Hybrid-Electric Regional Turboprop Final Design Report

Social and Environmental Impacts of Commercial Aviation

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Ryan Keller

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Technical Project Team Members

James Caputo
Darius Espinoza
Jannik Grabner
Ryan Grant
Eun Park
Kangyi Peng
Alex Poley
Alex Wang

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Introduction

The perpetuation of the commercial aviation industry in its present form is at odds with the societal imperative of mitigating anthropogenic climate change. With U.S. commercial airlines alone consuming about 1.3 million barrels of jet fuel a day in January 2020 (Barnett, 2020) and 5% of warming attributable to commercial aviation (Lee et al., 2010), the industry has significant environmental implications. Meanwhile, commercial aviation is vital for connecting people and enabling the globalized economy. In the U.S., commercial aviation facilitates $1.8 trillion dollars in economic activity annually and supports about eleven million jobs (FAA, 2020). Ultimately, the industry is an essential component of the modern economy, but, as with many other essential industries, is problematic environmentally.

Major technological breakthroughs will be necessary to decouple the growth of the industry from the growth of its greenhouse gas emissions. Research and development to this end has begun in the form of more efficient gas turbine engines, sustainable aviation fuels (SAFs), and electric propulsion systems. Incremental improvements to aircraft and engines have decreased block fuel intensity (fuel use per tonne kilometer) by 40% between 1970 and 2019 (Zheng & Rutherford, 2020). While it is undoubtedly a positive development, it will not solve the issue as significant amounts of greenhouse gasses will still be emitted. SAFs may be able to further reduce CO_2 emissions, however it is debatable whether enough can be sustainably produced to satisfy the industry's appetite. Even if enough can be produced, they would not eliminate emissions (Fleming et al., 2022). Electric propulsion is the ideal solution in terms of minimizing the environmental impact of the industry, however it is unlikely to become practical for some time. The issue with electric propulsion comes down to energy storage. Currently, state of the art batteries have a specific energy of about 500 watt-hours per kilogram compared to about 12,000 W-h/kg for jet fuel (Button, 2016). The immense gap dramatically reduces the benefits that batteries could provide in powering aircraft. Increasing the range or size of an aircraft would require the size of the battery to increase. This makes battery electric aircraft impractical for all but the smallest, shortest-range aircraft.

No single solution will be adequate on its own, at least in the short term. To optimally address the issue, a better understanding of the societal impacts of the industry is necessary. In addition to the global impact of greenhouse gasses, other emissions and noise have local impacts on people's health. Focusing on one segment of the industry, in this case fifty passenger regional aircraft, will allow a focused technological solution to the issue. For these aircraft, pure battery electric propulsion would be inadequate, however, a hybrid-electric architecture shows promise. Therefore, a conceptual design for a 50 seat regional turboprop will be developed with the goal of reducing emissions relative to the current state of the art.

Technical Topic

Regional aircraft are small aircraft (generally considered to have between 19 and 100 seats) that are used to serve short-haul (under 500 nmi), low-demand routes. Regional aircraft play an important role in connecting smaller markets to the wider world. There are about 9300 regional aircraft worldwide, with about 5000 of them being turboprops. This represents approximately 29% of the global commercial aircraft fleet (von Schoenberg & Doran, 2021). According to the Regional Airline Association, an American industry trade group, 66% of U.S. commercial airports are served only by regional aircraft (RAA, 2021). In their 2022 market forecast, ATR projected a demand for 2,450 new turboprops by 2041. 620 of these aircraft are projected to have between 40 and 60 seats. Airlines around the world committing to reaching net zero emissions by 2050 presents an opportunity to develop a fifty passenger turboprop aircraft that uses advanced technology to minimize fuel burn and emissions. In this vein, the 2023 American Institute of Aeronautics and Astronautics (AIAA) design competition request for proposal (RFP) is focused on a fifty passenger hybrid-electric turboprop with an entry into service of 2035 (AIAA, 2022).

Requirements

The RFP lays out various requirements that must be met in the final conceptual design. The figures of merit that it identifies are a reduction in block fuel burn (fuel used from takeoff to landing) of at least 20% for a 500 nmi mission and a reduction in CO_2, NOx, and soot emissions relative to a conventional, state of the art aircraft. Table I summarizes the key requirements laid out for the aircraft. Most of the performance metrics are similar or slightly better than the current aircraft in this segment, the ATR 42-600 and DeHavilland Dash-8 Q300.

Table I
Summary of Key Requirements

	Requirement	**Objective**
Entry Into Service	● Aircraft EIS of 2035 ● Engine EIS of 2034 or existing	N/A
Range	● Design: 1000 nmi fully loaded ● Economic: 500 nmi	N/A
Efficiency	● 20% reduction in block fuel on 500 nmi mission relative to current SOA	● Maximize as much as possible
Passenger Capacity	● At least 46	● 50
Cruise Speed	● 275 KTAS	● 350 KTAS
Regulations	● Must satisfy CFR Title 14 Part 25	N/A

In addition to the quantifiable requirements discussed above, the RFP requires that the aircraft be “visually appealing” and “marketable”. This will be important as turboprops have started to fall out of favor, especially in the U.S. Many see them as old fashioned and less safe than jets (Wall & Tangel 2019). One obvious marketable feature of a hybrid-electric turboprop is its efficiency, however that is no good if passengers want to avoid flying on it. Therefore, an effort should be made to make the aircraft appear cutting edge and passenger friendly.

Challenges

While hybrid electric aircraft propulsion may be a promising concept, there is still a long way to go until it is ready for use in commercial aircraft applications. These challenges include developing battery and electrical systems that meet the mass and efficiency requirements to make electric propulsion beneficial, thermal management necessary to keep those systems running efficiently, and ensuring that these new aircraft are developed in a way that ensures regulators and the public are convinced that they are safe. Addressing these challenges will require the development and maturation of various technologies.

For this project, the focus will be on finding and analyzing promising technologies that could feasibly have an entry into service of 2035. Any technologies used must be ready for test flights by around 2027. The time constraint is likely to be a limiting factor in the design as only so much technological advancement can be reasonably assumed in the given time frame.

Hybrid-electric aircraft would represent one of the most significant changes to commercial aircraft since the advent of the jet age. However, requiring significant changes to the way that airlines operate will make it more difficult to convince them to adopt new technologies. For example, if charging a large battery on the aircraft reduces the number of flights the aircraft can make in a day, it will be a less appealing proposition to airlines. One option that could address charging times is using removable battery packs. Unfortunately, this poses new challenges as it would become necessary to have machines to remove and replace the multi-ton batteries. Additionally, airports would have to add areas to store and charge those batteries. The need for additional infrastructure would limit operational flexibility and increase costs. Ultimately, the aviation industry is a complex system of systems that must be considered when designing an aircraft.

Approach

Approaching this problem will begin by researching the current market for regional aircraft, state of the art hybrid electric systems and components, as well as expected technological progress in the coming decades. Once a good understanding of the problem and potential solutions is developed, work will begin on designing the aircraft.

One of the first decisions that will need to be made is which hybrid architecture to use. The options range from a parallel hybrid architecture to turboelectric architecture. A parallel hybrid architecture uses both gas and electric propulsors and is generally heavily reliant on batteries. A turboelectric architecture utilizes a gas turbine to power electric propulsors, potentially eliminating the need for batteries (Antcliff & Capristan, 2017). The latter has the benefit of not requiring batteries, but if only one turboelectric generator is used, it may not be able to get regulatory approval due to one engine inoperative regulations. Understanding the advantages and disadvantages of each option will be critical. As such, important decisions will be made after conducting trade studies. These will allow trade-offs to be evaluated quantitatively. For example, the RFP has a cruise speed of 350 KTAS as an objective, with the minimum allowable 275 KTAS. Increasing speed requires increased power, which will require either increased battery capacity or fuel consumption. This conflicts with the desire to reduce emissions. Thus, it will be necessary to determine whether pursuing an increased cruise speed is worth it.

After the general configuration of the aircraft is determined through trade studies, software, such as OpenVSP, will be used to model, evaluate, and refine potential designs. This process will result in a conceptual design for an aircraft that conforms to the requirements laid out in the AIAA RFP.

STS Topic

The aviation industry, being reliant on fossil fuels, has a significant environmental impact. It is necessary to ask: What are the environmental costs, both global and local, of commercial aviation? And what communities are the most impacted by this?

Global Impacts and Climate Change

Climate change is an existential threat to society as a whole. Therefore, any activity, such as aviation, must have its impact on climate change evaluated. Commercial aircraft are, at this point, universally powered by the combustion of fossil fuels due to the fuels' superior specific energy (energy per unit mass). As such, the industry certainly plays a role in the continuation of climate change. Through emissions of greenhouse gasses such as CO_2 and the emission of water vapor, which can form cirrus clouds, aviation is estimated to contribute about 5% of global anthropogenic warming (Lee et al., 2010). The increase in average global temperatures is expected to result in various negative impacts such as drought and more extreme weather. Because commercial aviation is playing a considerable role in this potential human tragedy, it is necessary to consider its ethical implications.

Local Impacts and Health

Airports, especially large hubs, concentrate global connectivity allowing for convenient travel. However, they also concentrate aircraft emissions and noise, which is detrimental to the health of people living nearby.

Aircraft emit various substances, such as CO, NOx, and SOx that negatively impact people's health. These emissions increase the rates of respiratory diseases, increasing the morbidity and mortality of people living near airports. In 2013, the damage from these emissions was estimated to be approximately $1.9 billion (Nahlik, Chester, Ryerson, & Fraser, 2016).

Exposure to the elevated levels of noise near airports has been associated with worse health outcomes. In particular, it has been shown in multiple studies to increase the rate of hypertension, cardiovascular disease, and stress (Meister & Donatelle, 2000). In addition, the noise also negatively impacts children's cognitive development and increases the rate of hyperactivity. A study of children attending schools near London Heathrow airport found that for every 5 dB increase in average aircraft noise at a school, was associated with a two-month delay in reading age (Clark et al., 2021). This harm that is caused by airports to their local communities certainly raises ethical questions about their operation.

Environmental Justice and the Aviation Industry

The impacts of climate change are unevenly distributed around the world. While wealthy countries, including the U.S., have disproportionately contributed to the issue, poor countries are expected to be more significantly affected (Farbotko, 2019). This is an issue of justice as a group is being harmed by the actions of another. At the moment, it does not seem that wealthy countries are taking enough responsibility for mitigating climate change and addressing the harm already done in developing countries.

Locally, within countries with developed aviation industries, the negative impacts of aircraft operations are often concentrated in neighborhoods inhabited by typically socioeconomically disadvantaged groups. This has, in many cases, been the result of intentionally locating airports in the areas. A good example is Washington Dulles International

Airport in Loudoun, VA. At the dawn of the jet age, the U.S. government was looking for a site for a new international airport to serve Washington D.C. They initially settled on a location in Fairfax County. This was met by fierce opposition from the residents of the surrounding, predominantly white suburbs. Ultimately, the government backed down and changed course to a site in Loudoun County: Willard, VA, which was a predominantly Black town. The residents of Willard were evicted while the land the government had bought in Fairfax County became Burke Lake Park (Scheel, 2002).

Airport operations result in noise that can be harmful to nearby residents. A study looking at the decision of an Arizona regarding the adjusting of flight plans to address noise resulted in the location of a disamenity (in this case noise) in a predominantly Hispanic neighborhood. The option they chose resulted in more people being affected by the noise but was considered easier and cheaper to implement (Sobotta, Campbell, & Owens, 2007). This highlights an issue with justice in that a group of people seems to have been harmed unnecessarily.

Methodology

To answer the aforementioned research questions, actor-network theory (ANT) will be used to develop a framework that will allow the industry and its impacts to be understood. This analysis will focus on how interactions between different individuals, firms, and non-human actors are involved in this issue. The actors that will be analyzed include government policy makers who set regulations on the issues of aircraft noise and emissions, aircraft manufacturers who determine how the aircraft are built and therefore how much R&D spending is directed towards emission and noise reduction, airlines who operate the aircraft, and the public who are affected by the industry and, through demanding air travel, oblige its continued existence.

Prior literature, such as that discussed above, will be used to help quantify the environmental impacts of aviation. Many past studies involve surveys and interviews of people affected by aviation noise and emissions, which will help to understand the human impact of the industry. In addition, a better understanding of the industry and its participants will be developed. Together, this will allow for an ANT framework to be used to analyze the issue. Looking at the continued development of the aviation industry and the push for new, cleaner technologies will allow the role of different actors to be examined.

Conclusion

For the foreseeable future, commercial aviation will play a key role in how people do business, move goods, and escape their everyday lives. The industry has shrunk the world, which has undoubtedly had a positive impact on society. However, it is not ethical for the industry to maintain its current path due to its environmental impact. Innovation could drastically reduce aviation's environmental impact. For example, hybrid-electric propulsion systems could reduce fuel consumption significantly. However, further research and development will be necessary to realize the potential of such technologies.

2457 Words

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