rather than a real effect. This solution was repeated with changes to the air fare structure to reflect "cheaper" short-haul operations nationwide. The model produced similar results for both air fare reductions of 7.5% and 15% for the short-haul O-D markets.

Overall, short-haul operations from the added airports did not produce significant numbers of passengers. The average number of person trips produced at the additional 137 airports was 5,621 annually. This volume of traffic is not sufficient to support realistic airline operations. A histogram of the distribution of annual demand predicted by TSAM at the 137 new commercial airports is shown in Figure 41. The results were surprising but could be explained further if one considers that the 137 airport set was selected to be outside of the catchment area of larger commercial airports. This was done to test the hypothesis that passenger demand exists at these airports without commercial service, if only airlines had a low cost aircraft to operate in these O-D markets. The results produced by the model could be an indication on why airlines do not offer more short-haul services at airports in the United States.

Table 15. Year 2030 Restricted Markets scenarios developed in TSAM to model short-haul services.

Case	Mode Choice Type	New Short-Haul Airports	Commercial Air Person Round Trips (Millions)
Baseline Fleet	C-Logit	0	264.7
Baseline Fleet	Box-Cox	0	270.9
Short-Haul combined with Commercial Fleet	C-Logit	137	266.4
Combined Fleet w/ 7.5% Operating Cost Reduction for Short-Haul	C-Logit	137	266.6
Combined Fleet w/ 15% Operating Cost Reduction for Short-Haul	C-Logit	137	266.8
Short-Haul combined with Commercial Fleet	Box-Cox	137	270.2
Combined Fleet w/ 7.5% Operating Cost Reduction for Short-Haul	Box-Cox	137	270.4
Combined Fleet w/ 15% Operating Cost Reduction for Short-Haul	Box-Cox	137	270.4

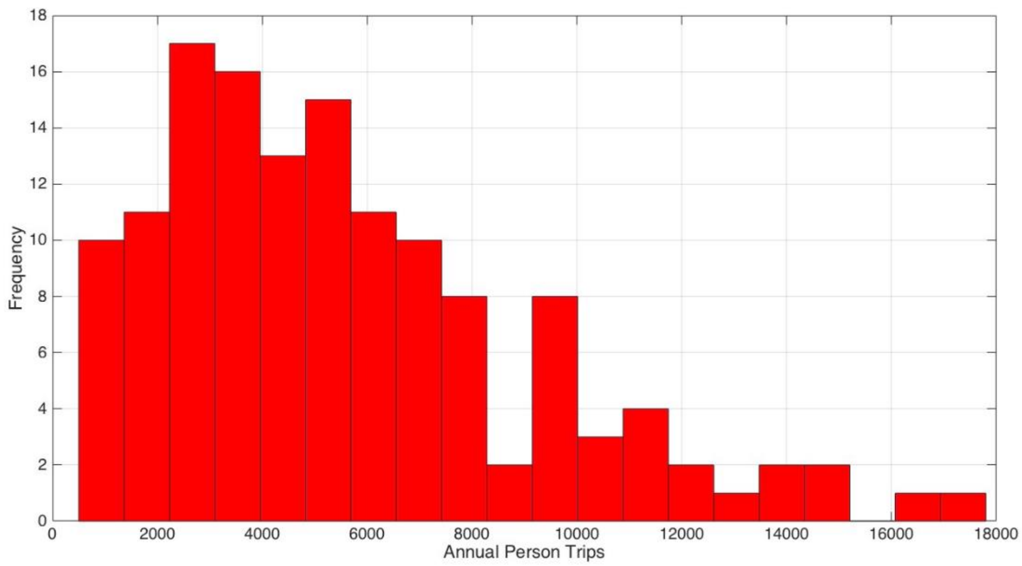

Figure 41. Histogram of annual person trips for the 137 new commercial airports set.

7.1.3. Essential Air Service Airports

Of the 117 EAS airports in the continental U.S. in 2011, only 6 had in excess of 25,000 yearly enplanements, which is roughly the needed demand in an unsubsidized O-D market for 2 flights a day by a 48 seat aircraft with a load factor of 0.75. EAS airports on the whole have very small demand with an average of 10,386 enplanements in 2011 for the 117 airports and are often serviced by 9 and 19 passenger aircraft. Without a subsidy from Congress, these operations will be highly unprofitable to most airlines with the current U.S. fleet of regional aircraft. During times of economic recession, cities have paid airlines to continue service into their airports (ref. 48). The EAS airports are politically sensitive due to relatively high subsidies per enplanements and would benefit greatly from lower cost, more efficient aircraft.

TSAM projects demand to grow to 25,000 enplanements or more at 73 of the EAS airports. Sixty-seven of these airports currently have less than the 25,000 passenger threshold. Although demand is growing, these 67 airports are part of an endangered market since they are still too small to support the larger seat aircraft replacing small RJ's and turboprops and are, thus, ideal candidates for a 48 seat short-haul aircraft. However, the FAA's Terminal Area Forecast (TAF) projects that only 16 EAS airports will have that much demand (ref. 49). TSAM projects much greater demand than the TAF at almost all the EAS airports. There are a number of possible explanations for this difference in forecasted demand. EAS airports are known to suffer extremely large passenger leakage due to high fares and limited or poor service. The TAF projections appear to assume that this leakage will continue. Cheaper, more efficient air service could move the demand numbers in the direction of the TSAM demand, which indicates an additional 67 EAS airports could support short-haul 48 seat turboprop service.

7.1.4. Non-hub Airports (excluding EAS airports)

Only about a dozen non-hub airports had less than 25,000 enplanements in 2013 and about half had over 100,000 enplanements (ref.50). On the whole, these airports could potentially support many short-haul 48 seat turboprop aircraft because much of the service to non-hub airports is currently regional jet and turboprop. Several reports that analyze traffic changes indicate that non-hub traffic has suffered little loss since peak traffic in 2007. While this is true for the sum all non-hub airports, the results at individual airports vary significantly. In fact, one fourth of non-hub airports have lost 20% or more in enplanements for 2007 to 2013. It can be speculated that much of these losses are due to the on-going phase out of small regional jet and turboprop aircraft. Often small regional jets are being replaced with larger regional jets and many small O-D markets have insufficient demand to support that change.

Both regional jets and turboprops in the size class of the 48 seat short-haul turboprop are still very active in the U.S. fleet. Regional jets with 50 seats or less (Canadair RJ 200 to 440 and Embraer 135 to 145) reported 1,672,278 departures in 2014 (last full year of data in TranStats). Similar size, out of production, turboprops (De Havilland DHC 100 to 300, Embraer 120, Saab Fairchild 340, and ATR 42) reported 317,774 departures in 2014. Together, these aircraft averaged over 5,400 flights per day in 2014 (ref. 50).

The Regional Airline Association reports roughly 1000 aircraft of the types mentioned above in the 2015 fleet of its members (ref. 51). The breakdown of the 1000 aircraft is just under 800 small regional jets and just over 200 turboprops with seating for 28 to 50 passengers. These aircraft make up approximately 42% of the regional airline fleet. Their phase-out or replacement will probably adversely affect service to a large number of smaller airports since these aircraft are being replaced by larger aircraft with much greater seating capacity. Assuming an advanced turboprop overcomes the lack of acceptability issue, there is the potential for a large operator demand to replace these aircraft, all of which are no longer in production.

Furthermore, TSAM projects the 2030 demand at non-hub airports to be more than two and one-half times the 2013 historical data. So, in addition to up-gauging on these routes, the potential operator demand for new short-haul aircraft will be much greater than just replacing the current inefficient and out-of-production aircraft.

7.1.5. High Entry Cost to Operate from Short-Haul Airports

The results presented in Section 7.1 require further inspection and justification of the new airports added to each scenario. Airlines are reluctant to offer commercial service from small airports without a minimum threshold of passenger demand. For small short-haul candidate airports, as the number of flight operations decreases, it becomes impossible to maintain the aviation infrastructure, security, parking, precision runways, maintenance hangars, staff, and aircraft operations and maintenance facilities required to keep the airport functioning. For the hybrid-electric aircraft proposed in this study, there would potentially be additional airport infrastructure requirements. It was observed that some of the airports selected by the model in the exploratory step would be located within 20 miles or less of existing large and medium size commercial airports. Although some of these airports could in fact be promising alternatives for passenger travel, airlines may be reluctant to relocate services to a small airport when they already operate at a larger airport nearby with a higher number of frequencies and better infrastructure. The airline cost to offer short-haul commercial services from airports located within the normal catchment perimeter of an existing commercial airport is high and presents an obstacle that either new start-up airlines or established carriers will have to assess. The startup cost of providing commercial services at short-haul airports was not considered in the TSAM analysis.

7.2. Market Analysis Summary and Recommendations

Two approaches using the TSAM model to study short-haul operations were presented. The first approach allowed TSAM to identify the highest demand O-D markets for short-haul service at all public access airports with a runway of at least 4000 ft. This approach provided additional trip demand in the system (ranging from 8.9 to 19.1 million person trips per year, depending on the regression model used). Most of the new commercial demand came from airports located in close proximity to medium or large hub airports. The process requires further scrutiny to understand if operating services from new airports proximal to hubs could be cost effective for airlines. An analysis of this type requires an in-depth understanding of the startup costs to be paid either by the airline or, in some cases, subsidized by the community.

The second approach restricted the new short-haul O-D pairs between hub airports and airports that currently have no scheduled air service, are located 50 statute miles or more from an airport with scheduled service, and have a runway of at least 4000 ft. The initial set was reduced to 137 airports with the highest demand. The results indicated that TSAM predicts little or no change in net passenger demand for airports selected farther away from the catchment areas of larger commercial airports. There would, however, be a benefit for passengers accessing nearby airports previously not connected to the commercial network. The results produced by the model seem to validate today's airline strategy of not offering short-haul services at small airports proximal to larger commercial airports.

TSAM demand projections indicate the EAS airports could be potential origin or destination markets for the short-haul aircraft. Sixty-seven EAS airports with less than 25,000 annual enplanements in 2011 are projected by TSAM to exceed that threshold in 2030. Most of these airports are currently served by smaller capacity aircraft, and airlines may be motivated to up-gauge to an efficient 48 seat aircraft. However, it should be cautioned that the FAA TAF forecast for these airports is much lower than the TSAM projection.

Potentially the biggest need for new short-haul aircraft is in the replacement of aircraft that principally serve non-hub airports. The details of how this aircraft replacement market develops are beyond TSAM capabilities because as the future passenger demand grows there will be both up-gauging as well as replacements with a similar number of seats. However, the passenger demand at non-hub airports is projected by TSAM to grow by a factor of over 2.5 times the 2013 enplanements, so there is significant opportunity for new short-haul aircraft to fill this demand.

8. Study Summary

A feasibility study was performed for an advanced short-haul aircraft concept with the goals of revitalizing the operator demand for commercial aircraft that operate out of regional and community airports and increasing short-haul transport safety, affordability, environmental compatibility, and customer acceptance. A survey was conducted of current short-haul aircraft and their operations in the U.S. and worldwide. This survey helped guide the design team in selecting the aircraft requirements. The TSAM tool was used in an analysis of potential O-D markets and trip distances that suggested a seat capacity selection of 48 passengers. A 600 NM design range was selected based on a sensitivity study of the passenger demand metrics.

A technology down-select was performed by the design team, and hybrid-electric propulsion was identified as the primary enabling technology for the advanced aircraft. A parallel hybrid-electric propulsion architecture was selected, which features two turboprop engines with electric motors supplying supplemental power to the shafts and batteries to supply power to the electric motors. A sizing methodology was developed for the advanced hybrid-electric aircraft, combining FLOPS sizing and external calculations for battery and propulsion weight in a modeling framework. A mission and sizing analysis was performed, comparing variants of the advanced aircraft with different levels of electrification, ranging from 0% Electric (no hybrid-electric technologies) to 75% Electric. Different battery specific energies were examined, as well as different design ranges for the aircraft.

The sizing study revealed that as the level of electrification increases, total energy used by the system is approximately constant for a BSE of 500 Wh/kg. However, for 750 and 1000 Wh/kg, the total energy decreases significantly. This decrease in total energy occurs because of the higher efficiency (93%) of the electric propulsion even though the weight of the aircraft is increasing. The energy cost of the 75% Electric aircraft is greater than the conventional advanced turboprop at a design range of 600 NM and a BSE of 500 Wh/kg, assuming an electricity cost of $0.11 per kWh and fuel cost of $3.33 per gallon. This aircraft needs a BSE of at least approximately 600 Wh/kg to result in energy cost parity with the advanced turboprop aircraft.

The D&P and O&S costs were estimated for the baseline aircraft, a 0% Electric advanced aircraft, and a 75% Electric advanced aircraft (with 750 Wh/kg BSE). The development cost of both the 0% Electric aircraft and 75% Electric aircraft increased compared to the baseline due to the new technology on those aircraft. Development cost of the 75% Electric aircraft increased substantially due to the hybrid-electric system. The average production cost per unit decreased for the 0% Electric aircraft and increased for the 75% Electric aircraft compared to the baseline. This trend was also seen in the break-even sales price for the aircraft, which was $22.6M for the baseline, $17.2M for the 0% Electric aircraft, and $23.4M for the 75% Electric aircraft. These D&P costs influenced the O&S cost, since the sales price affects the cost of ownership. The 0% Electric aircraft O&S cost was 15% lower than the baseline aircraft. The 75% Electric aircraft O&S cost was 10.1% lower than the baseline aircraft, but 5.9% higher than the 0% Electric aircraft. For the 75% Electric aircraft, the ownership costs (driven by the much higher D&P costs) offset all of the energy cost benefits of adding the hybrid-electric technology to the advanced aircraft.

In general, the economics of the hybrid vehicles become more favorable as BSE increases, design range decreases, or the ratio of electricity cost to fuel cost decreases. New or updated information for the cost analysis may change the outcome, especially additional data on the hybrid-electric system and battery technology. Different assumptions about the relative cost of fuel and electricity may also make the advanced hybrid-electric aircraft more or less attractive. A shorter design range may make more sense in terms of operating cost, as suggested in the mission performance analysis. The key will be for the energy cost benefits to outweigh the technology development cost impact on overall O&S cost.

Passenger demand for the advanced short-haul aircraft was modeled in TSAM using two different approaches: 1) allow TSAM to determine the highest demand short-haul O-D markets; 2) restrict the new short-haul O-D markets to routes between hub airports and airports with no current commercial service. The first approach resulted in a healthy increase in passenger demand (8.9 million person trips per year), but much of the demand came from smaller airports in close proximity to large hub airports. Although this scenario does increase mobility and passenger choice, it is not the scenario envisioned at the beginning of the study. In general, O-D markets did not open up in smaller regional and community airports, and service was not reestablished at closed airports. The second modeling approach focused on providing service at targeted airports to see if sufficient demand exists to support air service. There was no increase in overall passenger demand according to the TSAM analysis. A very small percentage of the demand was shifted to the 137 airports included in the analysis, but it was not enough to significantly impact the network. Some passengers would obviously benefit from access to nearby airports and shortened travel times, but there would be no incentive for airlines to invest in this strategy. The results were essentially the same even when air fares were lowered by 15% to simulate the potential benefits of lower operating costs. One area that was not addressed by this study is the cost incurred by the operator when opening new O-D markets and/or establishing service at new airports. This information would be key to understanding the potential of a new aircraft to increase mobility.

Research of the current commercial fleet and fleet operations indicates there would likely be operator demand for an advanced 48 passenger short-haul aircraft, even if the operational paradigm does not match the one originally envisioned by this study. There would be opportunities to operate in markets associated with EAS airports and non-hub airports as well as to serve as a replacement for retiring regional jet aircraft.

Although the advanced short-haul aircraft concept utilizing hybrid-electric technology did not fully meet a number of the original study goals, it is worthy of further study. A more comprehensive cost analysis of the 75% Electric aircraft compared to the 0% Electric aircraft is suggested to determine if the increased D&P costs really do offset the gains in energy cost and result in higher O&S cost. In addition, there are other operational scenarios for a short-haul mission that may better exploit the advantages of hybrid-electric propulsion. The next step would be to revisit the requirements to see if relaxing one or more (e.g., design range) makes sense. Changing the type of hybrid-electric implementation on the aircraft could yield greater benefits in terms of energy costs. Limiting the requirements on the batteries and better information about their development costs could bring down the estimated aircraft price and benefit the O&S cost. If a hybrid-electric aircraft can achieve a substantial O&S cost reduction, then the challenge will be to project how that aircraft might be operated in the air transportation system in a manner that would improve availability of service and passenger choice.

Appendix A

Evolution of Turboprop Aircraft Operations Worldwide

Although turboprops operate side-by-side with regional jets and larger narrow body commercial aircraft in many O-D markets, it is instructive to study markets served exclusively with turboprop aircraft. These markets can be used as indicators of the unique capabilities of turboprop aircraft. The analysis presented in this appendix divides the turboprop segment into three categories based on different seating capacities: a) small turboprop aircraft with less than 20 seats, b) medium capacity turboprops with 20-45 seats, and c) large turboprops with more than 45 seats. The analysis uses the OAG database for the third week of July of each year. This analysis focuses on markets that are served exclusively by one turboprop size category. For example, if a given O-D market is served by both small and medium capacity turboprops, it is not included in the analysis. Figure A - shows the number of distinct O-D markets served exclusively with turboprop aircraft for 2004 to 2014. The figure shows that between 2004 and 2014, the number of O-D markets served only by small turboprops with fewer than 20 seats decreased 9.2%. Similarly, the number of weekly frequencies of operation using small turboprop aircraft decreased 43% worldwide in O-D markets served exclusively by such aircraft (see Figure A -). Another observation is that the number of weekly frequencies using turboprops in the medium size category (20-45 seats) decreased 63% between 2004 and 2014. The medium turboprop aircraft category includes aircraft that are out of production such as the Saab 340, Embraer 120, Jetstream 32/31 and the Dornier 328. The only group to record a positive growth in O-D markets served exclusively by turboprops in that class was the larger turboprop group with more than 45 seats. The number of O-D markets served exclusively by these aircraft increased 90% in the decade 2004-2014. Following this trend, the number of weekly frequencies offered in these markets increased by 102% between 2004 and 2014 (see Figure A -).

Figure A - shows the number of weekly seats offered worldwide for the three turboprop aircraft categories. The figure shows a dramatic increase (111%) in the number of weekly seats in the large turboprop category between 2004 and 2014. In the same graph we observe a drastic reduction (63%) in the number of seats offered by airlines using medium size turboprop aircraft. This trend is persistent in that aircraft category as many aircraft in that group reach their retirement age and no alternatives exist to replace them.

Figure A - shows the average number of seats per flight in O-D markets served exclusively by turboprop aircraft worldwide. There is an important trend observed in the data: the small turboprop aircraft are downsizing with the introduction of 10-seat passenger Cessna Caravans in markets worldwide. The average seating capacity in the small turboprop market decreased from 17.5 seats in 2004 to 14.6 in 2014. The large turboprop segment (i.e., > 45 seats) has gained 7 seats per flight in a decade. That is significant and is a consequence of the large number of Bombardier Q400 and Aerospatiale/Alenia ATR 72 aircraft introduced into service in the past decade. The medium size turboprop segment has remained unchanged in average seating capacity because there has been no substitution of the aging aircraft in that segment over the past decade.

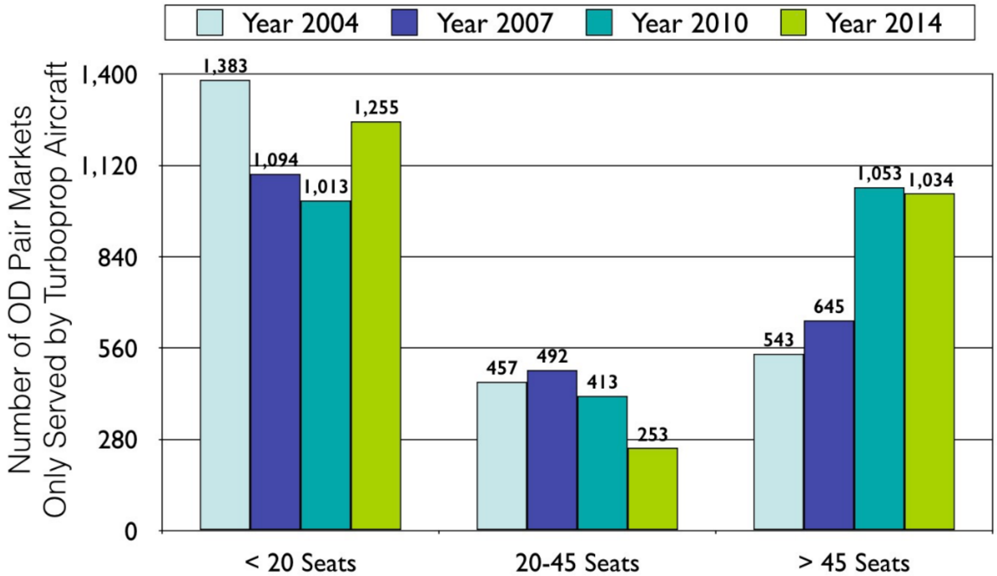

Figure A - 1. Number of origin-destination markets worldwide served exclusively by turboprop aircraft.

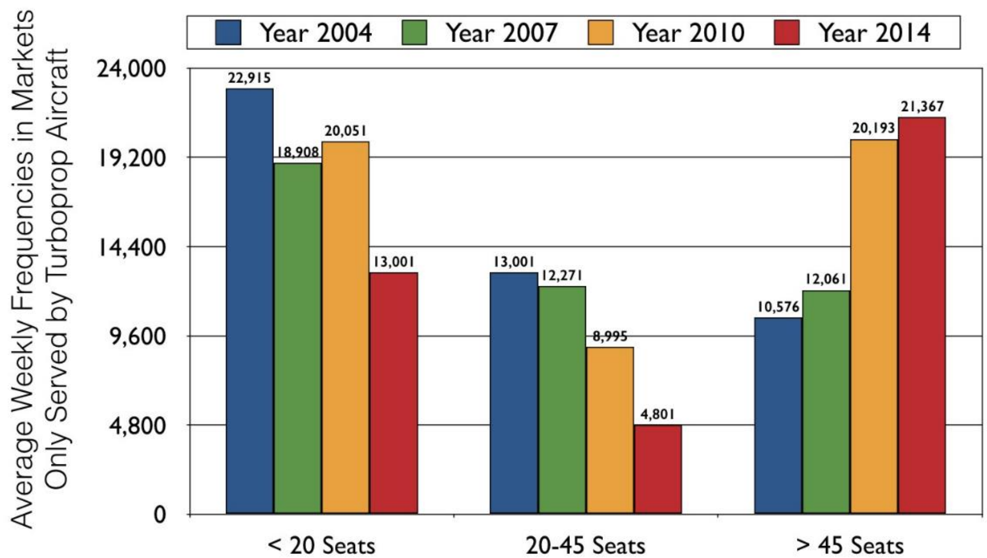

Figure A - 2. Number of weekly frequencies in worldwide O-D markets served exclusively by turboprop aircraft.

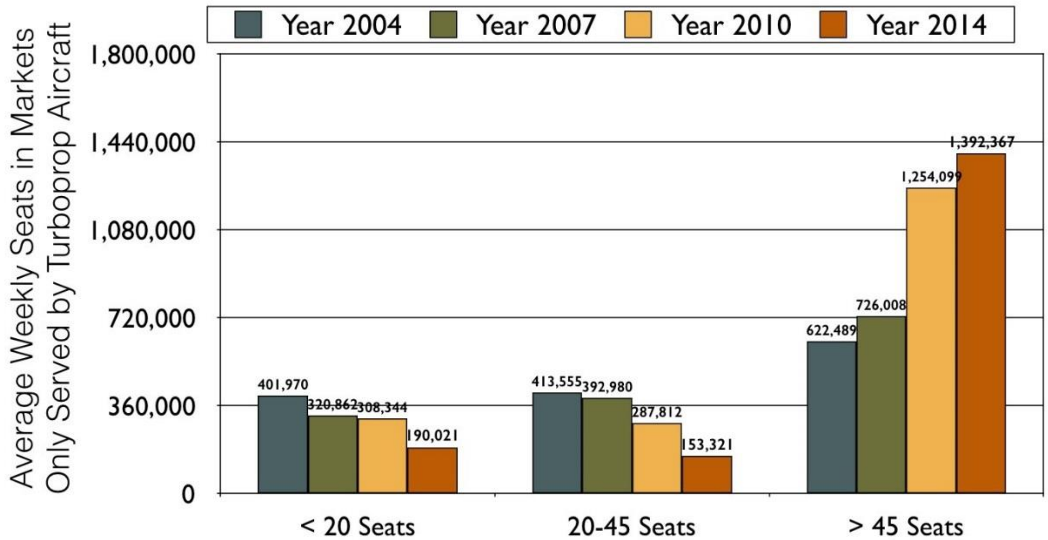

Figure A - 3. Number of weekly seats offered in worldwide O-D markets served exclusively by turboprop aircraft.

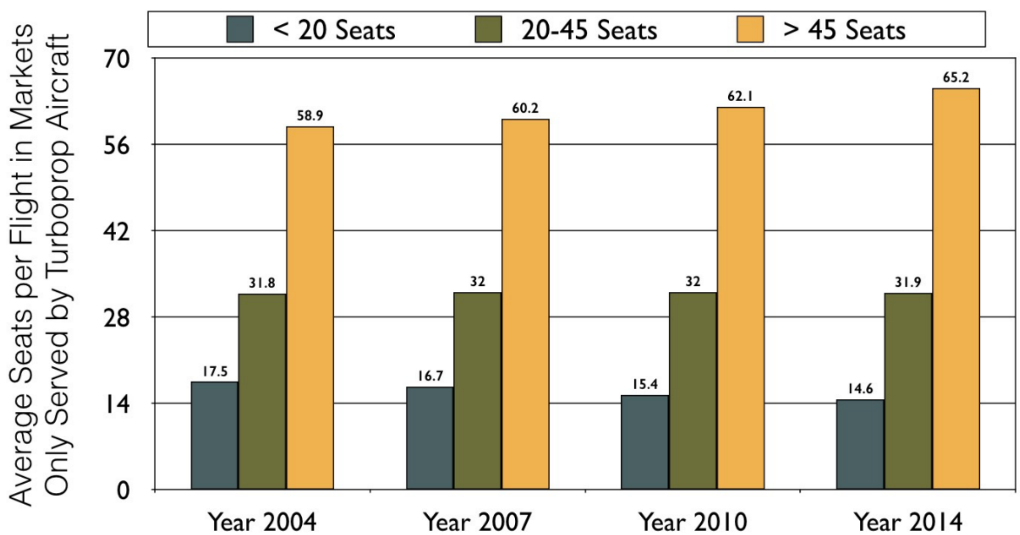

Figure A - 4. Average number of seats per flight in O-D markets served exclusively by turboprop aircraft.

Appendix B

Table B - 1. Tabular output for a battery specific energy of 500 Wh/kg.

	Units	0% Electric	25% Electric	50% Electric	75% Electric
Operating Empty Weight	lb	21,800	23,460	25,980	30,330
Payload Weight	lb	10,800	10,800	10,800	10,800
Total Fuel Weight	lb	3,360	3,060	2,580	1,720
Block Fuel Weight	lb	2,220	2,000	1,680	1,110
Total Battery Weight	lb	0	7,990	20,000	39,590
Takeoff Gross Weight	lb	36,000	45,310	59,350	82,430
Wing Area	ft^2	520	640	830	1,100
Thrust per Engine	SLS, lb	7,300	8,800	11,050	14,710
Max Electric Power per Engine	kW	0	470	1,190	2,360
Fuel Energy	kWh	12,020	10,860	9,080	6,010
Battery Energy	kWh	0	1,180	2,950	5,830
Total Energy	kWh	12,020	12,040	12,030	11,840
Electric Energy Cost	$	$0	$133	$333	$659
Fuel Energy Cost	$	$1,100	$996	$833	$551
Total Energy Cost	$	$1,100	$1,130	$1,165	$1,210

Table B - 2. Tabular output for a battery specific energy of 750 Wh/kg.

	Units	0% Electric	25% Electric	50% Electric	75% Electric
Operating Empty Weight	lb	21,800	22,860	24,020	25,660
Payload Weight	lb	10,800	10,800	10,800	10,800
Total Fuel Weight	lb	3,360	2,880	2,240	1,330
Block Fuel Weight	lb	2,220	1,890	1,460	860
Battery Weight	lb	0	5,030	11,630	20,610
Takeoff Gross Weight	lb	36,000	41,460	48,680	58,400
Wing Area	ft^2	519	586	673	790
Thrust per Engine	SLS, lb	7,300	8,300	9,610	11,390
Max Electric Power per Engine	kW	0	450	1,030	1,830
Fuel Energy	kWh	12,020	10,240	7,910	4,680
Battery Energy	kWh	0	1,110	2,570	4,560
Total Energy	kWh	12,020	11,350	10,470	9,230
Electric Energy Cost	$	$0	$130	$290	$515
Fuel Energy Cost	$	$1,100	$940	$725	$430
Total Energy Cost	$	$1,100	$1,065	$1,015	$945

Table B - 3. Tabular output for a battery specific energy of 1000 Wh/kg.

	Units	0% Electric	25% Electric	50% Electric	75% Electric
Operating Empty Weight	lb	21,800	22,440	23,260	24,130
Payload Weight	lb	10,800	10,800	10,800	10,800
Total Fuel Weight	lb	3,360	2,800	2,090	1,190
Block Fuel Weight	lb	2,220	1,840	1,370	770
Battery Weight	lb	0	3,670	8,180	13,840
Takeoff Gross Weight	lb	36,000	39,700	44,330	49,460
Wing Area	ft^2	519	560	624	675
Thrust per Engine	SLS, lb	7,300	8,070	9,010	10,200
Max Electric Power per Engine	kW	0	430	970	1,640
Fuel Energy	kWh	12,020	9,960	7,410	4,180
Battery Energy	kWh	0	1,080	2,410	4,080
Total Energy	kWh	12,020	11,040	9,820	8,260
Electric Energy Cost	$	$0	$122	$272	$461
Fuel Energy Cost	$	$1,100	$913	$680	$383
Total Energy Cost	$	$1,100	$1,035	$952	$844

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14. ABSTRACT
A feasibility study was performed for an advanced commercial short-haul aircraft to evaluate the potential for increased service for short-haul flights that operate out of regional and community airports. An analysis of potential origin-destination markets and trip distances resulted in a seat capacity selection of 48 passengers and a design range of 600 NM. A down-select of advanced technologies resulted in a hybrid-electric propulsion system being chosen as the primary enabling technology. A conceptual design of the advanced aircraft was developed, and a mission and sizing analysis was performed, comparing variants of the advanced aircraft with different levels of electrification. An aircraft cost and market demand analysis concluded that there is a potential demand for the aircraft, but not necessarily in the markets intended to be the beneficiaries of this new aircraft concept.

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aircraft cost analysis; conceptual aircraft design; hybrid-electric; market analysis; transportation demand

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