# Investigating the Efficiency of A Strut-Braced Wing Passenger Aircraft and its Potential Environmental Impact

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## Abstract

Man-made emissions have a significant impact on the earth's atmosphere. Consequently, researchers have been searching for ways to make the next generation of passenger aircraft more efficient and to reduce the emissions they release. The strut-braced wing is a design concept currently being investigated for this role. It has the potential to be a high-efficiency design because it increases the aspect ratio of the wing by amounts not possible with a traditional cantilever design. In this paper, the advantages and disadvantages of the strut-braced wing (abbreviated as SBW) design are examined through a combination of scientific literature review, and computer wind tunnel simulation. The characteristics of the SBW are directly compared to those of the cantilever wing design to determine the advantages one might have over the other, and the impact the SBW might have on the environment if implemented. Results show that the SBW has a higher lift to drag ratio and is considerably lighter than the cantilever wing. This indicates that the SBW is a more efficient design, and would have a lesser impact on the environment than current passenger aircraft.

## Introduction

Man-made emissions released into the atmosphere have been blamed for the rapid climate temperature change and are detrimental to the environment in many other ways as well. It has been reported by researchers that the earth's average surface temperature has increased by 0.6 ºC during the 20th century and will likely increase between 1.8 and 5.8 ºC by the year 2100 (Jardine, 2005). Aviation's role in this pollution, although small compared to some other contributors, is still great enough to have attracted the attention of those within the industry.

Researchers have projected that aircraft emissions will more than triple by 2050, and that "unchecked, between 2016 and 2050 global aviation will generate an estimated 43 gigatonnes of carbon dioxide emissions"(Pardee, 2015). Alarming facts such as these have prompted aviation companies to make considerable efforts to reduce the impact of aviation on the environment in recent years. Another major cause for concern is that aircraft pollutants which are released at high altitude have a greater effect on the atmosphere than pollutants released at ground level (Jardine, 2005). Ultimately, it is undeniable that aviation plays a large role in contributing to the pollution of the earth's atmosphere, which is why efforts have been made to reduce the emissions that aircraft release.

Figure 1. This photograph shows one of Boeing's newest airliners, The 787 Dreamliner, which is an excellent example of a traditional cantilever aircraft which has been made more efficient through the use of lightweight composites and improvements in engine technology. (Johnsson, 2016).

The majority of improvements to commercial aircraft, whose large numbers make them the most significant polluter, involve the refining of many small aspects of design, as well as lighter construction and more efficient engines (Carrier, 2012). Carbon fiber has significantly improve the efficiency of new aircraft by largely reducing their weight. This is achievable now due to the development of composites, which allows the majority of the airframe to be built with new lightweight materials. One airliner which has benefited from these developments is the Boeing 787 Dreamliner, depicted in Figure 1. However, this aircraft still utilizes a traditional cantilever design, where the wings are left unsupported by external bracing. What aircraft designers now realize is that the cantilever design has been pushed to the limit of its potential efficiency. In other words, most significant breakthroughs that are aiding in the efficiency of the design are occurring in areas separate from the aerodynamic shape of the design and instead in areas such as composites or engines (Gern et al., 1999). New technologies are now the only thing significantly improving aircraft efficiency, and it has become evident that designing an entirely new style of airframe is necessary to achieve a large improvement in efficiency.

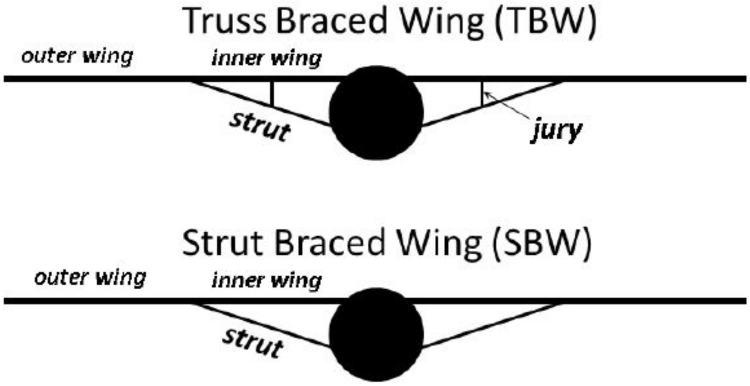

Figure 2. This diagram depicts the different components of both strut and truss-braced wings. On a cantilever wing, all of the components depicted would be missing except for one unsupported wing. (Zhao et al, 2014)

One aircraft concept, currently being developed by both NASA and Boeing for use on a passenger aircraft, is known as a strut-braced wing design (abbreviated as SBW), where a strut supports the wing and creates a stronger structure. Researchers have proposed a truss-braced wing design as well, where a strut is aided with another supporting member called a jury to increase the strength of the wing. The strut and jury can be used in many combinations making this design far more complicated to analyze. Furthermore, the truss-braced wing concept if not carefully designed can easily add enough drag to be detrimental to the efficiency of the aircraft (Bhaita, 2010). These designs can be seen in Figure 2. The complex nature of the truss-braced wing design has contributed to a greater emphasis on the SBW design, as its potential is more easily achievable. However, there are still many complex factors which play a role in the potential efficiency of the SBW design.

High aspect ratio wings are attainable through the SBW design, and are long, thin, and much more efficient than short and thick wings. Because less lift is wasted as high-pressure air spills out from underneath the wing, there are much smaller vertices which form off the wing tips, leading to less vortex drag. These wings are highly efficient and can be seen on sailplanes or other gliders that rely on their ability to conserve energy and lift to stay aloft. Additionally, the strut allows for the wing to have a decreased thickness to chord ratio, which reduces transonic wave drag (Zhang, 2012). All of these characteristics that can be achieved with an SBW lead aeronautical engineers to believe it could be more efficient than the designs currently used for passenger aircraft. However, there are some negative side effects to placing a strut underneath an aircraft's wing, one of which is the drag created by the strut itself. Drag created by the strut must be overcome by reductions elsewhere on the wing for a net reduction of drag to be achieved. Furthermore, reducing the vertical thickness of the wing while reducing drag also decreases lift. Therefore, it is critical that the thickness of the wing not be reduced to such an extent that the efficiency is negatively impacted. Despite these challenges which engineers face while designing an inherently complex SBW aircraft, the potential of a well-designed SBW aircraft could make the design a worthwhile investment for many large aviation-focused institutions.

The SBW concept is nothing new to aviation. Many small aircraft have used this design element before, such as the Cessna 172, Piper Cub, Hurel-Dubois HD.31 and others. The practical applications of the strut design have been well-proven on small aircraft, however, the design has never been implemented on the scale of a large modern airliner. Current research projects are taking place on SBWs to develop the design. One of these projects is the subsonic ultra-green aircraft research project, abbreviated as SUGAR, being conducted by Boenig and funded by NASA (Bradley, Droney, 2011). The SUGAR project has received help from both Virginia Polytechnic Institute and State University, and Georgia Institute of Technology, showing the large scale and potential for innovation from their research. A model of the SBW aircraft created by this study can be seen in Figure 3. Additionally, Virginia Tech has done a significant amount of research on SBWs independently and has made considerable progress of its own (Gern, et al., 1999). Another major research project conducted on the truss-braced wing is the ONERA project, which has developed an SBW design called the Albatross (Carrier, et al., 2012). Research projects such as these are important for determining the effectiveness of the SBW design. The complex nature of the design requires careful development and testing to ensure the wing is strong, efficient and handles well.

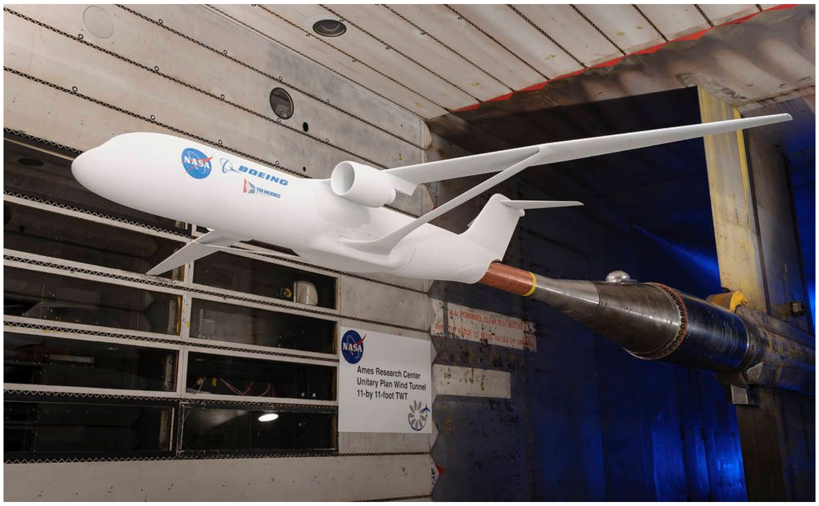

Figure 3. This photograph depicts a model of a strut-braced wing aircraft created by NASA in a wind tunnel ready for testing. This aircraft is part of their SUGAR program whose goal is to develop an environmentally friendly passenger aircraft (Retrieved from Hariharan, 2016)

## Purpose

The purpose of this research is to compare the efficiency of the cantilever wing design and the strut-braced wing design in order to determine the potential of implementing an SBW commercial aircraft with lower emission and smaller environmental impact than current cantilever wing designs.

## Research Question

Is it viable to implement a strut-braced wing design into a passenger aircraft in order to increase its efficiency and ultimately reduce the environmental impact of aviation?

## Hypothesis

The strut-braced wing will increase aircraft efficiency, reducing fuel consumption and lowering environmental impact.

## Methods

This theoretical research study was designed utilizing a mixed method which incorporated both systematic literature review as well as a computer wind tunnel simulation. These two methods were used in conjunction with one another in order to gain a more complete understanding of the cantilever and SBW designs which would not have been possible if only one method was used individually. Data from both methods were analyzed thoroughly to create a complete picture of the efficiency of each design. The systematic literature review was primarily used in order to understand aspects of the aircraft designs which could not be seen in the simulation, such as differences in weight and lift. The simulation provided data on drag, which was hard to come by in literature. In conjunction, these two methods allowed for a more thorough analysis of the relationship between an SBW and efficiency.

First, the computer wind tunnel simulation was done by creating models of aircraft using a CAD program called Fusion 360 (AutoDesk, 2018). One of these models was a control with a traditional cantilever wing. The aircraft model used as control was designed as closely to a Boeing 737-800 as possible. This aircraft was chosen as the control due to its simple design elements that could be easily replicated and because it is a popular passenger aircraft with more than 10,000 being built (Gates, 2018). When designing this aircraft special attention was given to the accuracy of the wings and their airfoil shape. A database of airfoil cross sections was used, and the 737-800 airfoil shape was copied exactly to Fusion 360. The other aircraft models were models of SBW aircraft with slight incremental changes to individual variables, such as wing length, width, vertical thickness, and sweep angle. All of the SBW aircraft have their wings shifted to the top of the fuselage, where the control aircraft has the wings at the bottom of the fuselage. This is because the Boeing 737 and most modern commercial cantilever airliners have the wings positioned at the bottom, and because all SBW aircraft must have the wings at the top of the plane to make room for the supporting struts. These models were analyzed with a wind tunnel computer simulation called Flow Design (AutoDesk, 2018). This simulator is able to show the air pressure differences across the aircraft, the airflow around the aircraft, the average drag coefficient, and a plot of the drag over time, all at constant wind velocities. All of these variables were recorded for every model. Then the results were graphed, and a comparison between the changes was made using a T-test to ensure statistical significance of the results.

Second, the systematic literature review involved the collection of articles from online databases, including Google Scholar, Research Gate, and EBSCOhost. Data was collected from these sources relating to the information not expressed through the results of the computer simulation. The focus of this aspect of research was to look for information relating to the weight, and lift, as well as to take into consideration the conclusions of those papers on the efficiency of the SBW design. Information on the design choices made by the researchers of these papers was considered when choosing what variables to test with the simulation as well. Papers were chosen for discussion in a number of ways. Primarily, the data had to have been collected by a reputable organization to ensure accuracy and reliability. Credible groups which had done research on this project include NASA, Boeing, and Virginia Tech. Consequently, a large amount of the useable data on this subject comes from those three institutions. Furthermore, the data had to be relevant to the focus of this paper, which as mentioned is the efficiency of the SBW. Many papers incorporated data necessary for their line of reasoning which was outside the scope of this paper. For instance, data regarding the strength of the SBW, lift distribution across the wing, and flight characteristics of the design, were mostly pertaining to that study's development of their optimized SBW model, and do not help to determine the efficiency of the design in comparison to that of traditional cantilever aircraft. Overall, great care was given to determining which studies and what data was reliable and relevant to the focus of this paper to ensure that a strong and trustworthy answer could be given to the research question.

## Results

Table 1. This table shows a comparison of the aspect ratios and weights associated with an optimized strut-braced aircraft and traditional cantilever aircraft, both designed in a study at Virginia Tech (Naghshineh-Pour, 1998).

| | Advanced Cantilever Wing | Optimized Strut-Braced Wing |
|---|---:|---:|
| Aspect ratio | 9.9 | 13 |
| Zero fuel weight (lbs) | 354,356 | 331,847 |
| Fuel weight (lbs) | 186,332 | 157,977 |
| Takeoff gross weight (lbs) | 540,689 | 489,826 |

The strut-braced aircraft shows weight reduction in every category while having a larger aspect ratio. These factors can ultimately be connected to lower fuel consumption.

Table 2. This table shows a comparison of the aspect ratio, lift to drag ratio, and weight between the Boeing 737-800, and the conceptual Boeing SUGAR SBW aircraft (Brady, n.d.) (Ouhib, 2014) (Wells, n.d.) (Boeing 737-800/900, n.d.).

| | Boeing 737-800 | Boeing SUGAR aircraft |
|---|---:|---:|
| Aspect Ratio | 9.45 | 19.55 |
| Empty Weight(lbs) | 90710 | 75600 |
| Lift/Drag Ratio | 17 | 24 |

The data for the SUGAR SBW aircraft comes from a wind tunnel test conducted by Boeing and NASA on a wind tunnel model of their design. The aspect ratio is much higher for the SBW while having a lower empty weight, and a higher lift to drag ratio.

The following tables and figures all contain the data collected through the computer wind tunnel simulation conducted specifically for this study using the programs Autocad Fusion 360 and Autodesk Flow Design (AutoDesk, 2018).

Table 3. This table shows the effects of changing sweep angle on the drag force and drag coefficient.

| Model | Sweep Angle | Average Coefficient | Average Force |
|---|---:|---:|---:|
| control cantilever | 25° | 0.17 | 15693.6 |
| strut control | 25° | 0.23 | 22515.8 |
| strut 1 | 20° | 0.21 | 20435.6 |
| strut 2 | 15° | 0.21 | 20568.4 |
| strut 3 | 10° | 0.23 | 22002.8 |

The model with both the lowest drag force and coefficient was the SBW model with 20° of sweep. The drag force and drag coefficient of this model were both greater than that of the cantilever aircraft.

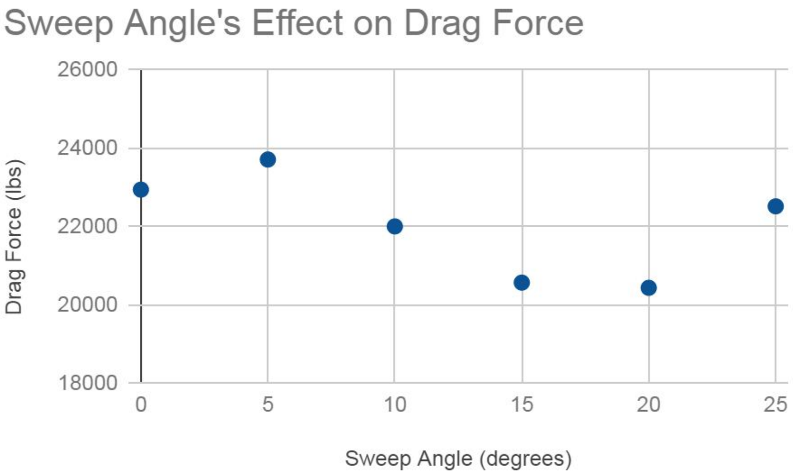

Figure 4. This figure shows the effect of changing the sweep angle on the drag force.

The model with the lowest drag force was the SBW model with 20° of sweep. The drag force of this model was greater than that of the cantilever aircraft.

Table 4. This table shows the effects of changing thickness on the drag force and drag coefficient.

| Model | Thickness | Average Coefficient | Average Force |
|---|---|---|---|
| control cantilever | 100% | 0.17 | 15693.6 |
| strut control | 100% | 0.23 | 22515.8 |
| strut 1 | 95% | 0.23 | 22486.4 |
| strut 2 | 90% | 0.21 | 19214.4 |
| strut 3 | 85% | 0.202 | 18518.2 |
| strut 4 | 80% | 0.19 | 16839 |
| strut 5 | 75% | 0.19 | 16635.6 |

The SBW model with both the lowest drag force and coefficient was the model with 75% of the original thickness. The drag force and drag coefficient of this model were both greater than that of the cantilever aircraft

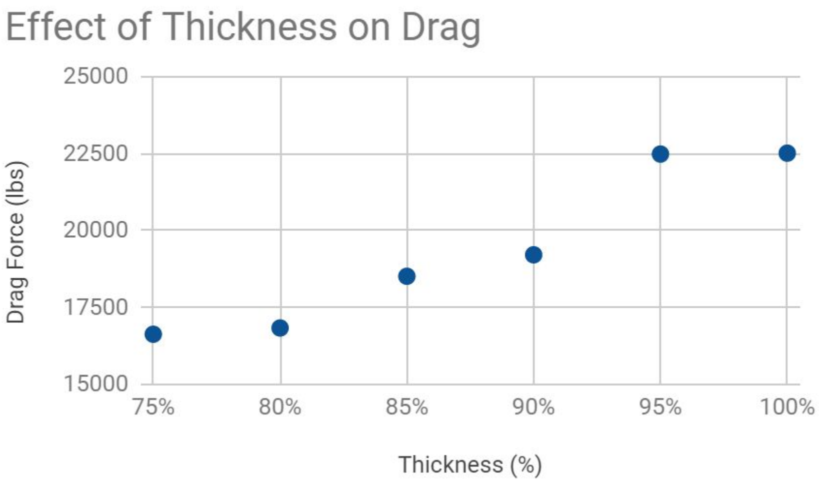

Figure 5. This figure shows the effect of changing thickness on the drag force.

The model with the lowest drag force was the SBW model with 75% of the original thickness. The drag force of this model was greater than that of the cantilever aircraft.

Table 5. This table shows the effects of increasing length on the drag force and drag coefficient.

| Model | Length increase | Average Coefficient | Average Force |
|---|---:|---:|---:|
| control cantilever | 0% | 0.17 | 15693.6 |
| strut control | 0% | 0.23 | 22515.8 |
| strut 1 | 5% | 0.21 | 20209.6 |
| strut 2 | 10% | 0.22 | 22195.6 |
| strut 3 | 15% | 0.24 | 24513.4 |
| strut 4 | 20% | 0.24 | 24104.6 |
| strut 5 | 30% | 0.22 | 23141.6 |

The SBW model with the lowest drag force and coefficient had a 5% increase in length; however, the length increase chosen for the optimized SBW was 30% since that model had comparable drag and likely offered more lift. Furthermore, most experimental SBW aircraft have length increases similar to 30%, and thus using this length increase would give a more accurate representation of what is currently being developed by other researchers.

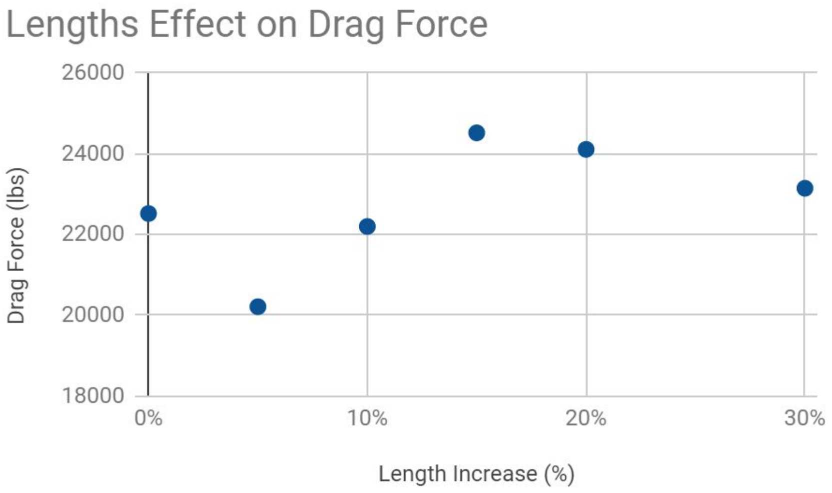

Figure 6. This figure shows the effect of increasing length on drag force.

An initial increase can be observed in the drag force between 5% and 15%, followed by a decrease in drag force between 15% and 30%.

Table 6. This table shows a comparison between the Control cantilever aircraft, control strut aircraft, and optimized strut aircraft.

| Model | Modification (made to the control cantilever) | Mean (drag coefficient) | Standard Deviation (drag coefficient) | Mean (drag force) | Standard Deviation (drag force) |
|---|---|---|---|---|---|
| Control cantilever | None | 0.17 | 0 | 15693.6 | 29.3 |
| Control strut | Strut added | 0.23 | 0 | 22515.8 | 58.3 |
| Optimized strut | Strut added<br>Thickness:75%<br>Length:130%<br>Sweep: 20° | 0.2 | 0 | 18265.2 | 18.91 |

The standard deviations of the drag coefficient are all 0 due to the limited variation of this value given by the simulator. The standard deviations of drag force are also fairly low, causing the high confidence level given by the T-tests. It can be concluded that the optimized strut has statistically less drag than control strut because the p-value of 4x10^-10 is less than .05. It can also be determined that the optimized strut has more drag than the control cantilever statistically because the p-value of 1.4x10^-13 is less than .05.

## Discussion

To begin, an equation is needed in order to determine how a specific variable will affect efficiency. The Breguet range equation, depicted in Figure 7, factors in lift, drag, weight, and other variables, to determine the range of an aircraft. This equation is useful for determining the efficiency of an aircraft because an efficient aircraft is one that can travel a great distance on a given amount of fuel. Ultimately, this can be related to environmental impact because “reducing the overall amount of fuel consumed for a given flight profile by improved configuration design will also reduce the total amount of emissions” released on that flight (Gern et al, 1999). Therefore, if a certain changed variable can be proven to improve range through the Breguet range equation, that changed variable will also reduce the environmental impact of the aircraft. The Breguet range equation relates higher lift, lower drag, and lower weight to improved range, meaning all those changes result in an aircraft having a lower environmental impact.

$$R = (v/c_j)(L/D)\ln(W_i/W_f)$$

where:

| | |
|---|---|
| $c_j$ | is the thrust specific fuel consumption (TSFC) |
| $(L/D)$ | is the Lift-to-Drag ratio |
| $W_i$ | is the initial airplane weight |
| $W_f$ | is the final airplane weight (aftere fuel burn) |

Figure 7. This image depicts the Breguet range equation, which considers engine efficiency, lift, drag, and weight, to determine the range of an aircraft (Aircraft Performance - Part 2 - Basic Calculations, 2015).

To continue, three variables were tested individually on multiple models to determine the most beneficial and likely option to incorporate into the optimized SBW model whose drag could be directly compared to the cantilever model. Sweep angle was the first of those variables tested. Six models had sweep angles varying from 25° to 0°. The models with the smallest drag coefficient of .21, as depicted in Table 3, had sweep angles of 20° and 15°. However, the model with the lowest drag force, as evident in Figure 4, was the model with the sweep angle of 20°. Thus, the sweep angle of 20° was implemented onto the optimized SBW model. Although the drag reduction created by the change in sweep angle was not enough to overcome the drag added by the supporting strut, as the drag of the SBW model with the sweep of 20° still had a drag force 4,742 lbs more than that of the cantilever model, its combination with other aerodynamic improvements could result in a net reduction in drag force.

The second variable tested was the vertical thickness of the wing. As depicted in Figure 5, there is a fairly linear correlation between the thickness of the wing and drag. The model with the lowest drag had a thickness of 75% of the thickness of the cantilever aircraft. The transonic wave drag created by the wing is reduced as the thickness decreases. Reducing thickness, however, also reduces the lift created by the wing as there is less of a pressure difference between the air at the top and bottom of the wing. This means that this lost lift will need to be supplemented by an increase in lift caused by a change to another aspect of the design. The length increase of the SBW is most likely where this lift is made up. Ultimately, the thickness of 75% of that of both control models was chosen for the optimized SBW model because it had the lowest drag force and drag coefficient.

The third variable tested was the wing length. What can be observed initially in Figure 6 is the steady increase in drag force with length between the 5% and 15% length increases. After 15% the drag force slowly drops as length increases. This is most likely due to a reduction of the size of the wingtip vortices which lowered drag significantly enough to overcome the drag from a larger wing. Vortex drag is the drag created by the vortices on the wingtip of a plane, and "accounts for a large fraction of airplane cruise drag (typically about 40%)." Additionally, this drag "is even more significant at low speeds where vortex drag typically accounts for 80%-90% of the aircraft's climb drag at critical take-off conditions"(Kroo, 2005). Despite the large part vortex drag plays on the overall drag of the aircraft, the wingtip vortices were not reduced enough to completely overcome the drag created by the increased length or the addition of the strut. This is in contradiction to most current studies which correlate increased length to reduced drag. For instance, researchers found that "if the span is increased by 20%, the induced drag can be reduced by about 31.3%"(Zhang 2012). The results of this simulation may vary from those of other studies because the wind tunnel simulator used might not place as large an emphasis on the drag created by wingtip vortices. Ultimately, the length increase chosen to be implemented on the optimized model was 30%. Despite this model not having the lowest drag force or drag coefficient, there are a couple of reasons why this was the most appropriate length increase to choose. Primarily, most studies which have designed their own SBW for testing have chosen a similar length increase, including the SUGAR aircraft, as well as the Albatros aircraft. It is crucial that the aircraft tested for drag is similar to those which are supplying data on lift and weight in order to draw an accurate conclusion on the efficiency of the SBW design. Furthermore, benefits such as higher lift, which can not be seen with this wind tunnel simulator, might contribute to this design choice being more efficient than the smaller length increase of 5% which had the lowest drag. The higher lift of a larger increase in length is probably the reason most other studies have chosen a length increase similar to 30%.

The final aspect of the computer simulation was the testing of an optimized SBW and to directly compare it with the control cantilever aircraft. The characteristics implemented on the optimized SBW model were a vertical thickness of 75% the control's, a length of 130% the control's, and a sweep of 20°. As seen in Table 6, the optimized SBW has less drag than the control SBW. A T-test was conducted to confirm this. The alternative hypothesis for this test was that the optimized SBW has less drag than the control SBW, and the null was that the optimized SBW had no change in drag. Because the p-value of 4x10^-10 is considerably less than .05, the alternative hypothesis can be accepted with a high degree of confidence. This shows that the design changes made did in fact reduce the drag of the control SBW. However, the optimized SBW can also be seen to have more drag than the cantilever aircraft. Another T-test was conducted comparing the drag forces of these two models. The alternative for this test was that the optimized SBW had more drag, and the null was that the optimized SBW had no change in drag. Because the p-value is 1.4x10^-13 which is considerably less than .05, the null can be rejected and the alternative can be accepted with a high degree of confidence. The T-tests yield very high confidence levels and very definitive results due to the standard deviations of drag force being relatively low. What the simulation has thus shown, is that drag created by the struts which support the wing is too great to be overcome by reductions in drag caused by the other changes made to the wing shape. Therefore, because the SBW causes higher drag, the lift or weight variables must be significantly improved by the design in order to have a net improvement in efficiency.

As discussed, weight is a contributing factor to the efficiency of an aircraft. As seen in the Breguet range equation depicted in Figure 7, overall lower weight will improve the range, and therefore the efficiency of an aircraft. In Table 2, which shows a comparison between the SUGAR SBW aircraft and the Boeing 787-800, it can be seen that the SUGAR SBW aircraft has a much lower weight than the cantilever 787-800. The lower weight of the SBW aircraft would help to improve the overall efficiency of that plane. Similarly, as seen in Table 1, the SBW created by Virginia Tech has a lower zero fuel weight, fuel weight, and takeoff gross weight, than that of the cantilever aircraft from the same study. This means that their SBW design had a lighter airframe that its cantilever winged counterpart, which contributes to improved efficiency. The lower fuel weight also indicates that less fuel would be needed by the SBW aircraft for a flight of the same distance, which correlates directly to being more efficient and having a lower impact on the environment. Overall, it can be observed that the SBW design is lighter than the cantilever design which increases the range and efficiency of the design.

Lastly, lift plays an important role in the range and efficiency of a design. According to the Breguet range equation, as depicted in Figure 7, higher lift increases efficiency. Because of the high aspect ratio of the SBW, it is capable of producing high amounts of lift. The high aspect ratio of the SBW can be seen in both Table 1 and Table 2. In Table 1 the aspect ratio of the SBW is 13, while the cantilever wing is 9.9. In Table 2 the gap is even greater, as the SBW has an aspect ratio of 19.55, and the cantilever wing has a ratio of 9.45. The high aspect ratio of the SBW reduces the amount of lift which is lost to wingtip vortices. As seen in Table 2, the SUGAR SBW has a lift to drag ratio of 24, while the Boeing 787-800 has one of only 17. A higher lift to drag ratio means there is more lift, or that there is less drag. Because, the simulation discussed earlier has confirmed that there is more drag on the SBW design, the higher lift to drag ratio means there is a significant improvement in lift created by the plane. Because the lift is increased by a higher amount than the drag, the lift to drag ratio is increased. Overall, this means that there is higher lift for the SBW design than the cantilever design, which will increase both efficiency and range.

In review, it has been shown that the SBW design has a higher lift, lower weight, and higher drag than the cantilever aircraft. The characteristics of higher lift and lower weight, both improve range and efficiency according to the Breguet range equation. However, the higher drag reduces efficiency. When analyzing all of these variables at once, to determine the overall impact of the SBW on efficiency, it is important to look at the lift to drag ratios of each design. The higher lift to drag ratio of the SBW as shown by Table 2 indicates that the benefits of improvement in lift outweigh the detriment of increased drag.

## Limitations

One major limitation to this study was the quality of both the computer simulator used and the computer which operated it. Lower simulation resolutions were needed to run the tests at reasonable speeds and within the given timeframe of this investigation. This may have resulted in data which is not completely accurate. However, the simulation ran to a high enough degree that the general trends could be determined definitively, which is all that was necessary for the simulation data to contribute to the discussion.

Another limiting factor is that many of the papers and all of the different organizations which discuss this topic use different SBW models for testing. This made it difficult to compile the data from large amounts of papers as different variables were tested for in each study, and data varied from study to study due to them being conducted with different parameters. For this reason, two papers which were representative of the research done by the entire community were chosen for the focus of the discussion, as it would be impossible to discuss the data from all papers on this topic in the given time frame.

## Conclusion

In review, it has been shown that the SBW design has a higher lift, lower weight, and higher drag, than the cantilever aircraft. The characteristics of higher lift and lower weight, both improve range and efficiency according to the Breguet range equation. However, the higher drag reduces efficiency. When analyzing all of these variables at once, to determine the overall impact of the SBW on efficiency, it is important to look at the lift to drag ratios of each design. The higher lift to drag ratio of the SBW as shown by Table 2 indicates that the benefits of improvement in lift outweigh the detriment of increased drag. This improvement in efficiency is only bolstered by the reductions in weight discussed earlier which would only contribute to higher efficiency for the SBW. Therefore, the hypothesis that the SBW design will improve the efficiency of an aircraft can be accepted.

Other papers have come to similar conclusions with a 30% reduction in fuel burn being estimated for the SBW design (Bhatia et al., 2009). Lower fuel consumption would also result in fewer emissions being released, minimizing the environmental impact of aviation. Infact, replacing a quarter of airliners with a SBW aircraft of that efficiency would reduce $CO_2$ emissions between 2016 and 2050 by roughly 3.2 gigatons (Pardee, 2015). The SBW design is ultimately capable of preventing large amounts of pollutants like $CO_2$ from entering the atmosphere. $N_2O$, is another chemical released by aircraft which is harmful to the earth's atmosphere which could be limited by the implementation of an SBW aircraft (Lim, et al., 2015). Preventing chemicals such as these from being released into the atmosphere, is an important step for preserving the environment for future generations. Furthermore, reducing fuel consumption reduces the cost of operation for airliners, as less money is spent on fuel. In 2018, U.S. airlines consumed 17,869.4 million gallons of fuel during domestic and international flights, costing 38,483.0 million dollars, and showing the importance of fuel efficiency to an airline (Airline Fuel Cost and Consumption, 2019). This also adds incentive for airlines to purchase a SBW design, as it could potentially make their business more profitable. Overall, the fuel reductions SBW aircraft are capable of, could help to preserve the environment, while also benefiting the airlines who use them with lower operating costs.

In the final analysis, it can be seen that there are significant advantages to strut-braced wings over the traditional cantilever design. The potential implementation of the SBW could mean a large reduction in the harmful emissions released into the atmosphere each year. The research currently being done by Boeing and NASA are profound steps toward this goal and could one day lead to the production of an actual SBW airliner. Of course, this hypothetical aircraft's efficiency would also be assisted by the advancements in propulsion and composites; however, the major breakthrough which would set it apart from the rest would be its unique and innovative SBW design. Ultimately, it is important to continue the advancement of aircraft technology and design because current technologies are too destructive to be left unchanged. The efforts being made to design and implement an SBW are significant in that their purpose is not solely to allow corporations to gain wealth, but more importantly to help preserve the planet for future generations.

## Further Work

Ultimately, there is much more work that needs to be done to determine the feasibility of an SBW passenger aircraft. This paper focused only on basic aspects of each design, such as the fundamental aerodynamic characteristics lift and drag, as well as the weight. Further work, would expand on this knowledge by examining the structural abilities and flight characteristics of the SBW design. These aspects are immensely important to the success of an SBW passenger aircraft. Knowing the strength of the SBW allows designers to push the limits of the design to ensure maximum efficiency, as well as complete safety, in all flying conditions. Similarly, knowing how such a high aspect ratio wing would handle during flight is crucial to the design of the aircraft to ensure the pilot can safely maneuver the plane in a wide variety of weather conditions. Knowledge of these aspects of the design are necessary for the eventual implementation of the design into commercial airliners, and thus are an important area of study. However, these aspects were not part of the focus of this study because they are not required to determine the potential of the design for high-efficiency flight.

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