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Evaluation of Sustainable Transonic Truss-Braced Wing Aircraft Configurations Using Liquid Hydrogen Fuel

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Abstract

There is pressing need for increase in efficiency and reductions in greenhouse gas (GHG) emissions for the next generation commercial passenger aircraft in order to reduce the environmental impact of the aviation industry. The focus of this work is on the design considerations for a mid-range single aisle commercial aircraft using liquid hydrogen for propulsion. A matrix of aircraft configurations is considered with varying size of fuel tanks placed external or internal to the fuselage. In particular, an aircraft configuration with a high aspect ratio truss braced wing is investigated to improve lift and range in comparison to a more traditional cantilever wing. The tradeoff between the tanks placed inside and outside is evaluated by considering their effect on the aircraft performance. Aircraft performance is assessed using the aircraft design and analysis tool RDSWin in conjunction with aerodynamics, propulsion, and weight estimation methods. Design and drag optimization of external liquid hydrogen (LH2) fuel tanks is achieved using a MATLAB code. The aircraft performance analysis shows that internal LH2 tanks are a better choice compared to external tanks due to additional drag added by the external tanks.

Introduction

The increasing concentration of greenhouse gases (GHG) such as carbon dioxide (CO_2) in the troposphere contributes to climate change and increase in warming of the earth that will have a multitude of adverse effects on human life and environment. Other aviation emissions such as soot, nitrogen oxide and contrail formation also contribute to the climate change [1]. Net warming of the Earth's surface will result in ocean rise resulting in coastal flooding and saltwater intrusion as well as extreme weather events ranging from hurricanes to wildfires that pose a threat to the global ecosystem, human lives and property [2]. In recent decades (1960-2018), CO_2 emissions from the aviation sector grew primarily as a result of increased passenger demands for travel from 109 to 8269 billion km/year [1]. In order to reduce the environmental impact of the aviation industry, there is need for reduction in emissions and an increase in efficiency for the next generation commercial passenger aircraft. This can be achieved through investigation of sustainable fuels, increases in aerodynamic and propulsive efficiency as well as structural and material developments to reduce aircraft weight. This is reflected in the Breguet range equation which is a key tool for the design of aircraft.

$$Range = \frac{h_f}{g}\frac{L}{D}\eta_{overall}\ln\left(\frac{W_{initial}}{W_{final}}\right) \tag{1}$$

According to Eq. (1), the energy density (h_f) of the fuel carried and burned in the propulsion system of aircraft is the dominant factor in determining the aircraft range. However, increase in aerodynamic efficiency by improvement in lift generation and minimization of drag can also contribute to greater aircraft range. In addition, the propulsive efficiency can also be improved through reductions in thrust-specific fuel consumption (TSFC). Lastly the weight of the aircraft

has an impact on the efficiency in terms of achievable range for a given fuel load. Many studies into advance composite materials are being conducted in order to reduce the weight of aircraft structures. The focus of this study is primarily on various types of fuels that can be used to reduce especially the carbon emissions as well as on the aerodynamic efficiency of the truss-braced wing design.

Alternative Fuel Candidates

With Jet A fuel as baseline industry standard, fuels such as Sustainable Aviation Fuels (SAF), hydrogen and ammonia have the potential to reduce GHG emissions from aviation, primarily the net carbon emissions. Although SAF does not directly eliminate the carbon emissions, it indirectly reduces the carbon emissions since it is produced from agriculture crops (non-edible). It is also a drop-in fuel for existing aircraft engines. However, it does not provide long term solution for zero-emission aviation. It can therefore be considered as a transitional fuel before zero emissions goal is achieved. In the meantime, the aviation industry is also exploring the potential and technological challenges of alternative fuels such as LH_2, NH_3 and BH_3NH_3 (Ammonia-Borane). This paper examines the potential of LH_2. The combustion of hydrogen gas yields an exhaust of water vapor and has heat of combustion of ~ 142 MJ/kg.

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$$

Implementation of liquid hydrogen fuel in an aircraft is ideal from green aviation perspective; however, it poses multiple aircraft design challenges. A comparison of properties of various types of fuels is shown in Table 1.

Table 1: Comparison of properties of various types of fuels.

	Jet A	SAF	Liquid Hydrogen	Ammonia
Density (lbs./ft^3)	~ 48.38-52.44	---	4.432	42.57
Energy Density (Btu/ft^3)	1,009,870.13	---	214,714	48,900
Heat of Combustion (MJ/kg)	42-46	42-46	141.8	22.5
Boiling Point (F)	~ 349	---	- 432.2	- 28.01

It can be noted from Table 1 that liquid hydrogen has significantly higher energy density and heat of combustion in comparison to Jet A, SAF and Ammonia. The higher energy density per unit mass is beneficial to the range and efficiency of the aircraft. Figure 1 shows the payload and range comparison for the Boeing 737-800 without winglets during long range cruise [3]. It can be seen that for a heavy weight configuration with a maximum take-off gross weight (TOGW) of 174,200 lbs. and an operating empty weight (OEW) of 91,300 lbs. Jet A fuel load of 46,063 lbs. is required to achieve a range of 2840 NM. Based on the heat of combustion, the 46,063 lbs. of Jet A in 737-800 can be replaced by 14,293 lbs. of hydrogen or 90,079 lbs. of ammonia.

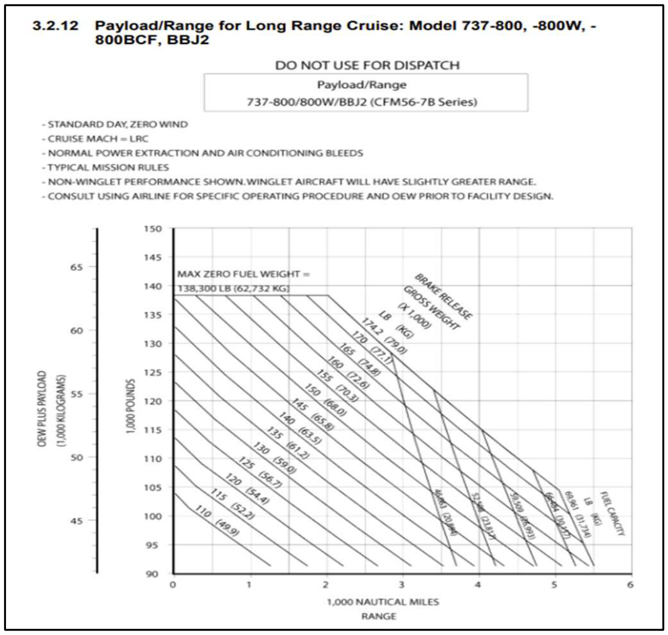


Figure 1: Payload and Range Comparison for 737-800 Aircraft [3]

Liquid hydrogen has nearly four times lower volumetric energy density in comparison to Jet A. This presents a significant problem for aircraft designers since the standard space in airliner wing boxes for fuel storage is not sufficient to accommodate the volume of liquid hydrogen with equivalent energy to that of traditional Jet A. A variety of solutions are being proposed by various research groups to design aircraft with large hydrogen fuel tanks. For example, the Airbus Zeroe turbofan concept has a liquid hydrogen storage system behind the pressure bulkhead in the rear of the aircraft. The present study investigates the aerodynamic effects of the location of the fuel tank – inside or outside the fuselage. Several configurations are analyzed using internal tanks, external wing mounted tanks, and a combination of the two. External wing mounted tanks increase the overall drag of the vehicle and require design changes for possible wheels up landing conditions.

External Tank Design

The aerodynamic design of the external tanks was done using a MATLAB code to optimize the tank shape for drag reduction. The code finds the minimum of a constrained nonlinear multivariable function; in the present case Hoerner's empirical correlation for the drag coefficient of bodies of revolution is employed [4].

$$C_{DV} = Re^{-\frac{1}{6}} * \left\{0.172 * \left(\frac{Length}{Diameter}\right)^{\frac{1}{3}} + 0.252 * \left(\frac{Diameter}{Length}\right)^{\frac{6}{5}} + 1.032 * \left(\frac{Diameter}{Length}\right)^{\frac{27}{10}}\right\} \tag{2}$$

A series of variables is used to define the geometry of the tank in a two-dimensional coordinate system. The length, diameter, volume, location of maximum diameter, nose and tail curvature and prismatic coefficient are set as variables with a combination of linear and nonlinear inequality constraints [5]. The leading edge radius is limited in order to mitigate risk of damage due to bird strike by improving probability of a glancing blow. The tanks are optimized for the cruise conditions of an aircraft flying at Mach 0.8 at an altitude of 35,000 ft. The curves generated by the

code, shown in Figure 2, can then be outputted, and included in a CAD package to create the three-dimensional tank geometries to be implemented in RDSWin. Figure 2 shows the tank geometries generated by the optimization code for three different fuel loads. The MATLAB code also has a function to account for the addition of internal tanks that could be potentially used in future designs to reduce external tank volume in a hybrid configuration. Figure 3 shows the correlation between the external tank volume and parasite drag. A linear trend is seen in the data points with an increase in drag with higher volume of external fuel tanks. Interference drag between the external tanks and the wing is later accounted for using RDSWin with an assumed interference factor of 1.5. The code is also used to calculate the weight of the fuel tank structures assuming an aluminum outer skin with a thickness of 0.05 in, inner skin with a thickness of 0.07 in and an EPS insulation layer of 4.5 in thickness. Due to its low boiling point, liquid hydrogen must be maintained in a cryogenic state with sufficient insulation to mitigate boiloff (evaporation) resulting in pressure buildup and eventually damage to the tank structures including the possibility of rupture. Approximately 4.5 inches of EPS foam is sufficient to minimize boiloff in the external hydrogen tanks. The structural weight is calculated from the volume of the materials and their respective densities. Furthermore, the MATLAB code accounts for the weight of longerons and bulkheads within the external fuel tanks. The external tanks pylons are assumed to have 20% weight of the external fuel tank structural weight. Figure 4 shows the total external fuel tank weights (fuel, structural weight, and pylons) in relation to total volume of the tank. A number of tanks with different volumes were tested and three cases were then implemented into RDSwin to evaluate the influence of the tanks on aircraft performance. The fuel tank properties for the three chosen tanks are tabulated in Table 2.

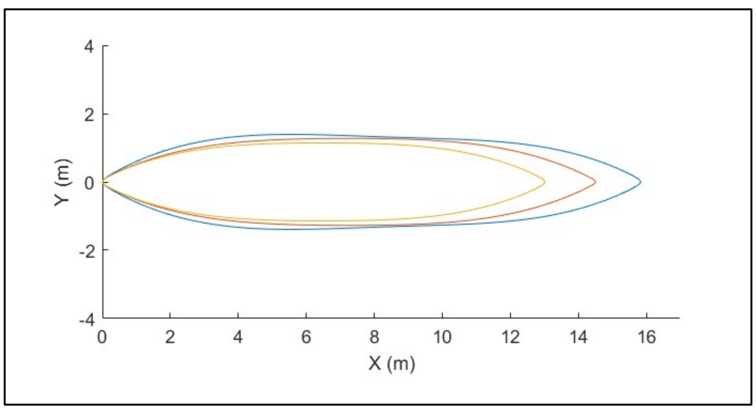


Figure 2: MATLAB code generated three external fuel tank geometries.

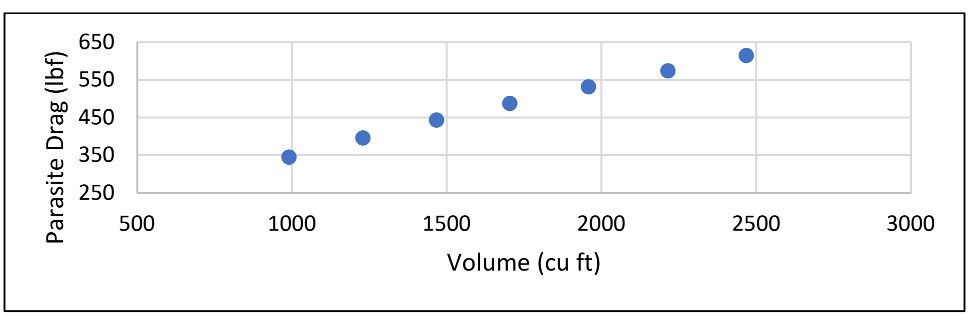


Figure 3: Parasite drag of fuel tanks of varying volume.

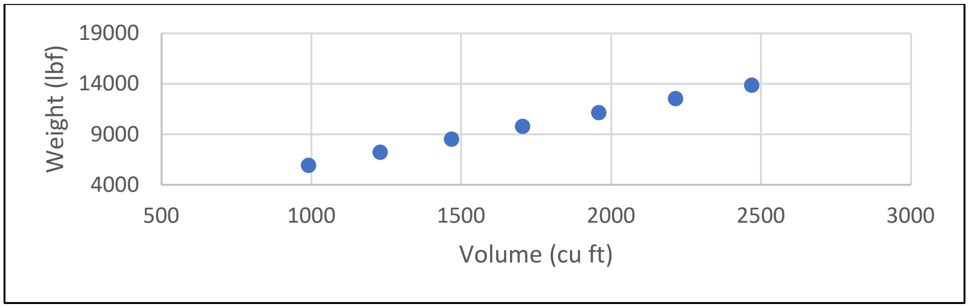


Figure 4: Total weight of fuel tanks of varying volume.

Table 2: Fuel tank design matrix

Fuel Tank	Length (ft)	Effective Diameter (ft.)	Volume (cu ft.)	Fuel Weight (lbf.)	Structural Weight (lbf.)	Parasite Drag (lbf.)
1	51.95	9.14	2215.38	9818.56	2930.61	574.50
2	47.61	8.38	1704.53	7554.49	2462.34	487.42
3	42.72	7.5	1229.83	5450.60	2002.09	396.40

Design Configurations

In this study, the 737- 800 was chosen as the baseline aircraft for a single isle mid-range aircraft. Figure 5a shows a model of the 737-800 recreated using the RDSwin software with a cantilever wing and wing mounted engines. This is compared to a configuration with the same 737-800 fuselage and wings converted to use external hydrogen tanks rather than Jet A stored in the wing boxes. The hydrogen powered configuration shown in Figure 5b. has external tanks mounted on the wings. For each case with wing mounted fuel tanks, the engines were shifted to the aft portion of the aircraft fuselage. This is beneficial because it reduces wing loading and improves the overall safety of the aircraft by minimizing the risk of damage to the fuel tanks caused by engine failure. A T-tail was also created for the hydrogen powered 737-800 to account for the shift in engine position. The other two configurations investigated swap the traditional cantilever wing for a truss braced wing. Boeing and NASA have been studying the truss braced wing concept as part of the Subsonic Ultra Green Aircraft Research (SUGAR) program aimed at reducing noise and emissions while improving aircraft performance. In Phase IV of the project, a transonic truss braced wing (TTBW) concept was investigated with a cruise Mach number of 0.80 [6]. The TTBW has high aspect ratio (~19.23) and span of 170 ft and can improve lift and vehicle performance in comparison to standard cantilever wings. This large span is supported by a truss and requires a wing fold similar to that of a Boeing 777X to improve airport gate accessibility. In this study, multiple aircraft configurations are investigated using a TTBW based on the SUGAR IV concept with varying fuselage and fuel tank designs. The hydrogen powered 737-800 configuration was modified by replacing the wing with the truss braced concept as shown in Figure 5c. Three different external tanks sizes were tested on both external tank configurations. The last model shown in Figure 5d also uses the truss braced wing, but has a larger fuselage comparable to a 767 to incorporate internal fuel tanks. The main capped cylinder tank is located at the rear of the aircraft behind the bulkhead while subsidiary smaller fuel tanks are located in the ceiling of the aircraft; the two models are further evaluated to compare the aerodynamic efficiency of internal vs. external fuel tanks.

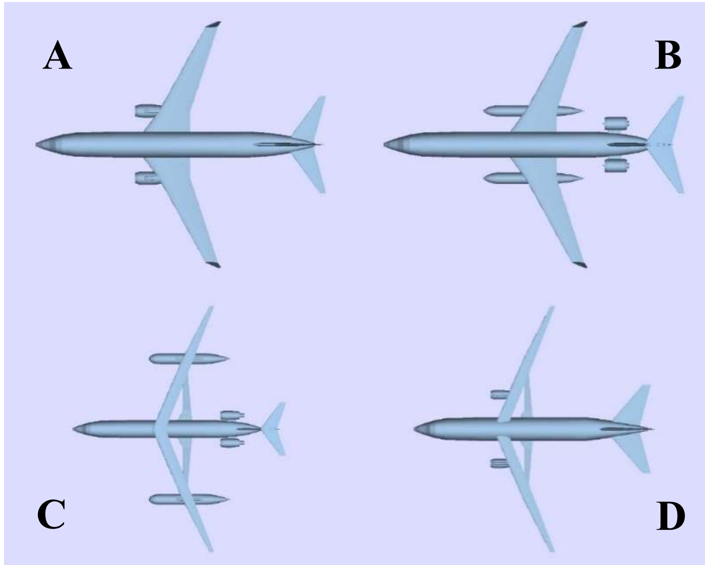


Figure 5: RDSwin designed models of the four aircraft configurations; 5a Jet A 737-800; 5b LH2 737-800 with external fuel tanks; 5c LH2 737-800 TTBW with external fuel tanks; 5d LH2 767 TTBW with internal fuel tanks

Aircraft Analysis with RDSwin

The initial design phase uses the aircraft design and analysis tool RDSwin to evaluate the aerodynamics, propulsion, weights, and sizing to a mission profile and performance. The weight estimation method of Daniel Raymer [7], Jan Roskam [8], Egbert Torenbeek [9] and the NASA Flight Optimization System [10] were used to get a weight average of the empty weight of the various aircraft configurations. These weight calculation methods account for the propulsion system, structures and subsystem components like landing gear and controls systems. An estimation of a CFM56-7B24 engine deck is implemented assuming similar thrust between Jet A and liquid hydrogen. The thrust specific fuel consumption for a hydrogen burning engine is obtained from the Jet A using the difference in heat content. Figure 6 shows a schematic of the mission profile utilized in RDSwin along with the fuel reserve requirements implemented across all four configurations [11].

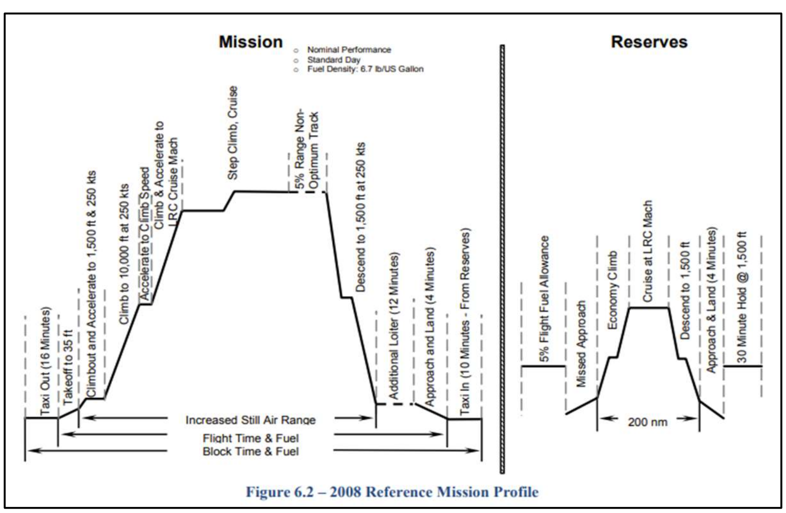


Figure 6: Mid-range single isle aircraft reference mission profile [11].

A summary of the aircraft performance results generated in RDSwin is shown in Table 3. The baseline 737-800 configuration was used for validation by matching the payload and range comparison chart shown in Figure 1. The hydrogen configurations show a drastic decrease in the required fuel weight required to travel a similar range to the 737-800 using Jet A. This is however partially offset by an increase in drag due to greater volume and surface area required for tanks. Due to the minimal increase in structural tank weight with the increase in tank volume for the three different external tank designs, the long range cases with greater fuel volume have better specific ranges for the hydrogen powered 737-800 and hydrogen powered 737-800 with TTBW. With similar fuel volumes used, it can be seen that the increased span and aspect ratio of the TTBW as well as weight savings improves the performance of the aircraft. Current work most likely underpredicts the effectiveness of the TTBW concept as the 737-800 airfoil is implemented across all four designs. Design and optimization of an airfoil for the TTBW configurations would show further increase in its range capabilities. As a results of reduce drag, the hydrogen powered TTBW 767 configuration performed best across all three test cases. The 767 has the best potential to be improved in future work by modification and optimization of the fuselage in conjunction with the internal tank shapes to reduce drag and weight.

Table 3: Aircraft Performance Comparison

	737-800 Jet A	**737-800 LH2**			**737-800 TTBW LH2**			**767 TTBW LH2**		
Fuel Weight (lb)	46067.8	10901	15109	19637.1	10901	15109	19637.1	10901	15109	19637.1
Range (NM)	2836.9	1477.5	2145.1	2934	1488.3	2349.7	3304.3	1585.9	2485.9	3426.1

Further analysis was done by evaluating the flight envelopes and specific ranges of the four aircraft. This was done for the Jet A 737-800 as well as the three hydrogen powered aircraft for the 15109 lb. fuel weight case. Figure 7 shows the flight envelope for the Jet A 737-800 with the expected flight ceiling approaching 41,000 ft. The increased drag caused by the external tanks reduces the service ceiling due to the 300 fpm rate of climb limitation at the service ceiling as shown in Figs. 8 and 9. The flight envelope of the 767 provided in Figure 10 shows its potential to reach a similar service ceiling to that of the baseline Jet A 737-800.

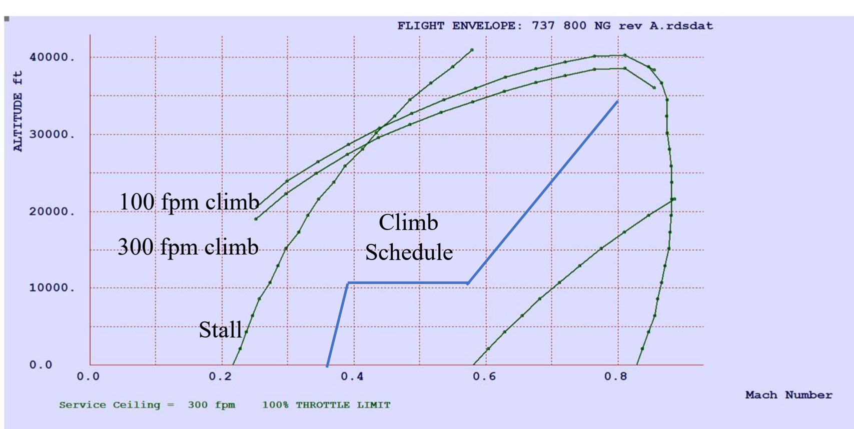


Figure 7: 737-800 Jet A flight envelope.

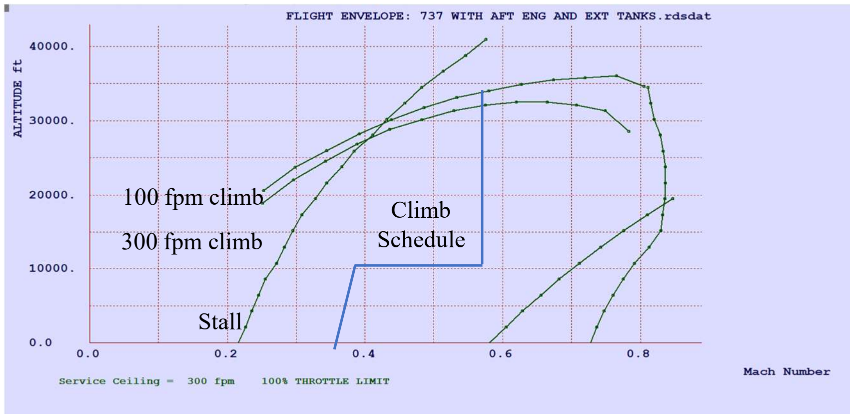


Figure 8: 737-800 LH2 flight envelope.

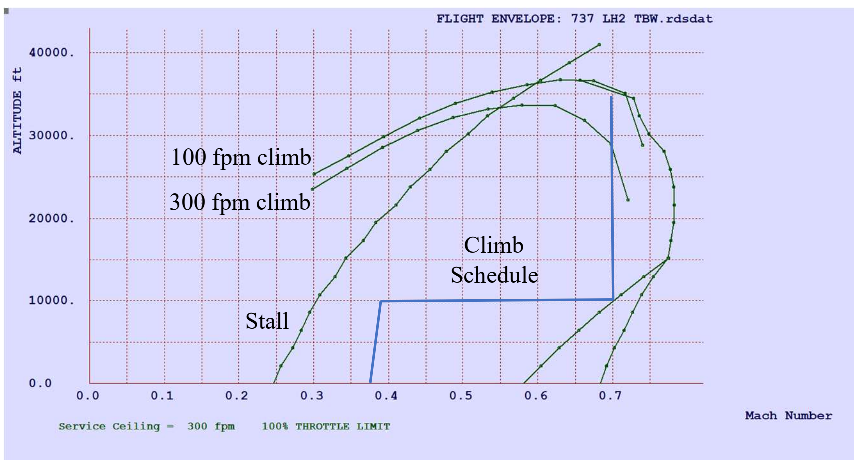


Figure 9: 737-800 LH2 TTBW flight envelope.

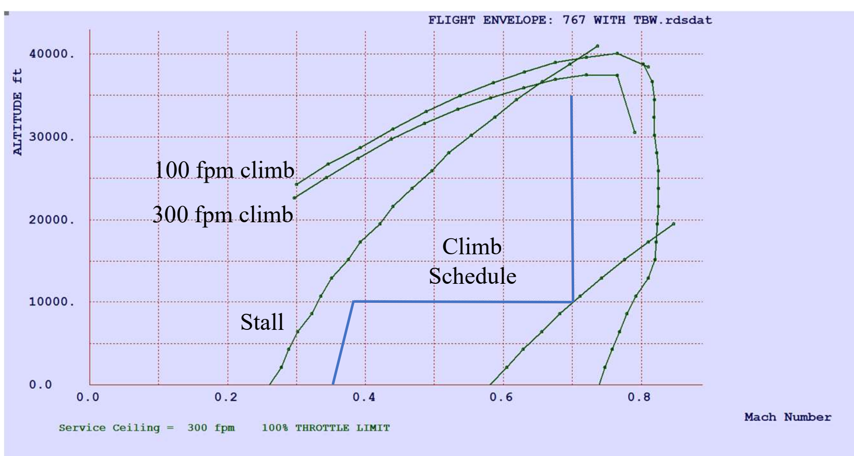


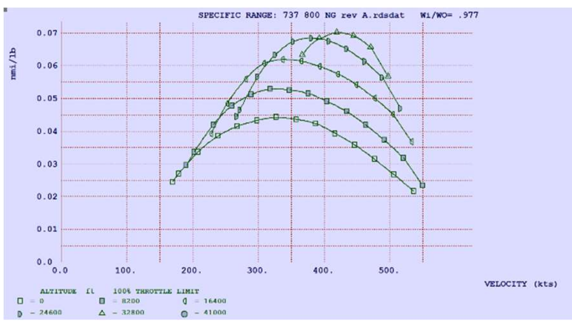
Figure 10: 767 TTBW LH2 flight envelope.

The cruise speed calculated by RDSwin is shown in Table 4. Due to variations in lift and drag caused by aerodynamic components and external tanks, the flight envelope and cruise speed varies across the design configurations. The cruise speed is limited for the 737-800 with LH2 external

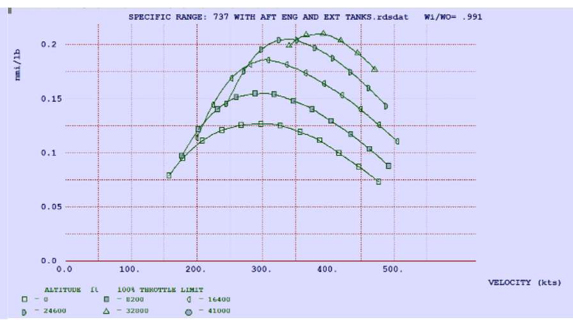
tanks due to the high drag relative to the engine thrust. These values are important for interpreting the plots of specific range. Figure 11 shows the plots of specific range with respect to velocity for the four aircraft. For each case the specific fuel consumption was calculated at the cruise condition using the ratio of the aircraft weight after climb to the TOGW. The Jet A 737-800 aircraft is shown to have a significantly higher specific fuel consumption. The truss braced wing (TTBW) aircraft is shown to improve the specific fuel consumption in comparison to the traditional cantilever wing for the hydrogen powered case. The 767 configuration with all internal tanks yielded the best specific fuel consumption among the all four concepts.

Table 4: Aircraft cruise speeds.

	737-800 Jet A	737-800 LH2	737-800 TTBW LH2	767 TTBW LH2
Cruise Speed (kts)	461.1	322.6	405.2	401.7

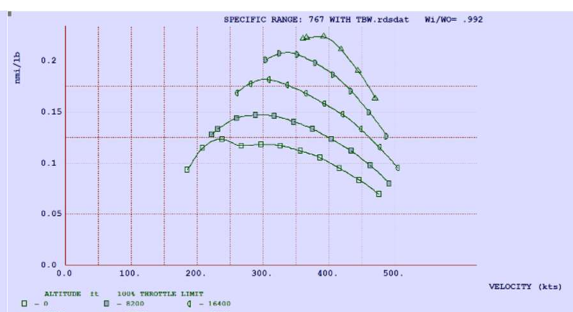


a.) 737-800 Jet A



b.) 737-800 LH2

c.) 737-800 LH2 TTBW



d.) 767 TTBW LH2

Figure 11: Specific range plots for the four aircraft configurations

Conclusions

The analysis presented in this paper provides the groundwork for further development of a hydrogen powered aircraft configuration based on a transonic truss braced wing (TTBW). It is shown that the internal LH2 tanks provide the best aerodynamic performance in comparison to external LH2 tanks mounted on the wing considering the specific range. Future work will focus on the use of higher fidelity analysis tools such as the vortex lattice method or computational fluid dynamics codes for optimization of the truss braced wing concept by focusing on the airfoil shape, aspect ratio and influence of the truss on lift generation. The TTBW can also provide the necessary ground clearance for future N+3 and N+4 engines and open fan concepts that can further bolster

the aircraft performance. The 767 fuselage with TTBW and internal LH2 tanks appears to have the best potential for a future zero carbon emission liquid hydrogen powered aircraft.

Acknowledgement
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Biography
Bryce Thomas is a third year PhD student at Washington University in St Louis, Missouri. Bryce is originally from Allen, Texas. He has a bachelor's degree in mechanical engineering and a master's degree in aerospace engineering from WashU. His research in computational fluid dynamics focuses on turbulence modeling and simulation of aircraft aerodynamics. Bryce hopes to pursue a career in green aviation to reduce the impact of modern technology on the environment.

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