Title
Achieving Sustainability in Aviation

Authors
Carreon, Jonathan
Zhu, Qiang

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Achieving Sustainability in Aviation

Jonathan Carreon

ABSTRACT

Over the past century, carbon emissions have continuously spiked to new levels every year. Subsequently the need for renewable and sustainable energy to be implemented into various industries is necessary now more than ever. The aviation sector is no exception; it remains one of the most popular forms of travel. Thus, it is crucial to consider its part in both carbon and overall emissions on a global scale. This report entails a comparative assessment of the benefits and flaws associated with aviation along with the advancement of incorporating sustainable aircraft technology. Additionally, I will be paying close attention to the patterns air travel emissions follow with respect to contributions from overall global emissions. Different forms of primary energy such as biofuels, electricity, and electrofuels are considered to analyze the benefits of their implementation. I also focus on methods of combustion, aerodynamics, design, and overall performance to aid me in comparing time sensitive implementations for the future of air travel. The Los Angeles World Airports (LAWA) and United Airlines' use of a biofuel/jet fuel mixture is used as a case study to extrapolate emissions on a larger scale. Finally, I use short-term and long-term years (2035 and 2050, respectively) to conclude what reasonable implementations can support the decarbonization of air travel.

INTRODUCTION

The growth of carbon emissions on a global scale continues to surpass emissions from years prior. With the ongoing pandemic at the time of writing, there has been a noticeable, yet temporary, decrease in the demand for fossil fuels. Of the numerous sectors directly impacted, air transport faced its largest decrease in emissions since it became commercially available to the public. However, this decrease in emissions is expected to be temporary as restrictions get lifted. In fact, preliminary studies demonstrate an exponential growth in aviation emissions because of the increasing demand for air travel. Aircraft emissions sum up to a 2.5% contribution to global carbon emissions and 4% when considering overall emissions (I.e., Nitrous Oxides, condensation trails, etc.) (32). The contribution is expected to continue growing as other sectors like the automotive industry begin to become fully electric.

Various global organizations including the United Nations are actively trying to set policies in place to decrease the rapid growth of the sector. Nevertheless, protocols like the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) have shown little to no progress in reducing emissions. CORSIA demonstrates firsthand the necessity to implement mandatory policies as opposed to voluntary commitments. It is instrumental to set up policies that incentivize airlines and airports alike to implement the use of different technology for their aircraft.

This literature review analyzes currently available technologies for climate change mitigation and highlights ongoing research dedicated toward emissions reduction. Finally, it will roadmap potential mitigation efforts to cover two end goals: short term and long term, or 2035 and 2050, respectively. The roadmap is motivated by the 2016 Paris Agreement (4) which aims to decrease emissions down to approximately 350 million tons in 2050. This drop in emissions would be 38% of aviation emissions in 2019. As a result, the use of aircraft modification is deemed necessary. Therefore, this work will specifically focus on the implementation of new aircraft design and alternative jet fuels for conventional aircraft efficiency improvements.

Emissions

2.1 Global Emissions

The commencement of the industrial revolution has brought a generation incredibly fond of technology. As a result, these technological advancements have come at a cost in terms of climate. The contributor with the most substantial impact on climate change is emissions due to carbon dioxide. Most of these emissions range from Transportation to Industry to Heat Generation. The consequences of climate change may not appear to be immediate, but when taking into consideration the Earth's atmospheric concentration, unnatural records have been broken.

Prior to the industrial revolution, the Earth's atmospheric concentration in parts per million (ppm) fluctuated anywhere between 186.10 ppm to a pre-industrial peak of 288.40 ppm over the course of several millennia (31). Over the last century, however, industrialization has caused atmospheric concentration due to greenhouse gases like CO2 to rise above 415 ppm in a fraction of the time. This in turn leads to the phenomenon of the greenhouse effect which is caused by thermal radiation trapped in the Earth's atmosphere resulting in warmer changes in temperature. For climate change due to industrialization, carbon emissions contribute to this warmth in a much more delayed response. More specifically, the temperature changes occurring presently are the result of emissions created decades ago meaning that the atmospheric concentration will continue to rise for coming years.

Countries like the United States, China, Russia, Japan, and India have grown to become the largest primary energy consumers contributing to nearly two-thirds of yearly emissions (see Figure 2) with fossil fuels being the most popular energy uses (6). Fossil fuels consist of natural gas, oil, and coal, all of which are abundant in everyday use. These fuels receive the most economic support through federal funding on the global level, hence making them cost efficient for consumption across various sectors. In fact, fossil fuels have accounted for 83% of primary global energy consumption (5, 6, 7). This large availability is the reason these fuels are also the largest contributors to carbon emissions given their high carbon concentrations and lack of renewability.

2.2 Aviation Emissions

The aviation industry is no exception when it comes to its contribution of carbon emissions; it accounts for over 2.5% of yearly carbon emissions (32). However, it is important to note that carbon emissions contribute to 80% of overall emissions. Therefore, when overall emissions are considered, aviation emissions rise up to nearly 5% of all emissions when considering contributions stemming from condensation trails, Nitrous Oxide, Sulfur, and soot particles. Prior to the COVID-19 pandemic, aviation emissions rose to 918 million metric tons of CO2 in 2019. To give a better perspective, this was the equivalent to the emissions of France, Spain, Portugal, and Italy combined. Together these countries house over 184 million people (Figure 2). Carbon neutrality as a result has proven itself to be of utmost benefit and importance for the reduction of carbon emissions. In comparison to other transportation sectors, aviation made up about 10% of transportation emissions in 2019 (see Figure 2). However, as ground transportation like cars, trucks, and heavy-duty vehicles progress towards an electric future, aviation is expected to grow as high as 27% and consume 25% of the UN's carbon budget by 2050 (28). This expectation becomes a reality given the historically rapid growth of aviation emissions. Over the last 40 years, emissions have doubled and continue to do so (32).

FIGURE 2: Yearly Carbon Emissions in terms of percentages. Figure is based off data from (6,7).

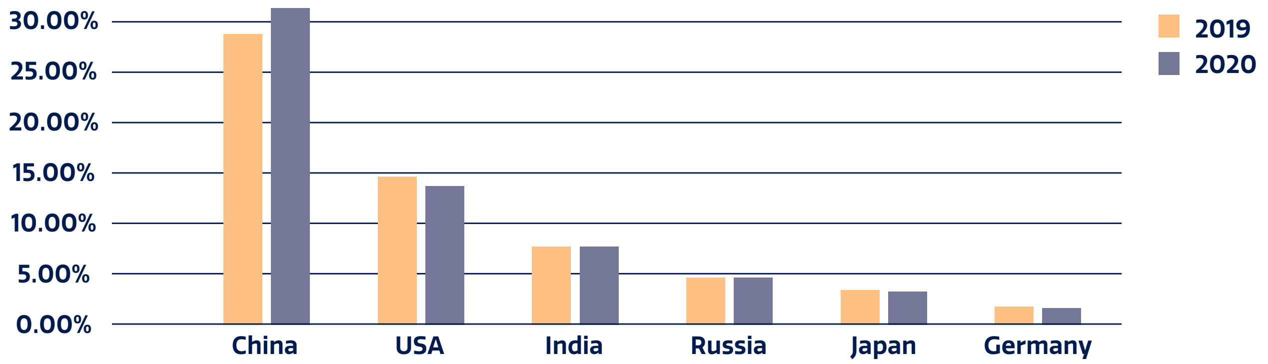
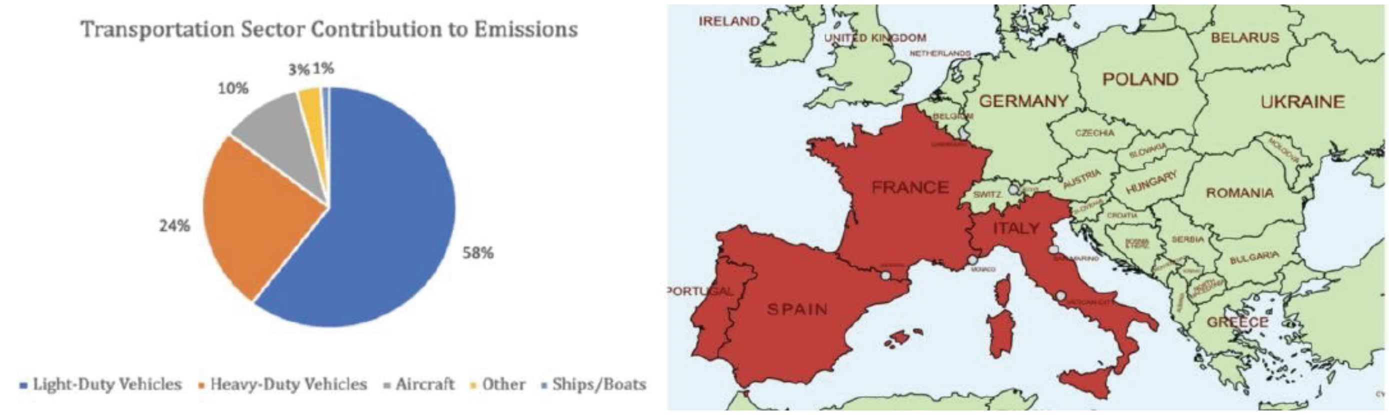


FIGURE 2: Transportation Emissions and Aviation Emissions. Figures based off data from (10) and (7, 32) respectively.



While this growth is attributed to CO2 emissions, the second highest emission from gas turbines comes from condensation trails. Condensation trails are a result of water vapor exiting the airplane engine and freezing at the high altitude at which the plane is traveling. This process contributes to 28% of aircraft emissions. In general, condensation trails have a short life span and a minimal contribution to the effect of global warming. However, air travel has become so convenient and regular that with over 35 million flights a year since 2016, (26) the impact of these emitted cirrus clouds has a larger effect than the initial emissions of when aviation first commenced. The remaining aircraft emissions, less than 2 percent, result from soot particles, Nitrous gases, and Sulfur gases which contribute to the remaining 20% of global greenhouse gases. Altogether, these emissions display the demand for necessary change in modern air travel. Such emissions require commitments from airlines and airports all the same which require government interference as well as corporate support.

2.3 Government Policies and Climate Change

The 2016 Paris Agreement set up the basis for what would be expected for the following decades. The act of requiring a carbon budget in turn is working to reach toward reaching an end goal, that of which various corporations and countries have agreed to try to meet.

The threshold necessary towards preventing climate impacts outside of our control has been set to be at around 2°C with respect to pre-industrial levels. The impact of surpassing the threshold provided by the UN is estimated to be catastrophic when considering the irreversible impacts that follow subsequently. One example of this comes from the rise of sea levels because of melted ice sheets. This highlights the urgency of needing to decrease the number of emissions from various sectors. In doing so, approaching a sustainable future also decreases the probability of people affected by water shortages by 50% (29).

In accordance with the Paris Agreement, the aviation industry is expected to reduce their emissions by 50% by 2050 with respect to 2005 emission levels, that is 350 million metric tons. Initially, the International Air Transport Association (IATA) and International Civil Aviation Organization (ICAO) agreed to cap emissions at 2020 levels to initiate the decrease in emissions. However, 2020 demonstrated substantial change in the field of aviation because of COVID-19 decreasing the demand for jet fuel by over 40% and the passenger air traffic by over 65% (18). The dramatic decrease in air travel in turn dropped emissions to a record low of 700 million metric tons. Even so, emissions are not expected to rise above a quarter below pre-pandemic emission levels by the end of 2021. This in turn required the ICAO and IATA to consider 2019 to be the cap for emissions giving the aviation sector a temporary advantage to implement useful policies. Much more modification is necessary to accomplish goals expected by the ICAO and IATA. The Carbon Offsetting Reduction Scheme for International Aviation (CORSIA) protocol was created in effort to structure a plan to achieve the Paris Agreement goal but fails in terms of commitment. Countries and companies were able to participate in it without any necessary accountability. However, it is projected that this agreement would only cover a 6% decrease in emissions by 2035 and considers fuels with a 10% shorter lifespan than kerosene to be a “clean fuel” (11) hence making it exceedingly difficult in terms of timing. With the urgency of meeting goals established by the UN and IATA, CORSIA is not sufficient towards reducing emissions with respect to the 2050 deadline.

When considering aviation emissions globally, pinpointing emitters becomes more difficult due to international emissions. These international emissions are referred to as bunker fuels and are difficult to decrease because countries do not account for them in their yearly emissions. As a result, these countries have less incentive to act, hence making it much more difficult to reduce emissions (32). Nevertheless, companies worldwide are currently striving to achieve sustainability through various aspects including aircraft modification, new forms of combustion, and fuel replacements.

Climate Mitigation Alternatives

The use of petroleum-based fuels serves as the core of aviation emissions. Contemporary jet engines heavily rely on gas turbines for combustion which require the use of kerosene. Jet A and Jet A-1 are the most abundant fuel sources in aviation which is what this study will be primarily focusing on. In general, for every 1 kg of jet fuel burned, there is 3.16 kg of CO2 emitted, 1.2 kg of water vapor, and 1-2.5 g of soot particles (27). However, Jet A/A-1 fuels continue to be immensely popular given how well they adapt to rigorous flight conditions. For instance, it has a low freezing temperature to remain useful during high flight conditions where the temperature is low, high lubricity to require minimal maintenance and longer lifetime, and has a low cost in comparison to other fuel sources averaging anywhere between $1.50 to $4 a gallon (19).

The dilemma with decarbonizing air travel then resides in finding a fuel replacement that negates the negative effects of kerosene fuels. Unlike ground transport, it is much more difficult to make air travel electric given the high energy density of Lithium-ion batteries for example. The high energy density fails conventional aircraft as it increases the weight of the vehicle subsequently increasing the demand for power (23). Many alternative sources have been suggested, but given the exponential growth of climate change, it is necessary to consider an alternative source that promptly adapts to current technologies and brings an almost immediate reduction in emissions. Additionally, it is necessary for these alternatives to also be capable of matching the characteristics of jet fuel to make the transition into another alternative feasible.

3.1 Alternative Jet Fuels:

Alternative jet fuels (AJFs) have shown promising results when it comes to the replacement of jet fuels. The production of biofuels, for example, follows a similar route to that of kerosene except for when it comes to emissions. Following emissions, biofuels follow a cycle in which they can be reused into feedstock growth (See Figure 3). Formally, biofuels are defined to be a liquid fuel produced from renewable biological sources ranging from plants to animal fats. Carbon intensity is not entirely eliminated with the use of biofuels, Kharina and Plavenko (22) consider LAX's contract with AltAir, a biofuel company, and describe a carbon intensity 65-85% lower than standard kerosene when using animal fats (tallow). As a result, it follows that a decrease in emissions comes from the use of these fuels.

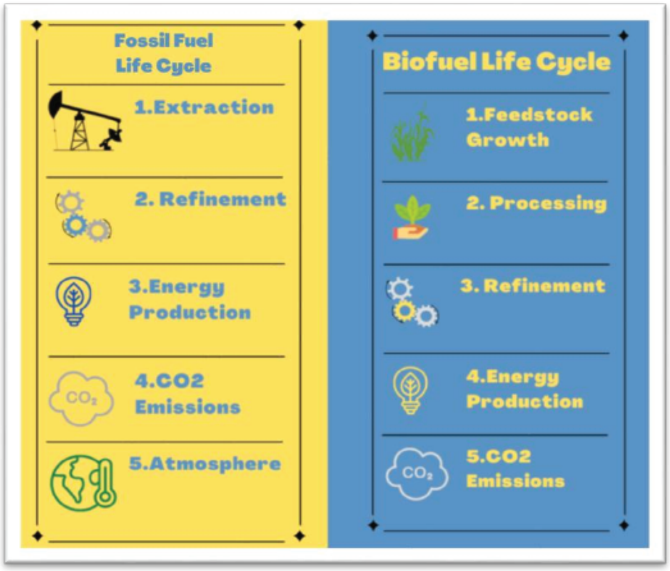
Moreover, the production of biofuels can be initiated from a large variety of crops, both edible and non-edible (16). Some of the benefits of utilizing non-edible crops (I.e., Jatropha, algae, camelina) is that there is minimal maintenance required during farming and they are not perishable due to pests or other environmental factors. Nonetheless, along with a diverse set of choices for fuels comes a change in energy density for the fuel options reducing the efficiency of biofuels to be used independently (16). Despite potential decreases in emissions, proper funding is necessary for biofuels to reach commercial production. At the moment, the price gap between biofuels/biodiesel and kerosene is too large to implement into commercial production which is a major drawback in terms of competitiveness (3).

3.2 Electrofuels & Fuel Cells

Electrofuels are also another form of renewable energy that have demonstrated carbon neutral success. Such fuel replacement thrives on using other renewable sources to store electrical energy into the chemical bonds of gaseous or liquid fuels otherwise known as powerto-gas or power-to-liquid (12). When implemented into combustion engines, several modifications are necessary for electrofuels. However, a "drop-in" practice poses a solution demonstrating efficiencies for combustion and emissions when using n-Octane. Most notably, the largest disadvantage of considering an electrofuel approach is the cost; in 2018, Goldmann et. al. concluded that the price of electrofuels was five-fold that of kerosene. Most of the cost applies to the production and maintenance of the synthesis in power plants for the various methods put into place (20).

FIGURE 3:

Comparison between Biofuels and Fossil Fuels interpreted from (3).



While Power-to-X fuels demonstrate potential to decrease the effects of climate change from combustion, much more research and funding is required in the consideration of engine modifications (12). Fuel cells similarly promote climate-friendly aviation through its silent form of combustion through its reliance on electricity as a source. Not to be mistaken with a battery, a fuel cell uses a fuel source to produce electricity and does not need to be charged. Through the use of natural gas or diesel and the outside air entering the cathode and anode, heat and electricity are generated.

Much less space is required as well to power an aircraft, making the fuel cell an incredibly attractive replacement. Baroutaji et. al. (1) analyzes the auxiliary power unit (which accounts for 20% of aircraft emissions) with solid oxide fuel cell implementation finding a 40% reduction in fuel consumption during cruise and 75% reduction stationary/during taxi. Similarly, Seyam et. al. (32) used a solid oxide fuel cell with a 75/25 natural gas and hydrogen mixture, respectively, which. was 87% as efficient in comparison to a standard engine. While efficiency has proven to be beneficial, fuel cells are still in the preliminary stages of production when it comes to conventional aircraft use. Further research is necessary to determine how fuel cells perform under colder temperatures and lower pressures to match the atmosphere of higher altitudes.

3.3 Hydrogen

Hydrogen is an adaptable fuel source that can be used in its gaseous, solid, and liquid states which are also expected to reduce emissions. Numerous studies have been conducted which have found a multitude of ways to implement hydrogen into combustion or through fuel cells (1, 2, 13). Seyam (33) et. al. considered 5 different fuel combinations all having 25% or more Hydrogen concentration all of which decreased CO2 emissions anywhere between 50% to 74%. Additionally, the thrust produced by the fuel combinations also proved to perform competitively when compared to kerosene demonstrating thrust levels between 37.8 to 39.8 kN, +/-1% above kerosene levels (38.4 kN). Hydrogen blending is not uncommon, in fact, Grewe et. al. (13) simulated a 30/70 blend of LH2 and biokerosene on the AHEAD aircraft finding a 50% increase in water vapor emissions, but a 75% decrease in CO2 emissions when compared to a 2014 Boeing 787. This tradeoff between emissions is attractive given the significantly lower lifetime of water vapor condensation trails compared to CO2 emissions.

Similar to other fuel replacements, hydrogen jet fuels present very optimistic results in reducing aviation emissions. Nevertheless, hydrogen becomes difficult to work with when it comes to its storage. The energy density is larger when compared to regular jet fuel increasing the weight as much as 4 times (1). Proper insulation is also a crucial factor when using hydrogen in its liquid form given that the need for low temperatures may cause embrittlement on the metals hence the need for steel and potential overall design change. Finally, like the aforementioned alternatives, hydrogen requires a lot of funding as well which makes it more difficult to get ahold of on a commercial scale (2).

Aircraft Design

Aircraft efficiency does not solely rely on the fuel sources used to produce combustion. In fact, the design of the aircraft has the potential to decrease fuel consumption by up to 25% depending on the modifications (9). Current aircraft designs are flawed in many respects which contribute to the shortfall of aerodynamic properties such as maximizing lift and laminar flow. Over the past several years, there have been various contributions that have considered even challenging traditional aircraft design. Design modifications for the body of the aircraft create a linear relationship between drag and fuel efficiency where for every 1% of aerodynamic drag reduction, there is around .75% reduction in fuel consumption (30).

4.1 Winglet Modifications

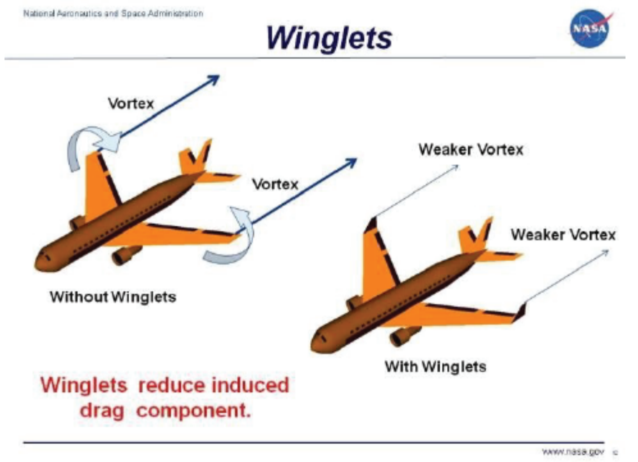
The conventional aircraft design heavily relies on its wings to generate lift throughout its flight. One of the most rigorous barriers to overcome during flight is drag, more specifically, lift induced drag. This is reliant on design optimization and accounts for around 40% of drag experienced during flight (9, 30). The use of a wingtip/winglet (see Figure 4) during flight contributes to a reduction of fuel consumption by manipulating the strength of wind vortices during take-off and cruise flight away from the wingtip in turn reducing drag. The camber morphing winglet (CMW) has been proposed by Eguea et. al. (9) to optimize fuel efficiency during flight on a business jet. Through this modification, a 6% decrease in overall fuel consumption was achieved by having the winglet adapt to changes in environment so as to optimize drag reduction as opposed to a fixed winglet that achieves minimal drag reduction during flight.

4.2 Overall Body Optimization

As previously mentioned, the design for conventional large-scale aircraft generates lift primarily on its wings with little to no lift being generated on the fuselage. However, most of the load for a cantilever designed aircraft is carried within the fuselage making it aerodynamically

FIGURE 4:

Glenn Research Center (15).



inefficient with a relatively low lift-to-drag ratio (L/D) of 19 (21, 25). The higher L/D ratio that is achieved, the less work is required during a flight. Consequently, the design for conventional aircraft has since been experimentally modified in order to increase aerodynamic efficiency overall.

The Truss-Braced Wing (TBW) and Strut-Braced Wing (STW), for example, follow a very similar design to that of the conventional aircraft design with the exception of a truss component added to support the wing. Gur et. al. (14), for instance, considered three cases in which their designs achieved a minimum takeoff gross weight (TOGW), minimum emissions, and maximum L/D using a Multidisciplinary Optimization framework (MDO) subsequently finding that the truss members allowed a larger aspect ratio and in turn a higher L/D anywhere between 22-30. Additionally, when placing emphasis on fuel reduction/emissions reduction, Gur et. al. (14) were able to simulate a fuel weight reduction of up to 45% using the longer wings with minimal flutter on the TBW.

One of the design descendants of the Flying Wing Aircraft is the Blended Wing Body (BWB) which introduces a concept much different from that of the cantilever wing. The BWB fuses together the wings and the fuselage into one shape hence giving it its unique shape which has received great attention from Boeing, Airbus, and NASA over the last several years (see Figure 5). Unlike the CLW, the BWB generates lift below the "fuselage" as well while also maintaining a larger aspect ratio resulting in a higher L/D (21). As pointed out by Liebeck (25), when compared to the Airbus A380-700 and Boeing 737, using an MDO framework demonstrated a L/D ratio of 23, decreased fuel burn per seat by 27%, and 15% reduction in TOGW. Given its design, there is less wetted area on the aircraft which reduced the drag during flight. Humphreys-Jennings et. al. (17) found that when utilizing a flight simulator, the BWB was significantly more efficient in a similar manner to previous studies.

Initially, the use of the BWB seemed to conceptually threaten flight safety given the lack of vertical stabilizers. More specifically, during roll maneuvers, yaw becomes somewhat difficult to manage (17). However, this was a design implementation heavily flawed until the optimization of algorithms was enabled to manage them. Another solution is also seen in Karpuk et. al. (21) and Humphreys-Jennings et. al. (17) with the implementation of winglet rudders. In general, rudders are implemented on the tail of an aircraft, but this implementation on wingtips provided yaw and pitch control during roll. This has since been a major contributor making the use of a BWB more likely. In fact, Airbus announced that it intends to implement the use of a BWB by 2035 for commercial use.

FIGURE 5:

NASA Blended Wing Body – Langley Research Center (8)

DISCUSSION AND CONCLUSIONS

With the intention of reaching goals set up by the UN and ICAO, it is instrumental to have stricter policies in place to deal with funding for AJFs as well as significant investments from larger corporations (11). There are currently programs in place to incentivize companies like Low-Carbon Fuel Sources (LCFS Certification) which award points to companies for their renewability qualifying them to more government support and funds in their state. More importantly, it is worth recognizing the feasibility of implementing such fuel replacements and sustainable technologies.

Currently, there are only 5 airports globally which regularly implement the use of biofuels throughout their whole airport (24). One of the benefits of biofuels comes down to being able to implement a mixture of biofuels into current aircraft requiring no change to the conventional gas turbine. While there have been some drawbacks in terms of efficiency with biofuel energy density being relatively lower and higher freezing temperatures, some of these issues can be remedied with preheating prior to flight (3).

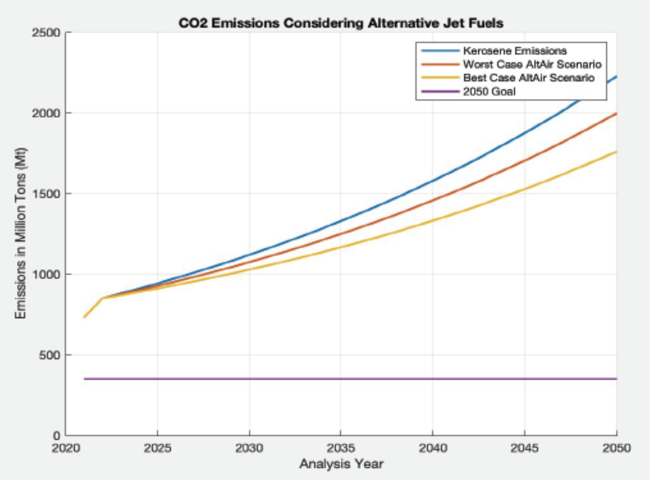
Furthermore, it is of interest to consider LAX (one of the five airports) as a case study when looking at their 30/70 fuel blend using AJF based on animal fats and kerosene, respectively (22). Figure 6 demonstrates a projection of aviation emissions solely based off using the Altair fuel mixture on a hypothetically global scale with a best case (85% lower carbon intensity) and worst case (65% lower carbon intensity) scenario. Considering a Business-As-Usual (BAU) protocol from now until 2050, the ICAO expects aviation's growth rate to be at 3.5% with 3% being considered optimistic (11). As seen on the figure, with the LAX blend being the minimum, the necessity for new technology is still crucial to meet the UN's goal of a 50% reduction (4) but decreases projected emission growth by 6-12% in 2035. This is in consideration of only the fuel blends being modified on the aircraft. However, emissions can substantially decrease over the years as other modifications are combined.

As the analysis year continues progressing, it becomes clearer that the effectiveness of AJFs contributes to a slower growth rate in CO2 emissions. However, 2035 is highlighted in this report given that in that year, it is projected that Airbus (35) will deliver the first zero-emission aircraft reliant on Hydrogen. Currently, the implementation of hydrogen discussed earlier is not necessarily feasible given the lack of economic competitiveness and necessity to adjust engines assuming a non-fuel cell replacement to be fully carbon neutral. Hence, further research is needed to understand its implementation on a commercial level. Nevertheless, with the proper funding, it is possible to expect biofuels to become more common in the aviation industry.

In addition to aircraft dependent on hydrogen, one of the three models being considered by Airbus is the BWB which when compared to the TBW, the BWB potentially achieves potentially higher fuel reduction benefits of 10-25% whereas the TBW ranges from 10-15% (9). Additionally, it is more reasonable to expect a BWB to hit the air before a TBW considering the proper funding that has been ongoing for the BWB design. While the BWB does challenge conventional aircraft design, it ultimately

FIGURE 6:

Projected Emissions Globally using Altair AJF contract with LAX as a Case Study (22)



does provide significant benefits for the future of aviation.

As a result, for the upcoming deadlines and aspirations set up globally, it is reasonable to suggest that by 2035, the proper funding and policies set up to support AJFs can potentially reduce emissions by over 10% with biofuels and over 25% with different implementations of alternatives (11). This combats the slower reduction of 6% initially mentioned by the CORSIA Agreement. Furthermore, once this analysis year is reached, the potential release of the BWB will be pivotal in demonstrating drag reduction and in turn much larger emissions reductions. The use of cost-effectiveness of hydrogen will need to be further evaluated in upcoming years so as to better understand what kind of funding it may receive on a commercial level. Lastly, drastic measures will be necessary in the upcoming future regardless of what methods are adopted.

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Jonathan Carreon

McNair Cohort: 2021

Biography:

My name is Jonathan Carreon and I am entering my 4th year at UCSD. I am a Mathematics-Applied Science major with a minor in Mechanical and Aerospace Engineering. I am the co-chair for Hermanos Unidos de UCSD and a former peer mentor for UCSD's Summer Bridge. Some of my goals are to contribute to the field of space travel, lessening the effect of carbon emissions through aviation, and potentially teaching. I am also planning on applying to Graduate programs this upcoming Fall. Outside of school I really enjoy watching movies, photography, reading, and exercising.

> *"As someone whose family is directly affected by [climate change] ... My personal aspirations are to contribute to the betterment of low-income and disenfranchised communities by reducing the health issues that they face as a result of climate change...[and] by achieving sustainability worldwide"*

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