PERFORMANCE ENHANCEMENTS BETWEEN DIFFERENT APPLICATIONS OF ALTERNATIVE FUELS AND NOVEL AIRCRAFT CONFIGURATIONS

Joseph Lok Chun Chan[1], Yicheng Sun[2] & Howard Smith[3]

[1]PhD researcher, Cranfield University
[2]Research fellow, Cranfield Univertsity
[3]Professor, Cranfield University

Abstract

Net Zero Emissions goals are set to be achieved by 2050. The aviation sector has 2 - 3% contribute to the total global greenhouse gas emissions. To help address this matter and achieve the emissions goals, the International Civil Aviation Organisation, International Air Transport Association (IATA), National Aeronautics and Space Administration and United Kingdom Sustainable Aviation propose different technology roadmaps for future developments of aircraft. Among these forecasts, novel configurations such as high aspect ratio wings, blended wing bodies; and alternative fuels like biofuel and liquid hydrogen will aid with sustainable aviation. Some hypotheses arise that certain advanced configurations and alternative fuel combinations will introduce additional performance advantages. This paper investigated the performance enhancement introduced by different design combinations between novel configurations and alternative fuels. The results show that there are noticeable changes to the design of the aircraft and improvements in different aspects of performance, such as aerodynamic performance and fuel consumption. Additionally, based on different mission requirements, there will be different optimum design combinations. For example, a high aspect ratio wing with liquid hydrogen has the best performance at low capacity short haul missions whilst a blended wing body with liquid hydrogen is best for high capacity and long range missions.

Keywords: Alternative fuels, Advanced configurations, Net Zero Emissions, Sustainability, Novel designs

1. Introduction

Net Zero Emissions goals are set to be achieved by 2050, with a 45% reduction in greenhouse gas emissions to be met by 2030 and a 50% reduction in overall carbon dioxide (CO_2) emissions by 2050 [1, 2]. Currently, the transportation sector is one of the prime contributors to greenhouse gas (GHG) emissions, with 16.2% of total greenhouse gas emissions [3], the aviation section contributes 11.6%, following road vehicles of 74%, shown in Figure 1 and 2[4]. A total of 3% of global GHG emissions is from the aviation industry [5, 6]. With the intention of reducing GHG emissions, several guides and technological roadmaps are proposed by the International Civil Aviation Organisation (ICAO), the International Air Transport Association (IATA), the National Aeronautics and Space Administration (NASA) and the United Kingdom Sustainable Aviation. Among these forecasts, alternative fuels and novel configurations are two main approaches which show a lot of potential individually to reduce GHG emissions. Some hypotheses arise that certain novel configuration and alternative fuel combinations will bring additional performance advantages. For instance, both high aspect ratio wing (HAR) configuration and liquid hydrogen (LH_2) are shown to be suitable for long range missions because of their properties. Therefore, it is presumed that there will be additional merits in combining the two. This paper aims to conduct fair comparisons between different design combinations of advanced configurations and alternative fuels to identify any additional advantages or disadvantages among them. This paper starts by defining the design aim and methodologies, followed by two case studies of different mission ranges with different design combinations and finished with a conclusion.

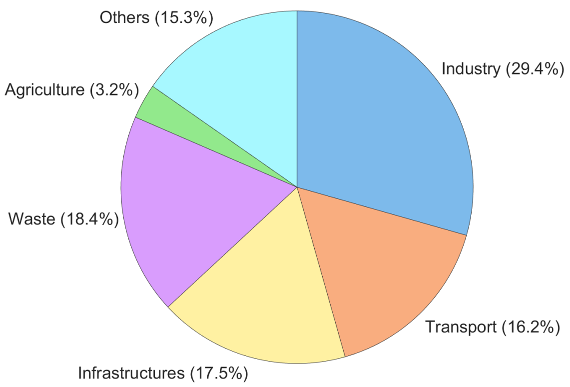

Figure 1 – 2023 global GHG emissions distribution between different sectors

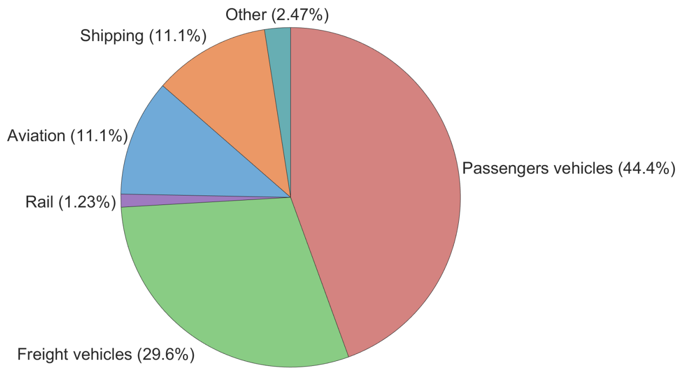

Figure 2 – 2023 global GHG emissions distribution within transport sectors

2. Design aim

A significant number of research have been conducted for the design of next generation passenger aircraft. Of all, high aspect ratio wing (HAR) and blended wing body (BWB) designs are the two most favourable novel designs which major aircraft manufacturers, Airbus and Boeing, have looked into, namely Airbus's ZEROe and Boeing's SUGAR programs [7, 8]. At the same time, several alternative fuels, including biofuel, liquefied natural gas (LNG), liquid ammonia and liquid hydrogen (LH_2) bring attention to the aviation industry to become the new aviation fuel and contribute to sustainability. These fuels have promising properties which can help reduce GHG emissions, specifically CO_2. However, the use of alternative fuels is not that straightforward since some new properties of alternative fuels will require new adaptations which results in new aircraft layouts or designs.
The traditional tube-and-wing (TAW) aircraft is designed for kerosene-based fuel with fuel stored in the integral wing tanks. However, this is not feasible for cryogenic fuels such as LNG or LH_2. Therefore, with the introduction of the new configurations and packaging, more suitable fuel system layouts can be taken into consideration for alternative fuels. The ultimate aim is to investigate if any configuration is more fitting for a specific alternative fuel or vice versa. Furthermore, if any of these new design combinations is more appropriate for a particular mission range and capacity.

3. Designs exploration

GENUS, an in-house built design and analysis software, is used to conduct comparisons between different configurations and alternative fuels. GENUS is a generic platform in which a wide range of configurations can be modelled and analysed based on the same set of assumptions. This ensures a fair comparison between different designs and hence more accurate results. GENUS incorporate a list of design modules, including geometry, mission, mass breakdown, aerodynamics, propulsion, performance and stability, which the user can modify and change the parameters to simulate different missions.

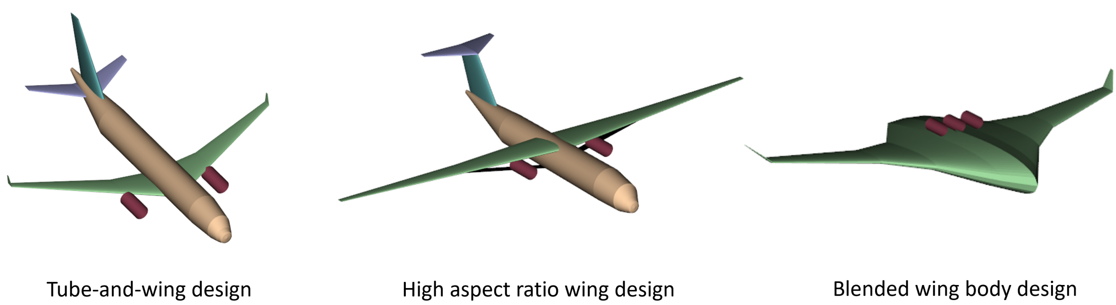

Figure 3 – Different aircraft configurations generated by GENUS

3.1 Geometry & packaging

Various aircraft configurations can be modelled using geometry modules. GENUS defined geometries using body components and lifting bodies, which include fuselage, nacelle, wing, fin and stabiliser. This allows flexible modelling where the user can fully customise the aircraft into different configurations as required, demonstrated in Figure 3.

Apart from the exterior design, the internal layout of an aircraft is equally important for the design and the calculation of the centre of gravity position. This is especially true when it comes to advanced aircraft configurations and new fuel tank layouts for cryogenic fuels. This makes sure the sizing of the aircraft is correct in which there will be enough physical space for the number of passengers and sufficient room for the required fuel tanks. GENUS takes into consideration with cockpit, cabin area, cargo area and fuel tanks as the main interior components. Similar to the exterior shape, the internal components can be shaped and positioned accordingly to meet the needs of the user, as demonstrated in Figure 4.

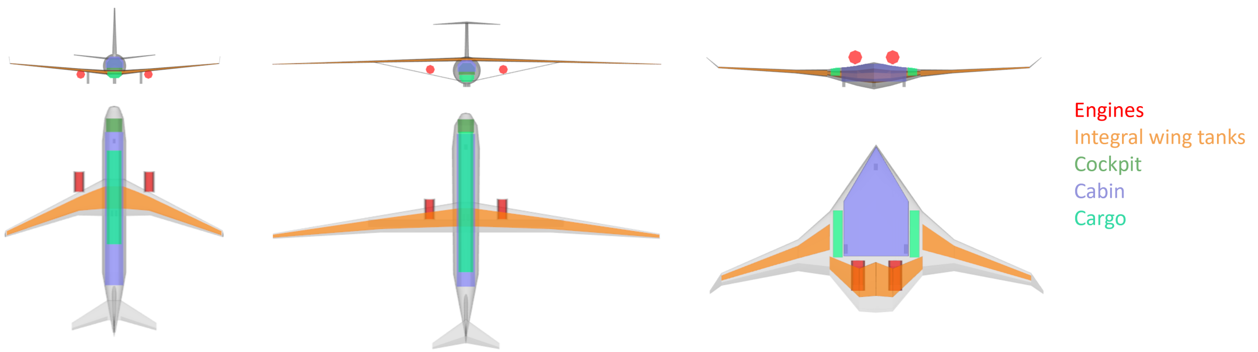

Figure 4 – Interal components layout of different aircraft designs with drop-in fuels

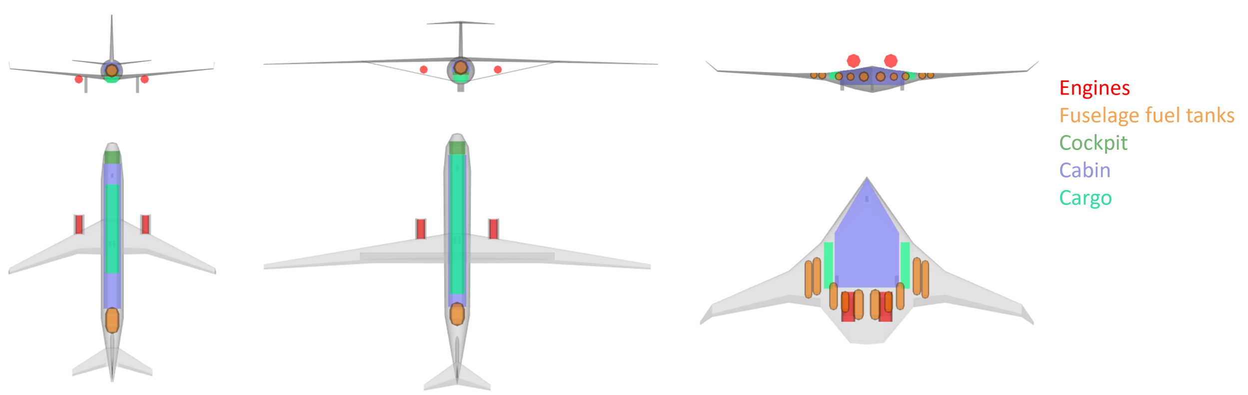

Figure 5 – Interal components layout of different aircraft designs with cryogenic fuels

3.2 Mission & performance

Different mission requirements can be defined in this module. This includes the number of passengers, total payload, mission range, flight speed, altitude and so on. This allows the user to simulate different flight routes. In this paper, two different popular flight routes, London to Barcelona and London to Hong Kong, will be used as case studies.

Furthermore, specific mission profiles can be broken down into different flight segments, such as take-off, climb, cruise, loiter, descend and landing, illustrated in Figure 6. These segments can be changed and arranged into different orders which can then simulate any specific mission or manoeuvres.

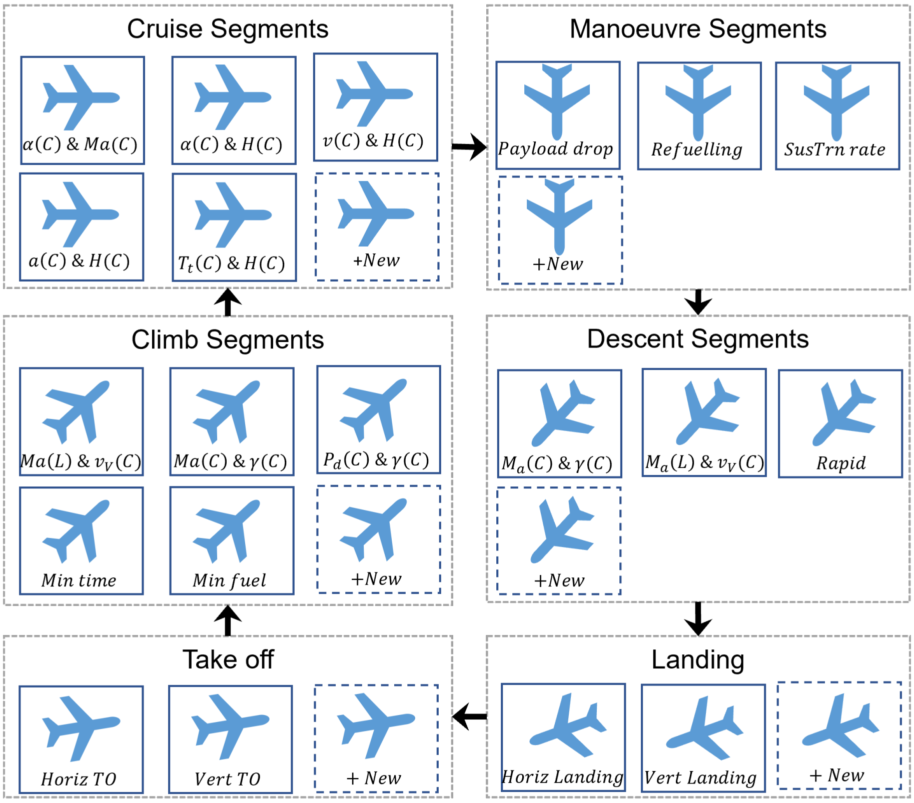

Figure 6 – Mission segment combinations

3.3 Mass breakdown & centre of gravity

Empirical mass breakdown methods are used in GENUS. These include Daniel Raymer [9], Denis Howe [10] and Cranfield mass prediction methods. These methods will provide an estimated total mass of the aircraft, as well as the mass of different components. The results of the calculations will later be used to determine the centre of gravity position in the stability module.

3.4 Aerodynamic

Similar to the mass breakdown module, different methods are used in the aerodynamic module, namely DATCOM [11, 12], PANAIR [13] and AVL [14]. Each of these methods uses different algorithms. DATCOM provides a robust and rapid aerodynamics calculation yet it has limitations in analysing unconventional configurations such as twin vertical tails. PANAIR uses panel methods which calculate the aerodynamic forces based on the actual modelled surfaces. This not only allows a more accurate prediction but allows a wider range of configurations. Yet, PANAIR requires a higher computational power and can only calculate symmetric designs [15]. Last but not least, AVL uses a vortex-lattice model which is suitable for lifting surfaces. AVL is still capable of considering body components such as fuselage. That said, AVL is unable to calculate the aerodynamic force of a lifting body.

Table 1 – Alternative fuel properties

Fuel	Density (kg/m^3)	Specific heat density (MJ/kg)
Kerosene	808	43.2
Biofuel	870	389
LH_2	70.8	120
LNG	430	48
NH_3	730	22.5

3.5 Propulsion & emissions

EngineSim created by NASA [16] is used in the propulsion module. EngineSim can simulate different types of turbo engines, including turbofan, turboprop, turbojet and afterburner. On top of that, different parameters such as engine diameter, bypass ratio, materials and so on can be modified to create rubber engines.

Different fuel sources can also be changed in the propulsion module. Different properties of alternative fuels are collected from different reports and literature reviews [17, 18, 19, 20], presented in Table 1. These data will then be input into the propulsion module and subsequently simulate the use of alternative fuels. The required fuel will be estimated based on the mission and performance of the aircraft that is defined in the previous module. In addition, both the in-flight and life cycle CO_2 emissions can be estimated based on the total fuel requirement and emissions factors of specific fuels, listed in Table 2. The emission factor is a coefficient which converts activity data into GHG emissions. The table also contains an idealistic and a realistic estimation, where idealistic estimation assumes fuels are produced through the most green and sustainable pathways whilst realistic estimation is based on current industry practices.

Table 2 – Emission factors

Fuel	Well-to-Wing emissions	Combustion	Emissions (idealistic)	Emissions (realistic)
Kerosene	12.25	73.2	N/A	85.45
Biofuel	-63.1 $\sim$ 83.7	70.4	7.3	154.1
LH_2	8.6 $\sim$ 221.65	0	8.6	221.65
LNG	42.1	57.29	N/A	99.39
NH_3	50.57 $\sim$ 114.19	0	50.57	114.19

3.6 Stability

The stability module calculates the longitudinal and lateral stability using the centre of gravity calculated in the mass breakdown module and the aerodynamic centre calculated in the aerodynamics module. Over and above, the controllability and trim ability of the design is also calculated based on the defined control surfaces in the geometry module.

3.7 Optimisation

GENUS consists of an optimisation module as well which runs on a genetic algorithm and/or large scale generalised reduced gradient 2 (LSGRG2) algorithm. The optimisation objective can be selected from the list of output values. With the upper and lower boundaries of design variables and constraints conditions can be set separately through the list of input and output respectively.

4. Case studies

Three existing popular flight routes, London to Barcelona, London to Hong Kong and London to Dubai are selected for case studies, illustrated in Figure 7. Each of the routes represents a narrow body short-haul flight, wide body long-haul flight and wide body transition flight respectively. Their flight missions are listed in Table 3. The comparison between these three scenarios can provide more comprehensive views towards how different design combinations between advanced configurations and alternative fuels will affect the performance of the aircraft and in different flight missions.

5. Scenario

In each case study, designs will share the same mission, including number of passengers, payload and mission range, for fair comparison. However, other parameters of the designs are subject to change, including aircraft geometry, engine sizing and flight condition in the hope of achieving their optimum performance. There will be in total 15 different design combinations between different configurations and fuels, exhibited in Figure 8. They will be analysed in two main aspects: 1) the performance of the aircraft, including total energy consumption and total emissions; and 2) the logistics of the operation, such as flight altitude, cruise speed, flight time, and operable aerodromes.

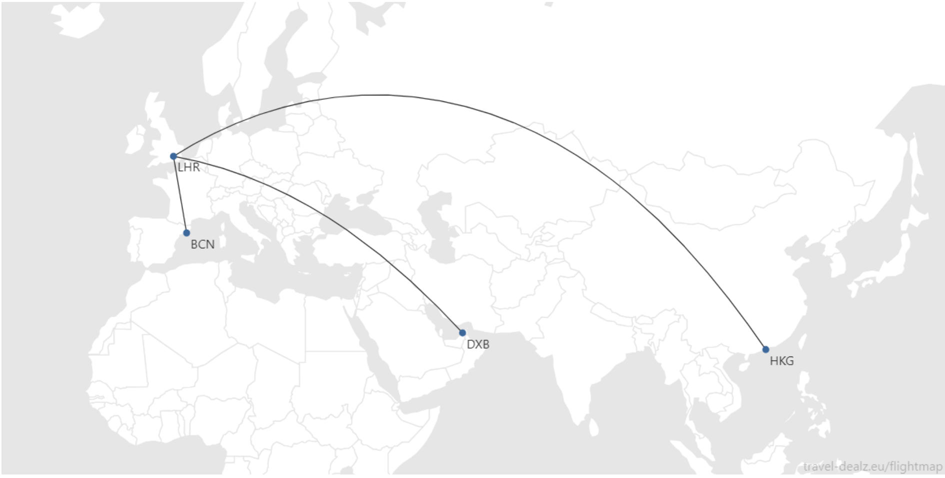

Figure 7 – Three case studies route illustrated in the map

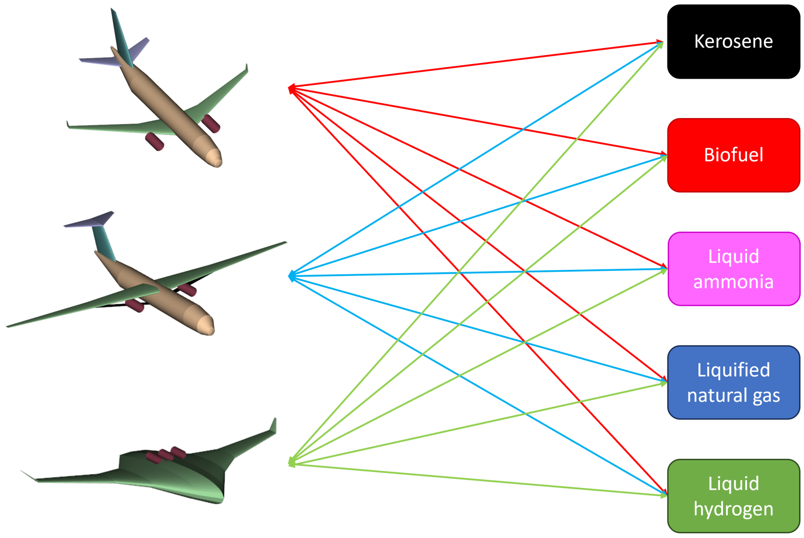

Figure 8 – Different design combinations

5.1 Scenario 1: Narrow body short haul flights

Narrow body short haul flights are one of the most operated flights, the London to Barcelona flight is one of the examples of the busiest short haul flights in the UK and EU. There are over 25,000 flights per year from London to Barcelona. This route is normally operated by an Airbus A320 class or a Boeing B737 class narrow body aircraft.

5.2 Scenario 2: Wide body long haul flights

London to Hong Kong is an example of a popular wide body long haul flight. The main difference of wide body long haul flights is the increase in passenger capacity and mission range. These flights are normally operated by Boeing B777 or Airbus A350 aircraft, flying directly from London to Hong Kong. There is just under 4000 direct flights per year.

5.3 Scenario 3: Wide body transitional flights

London to Dubai is an example of a popular wide body transition flight. Different to wide-body long haul flights, the idea of this operation is to gather passengers from different locations into the same transitional point, such as Dubai or Singapore, and redistribute them to their final destinations. The transitional flight is mostly operated by Airbus A380 or Boeing B777, with the intention of a high capacity. Over 11000 flights operate between London and Dubai every year.

Table 3 – Different mission range and requirement

Mission type	short haul	long haul	transition
Number of passengers (pax)	156 $\sim$ 189	296 $\sim$ 350	350 $\sim$ 525
Flight distance (nm)	$\sim$ 620	$\sim$ 5210	$\sim$ 3000
Cruise speed (knots)	430	560	560
Flight time (hours)	2	13	7
Flight altitude (km)	10700 $\sim$ 12200	10700 $\sim$ 12200	10700 $\sim$ 12200
Aerodrome requirement	Catorgrey C	Catorgrey E	Catorgrey F

6. Results

6.1 performance comparison

The performance of the aircraft is affected by both the properties of the configurations and alternative fuels. On top of that, the designs of the aircraft will be slightly altered to accommodate different alternative fuels, which further impact the performance of the aircraft. Even though the geometry of aircraft changes due to different fuel types are generally subtle, there is a noticeable difference in fuel tank layouts between drop-in fuels and cryogenic fuel designs, which applies to all three configurations.

Furthermore, as the mission requirements change, such as passenger capacity and/or mission range, the design of the aircraft will update accordingly. BWB configurations hold an advantage when sizing up for higher capacity. The total wetted area of BWB designs is much less sensitive to the changes in volume compared to TAW and HAR designs. For high capacity design, BWB is generally 50 to 70 % less in wetted area compared to TAW and HAR. Therefore, BWB designs are more suitable in high capacity missions, which will be reflected in a later section.

6.1.1 Total energy consuption

Figure9, 10 and 11 show the total energy consumption of different design combinations for different flight missions. All three show that TAW and HAR designs have very similar behaviours in responding to the changes in fuels. This is because of the high similarity between the two configurations and parallel component layouts. In addition, HAR configurations have a better energy consumption performance on average compared to TAW configurations. This is the result of improved aerodynamic performance from HAR configurations and resulted in an average of 13% improvement in energy consumption.

On the other hand, BWB configurations responded differently to the use of different alternative fuels. With the completely new configuration, BWB has a completely different aerodynamic characteristic and novel layouts for both payload and fuel tanks, which directly affect the performance of the aircraft. Despite the low density properties of LH_2, there is only a 2.7% improvement in energy consumption compared to BWB/kerosene based jet fuel combination. This is mainly because of the weight penalties from the cryogenic fuel tanks. With the new cryogenic fuel tank arrangement, there will be multiple tanks instead of one big one, as demonstrated in Figure 5, which significantly increases the operational Empty Weight (OEM). For scenario 1, BWB/LH_2 has a 78% increase in OEM and 519% increase in total tanks weight compared to TAW/LH_2. The percentage difference decreases as the range and capacity increases.

Even though LH_2 has a low density and a high specific energy density, which makes it more suitable for long range missions. It still suffers seriously from weight penalties coming from cryogenic fuel tanks which leads to higher energy consumption compared to drop-in fuel options.

Designs using NH_3 have a significantly higher energy consumption compared to other fuel options. This is a direct result of the fuel properties where NH_3 has a high density and a low specific energy density compared to the others. Concurrently, this creates significant challenges for long range missions using NH_3. In some cases, NH_3 is not even feasible to fulfil the required mission range due to the required fuel mass rising exponentially.

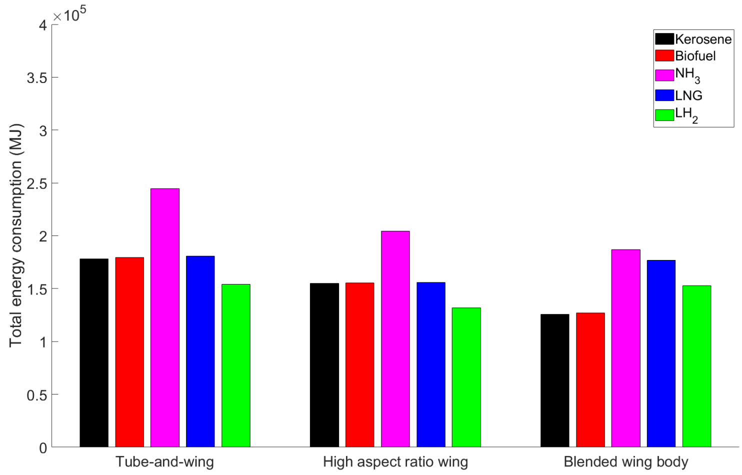

Figure 9 – Total energy consumption of narrow body short haul flight design combinations

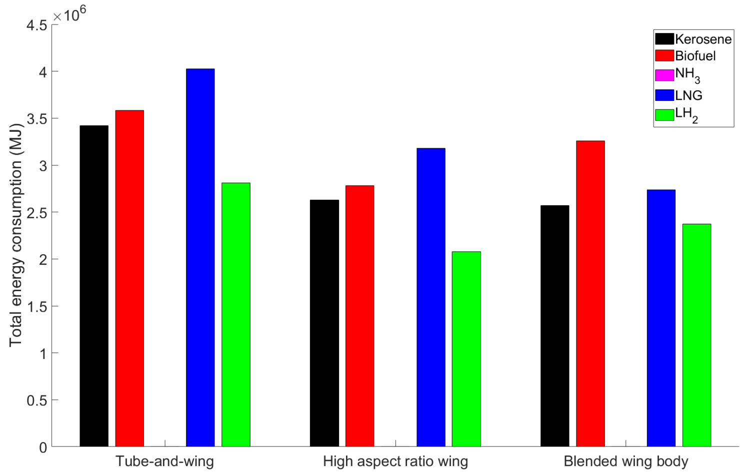

Figure 10 – Total energy consumption of wide body long haul flight design combinations

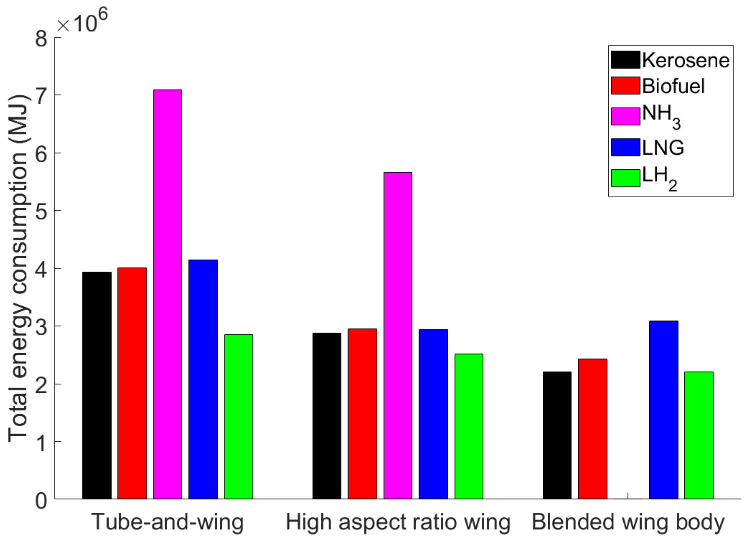

Figure 11 – Total energy consumption of wide body transition flight design combinations

6.1.2 Emission

By translating the energy consumption into GHG emissions, it is possible to compare the level of sustainability between different designs. Figure 12, 13 and 14 exhibit the estimated idealistic and realistic GHG emissions in different design scenarios. From the figures, it is clear that there are significant differences between the idealistic and realistic estimations. Biofuel, NH_3 and LH_2 which are produced through the sustainable pathways show a promising reduction in life cycle GHG emissions. As anticipated, green LH_2 provides the most significant reduction in direct GHG emissions. Despite the high energy consumption, NH_3 fuelled aircraft also have the potential to provide a very sustainable flight. Biofuel's GHG reduction is not as significant as LH_2 nor NH_3. But it still brings a favourable improvement compared to kerosene-based jet fuel. However, GHG emissions reduction can only be achieved by fuels produced through sustainable pathways.

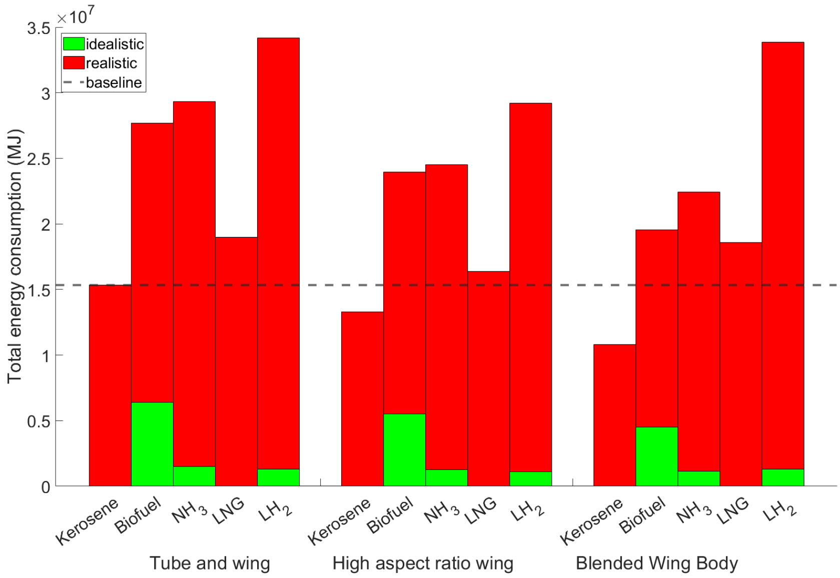

Figure 12 – Emission estimation of narrow body short haul designs

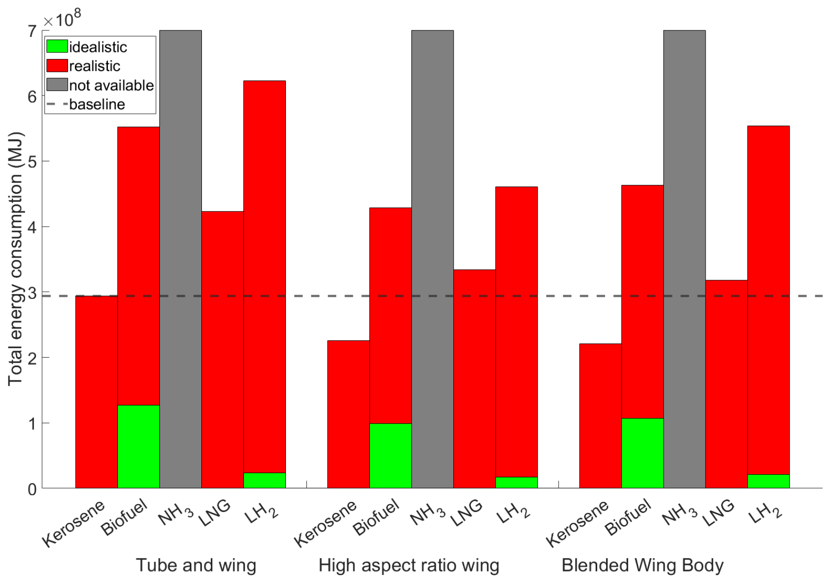

Figure 13 – Emission estimation of wide body long haul designs

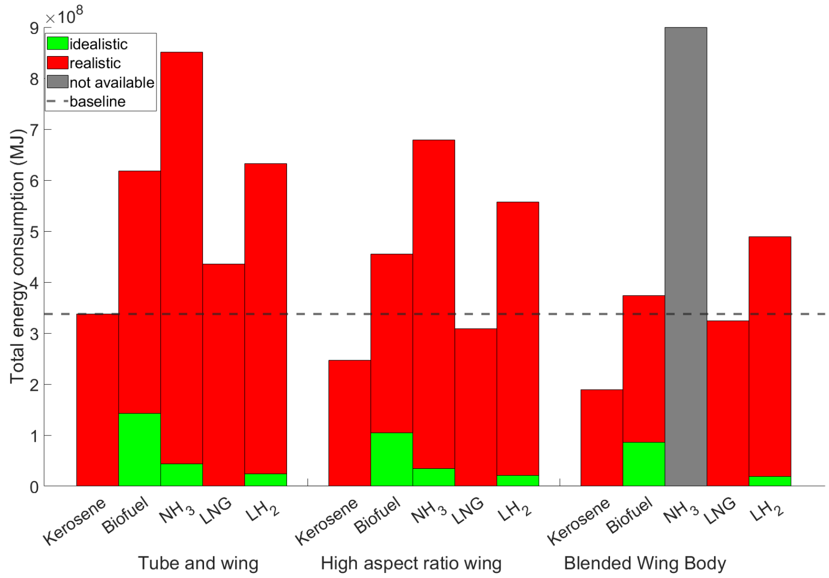

Figure 14 – Emission estimation of wide body transitional design

6.2 Operational

6.2.1 Flight condition

Much research has shown that novel configurations such as HAR and BWB are better at operating at slightly different cruise altitudes and/or cruise speeds to achieve optimum flight conditions. For traditional TAW configuration, the normal cruise altitude is around 11 km and at Mach 0.8; HAR is recommended to operate at a lower Mach number and/or higher altitude, such as 12.5 km at Mach 0.7 [21]. There are several studies suggesting the optimum cruise speed is between 0.8 to 0.85 with a potential higher cruise altitude between 13 to 15 km [22, 23].

As a consequence of a slower cruise speed, the total flight time increases for both HAR and BWB configurations in general. An average of 10% increase in flight time is estimated in HAR designs. This becomes more significant in long-haul flights. In other words, around 10 minutes increase in a 2 hours flight; 30 minutes increase in a 7 hours flight; an hour increase in a 13 hours flight. This will raise a small concern about passengers' acceptance.

Figure 15 shows the L/D polar of different designs operating at their recommended flight condition. HAR configuration designs have the best L/D ratio around 20 to 23, followed by BWB configuration designs with L/D ratio between 18 to 20 while traditional TAW designs have an L/D ratio around 15. Apart from the optimum L/D ratio, the shape of the curve also shows that BWB configurations' cruise L/R ratio is more sensitive to the coefficient of lift, in other words, the flight conditions. In reality, the performance of BWB configurations might suffer a bigger impact compared to TAW and HAR designs as aircraft is not always able to operate in its optimum flight conditions due to air traffic controls.

6.2.2 Residual fuel

In nearly all the current commercial flight routes, it is unlikely that the aircraft is operating at its maximum range. For instance, the Airbus A320-200 is capable of reaching a range of 3000 nautical miles with a full payload, while most flights operate between 500 to 2000 nautical miles. In other words, the designs have a higher flexibility to operate various mission and flight routes. Yet cryogenic fuelled designs have their tanks sized for particular missions given the flexibility of the cryogenic fuel tank sizing compared to traditional integral wing tanks. This helps reduce the excessive weight penalties introduced by cryogenic fuel tanks. However, as a trade-off, the new aircraft designs are more restricted to specific missions and potentially compromise the safety of the aircraft with less residual fuel being carried on board. Additionally, there might be an increase in model variations to satisfy different missions.

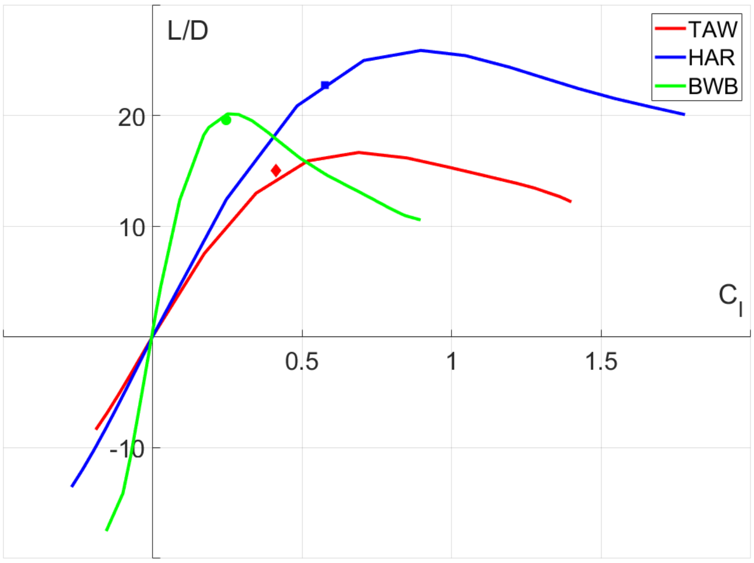

Figure 15 – Lift to drag ratio vs coefficient of lift

6.2.3 Aerodrome

With the pioneering of HAR and BWB configurations, ground operations are subjected to changes too. One of the key factors is the operational aerodromes for new aircraft designs, especially for HAR designs. Aircraft can only operate in specific aerodromes if they meet the requirements, including runway length and aircraft wing span. As for HAR designs, the wing span is naturally longer than traditional TAW designs, which imposes a few challenges. For low capacity, short haul design, HAR cannot be operated in the same category of aerodromes as TAW or BWB designs. This is especially the case for short haul flights which normally operate at a code C airport, such as London City Airport and Southampton Airport. Instead, HAR designs with the same capacity need to be operating in code E airports like Heathrow Airport. Operating in a larger airport will likely result in an increase in ticket fares as well as an increase in airport tax. Furthermore, in a high capacity design, the wing span exceeds the longest existing wing span, which is the Airbus A380 with 80 meters of total wing span. A new aerodrome category might need to be tailored for this. Last but not least, parking at the gate will also be affected by the long wing span. However, this problem can potentially be resolved by using foldable wings.

7. Result presentation

The results from the calculations show that there are improvements in aircraft performance in different aspects between different alternative fuels and configuration combinations. LH_2 improves both TAW and HAR configurations' fuel consumption by reducing the weight of the aircraft. The reduction is more significant as the mission range increases. LH_2 enhances the fuel consumption performance of BWB configurations by reducing the weight of the aircraft too. However, this is only limited to high capacity and long mission range designs due to the weight penalties from the cryogenic fuel tanks.
HAR configurations have the best aerodynamic performance with a maximum L/D ratio of around 27, outperforming both traditional TAW and BWB designs, 15 and 20 respectively. Alternative fuels do not directly contribute to the aerodynamic performance of the aircraft but still affect the CL position on the L/D curves. For example, the use of external tanks for cryogenic fuels imposes additional drag penalties. As mentioned earlier, alternative fuels with different densities can greatly affect the weight of the aircraft, which will result in a shift in flight conditions and likely push the aircraft to operate away from its optimum L/D ratio. This is especially true for BWB configurations as its flight condition is very sensitive to changes.

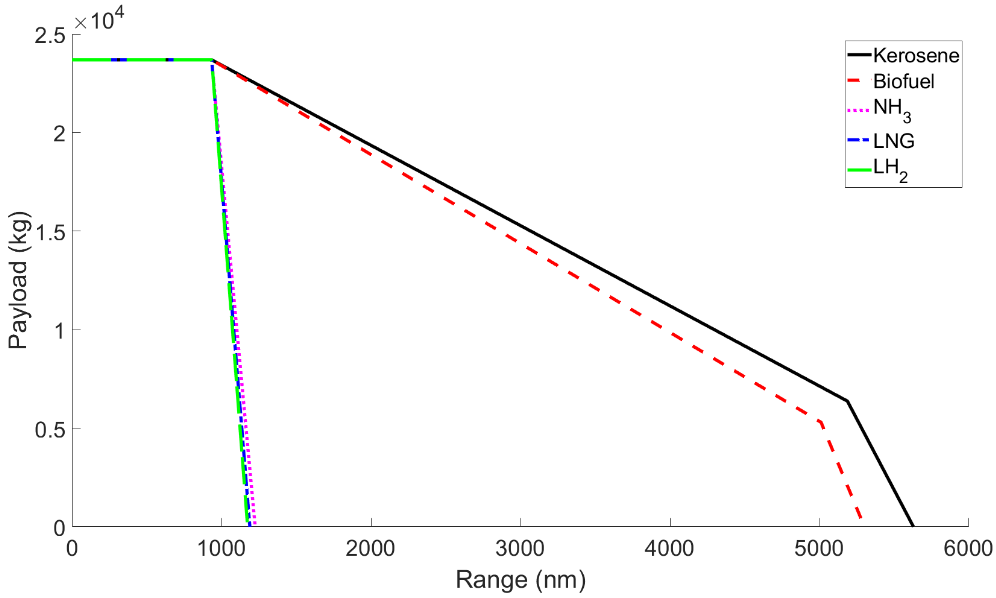

Figure 16 – Payload range diagram of different TAW design combinations

From a sustainability perspective, alternative fuels bring a more significant impact compared to different configurations. Using biofuel, NH_3 and LH_2 produced through a green pathway show a substantial reduction in GHG emissions, which can be up to 91.5 %. Meanwhile, the improvement brought by different configurations is around 29%. The different configurations provide a platform for alternative fuels in which they can show their potential.

However, there are some drawbacks to these new designs. Besides the technical challenges and modifications needed, there are more potential problems from the operational point of view. Due to the high wing spans of HAR designs, they can only be operated in large airports, such as Category E or above, even for a small capacity design. This might increase the airport capacity by increasing the number of domestic flights and also have a higher ticket fee as a result of airport charges. On top of this, both HAR and BWB designs are recommended to operate at a lower Mach number, to operate at their optimum point. This will increase the flight time by around 10%, which directly affects the passengers' acceptance, especially on long haul flights.

8. Summary – Case studies

In conclusion, this research conducts a fair comparison between different design combinations of novel configurations and alternative fuels by using the same tool set in GENUS. The results show that there are improvements in aircraft performance through different alternative fuels and configurations. This includes overall weight reduction by using a low density fuel like LH_2 and improvement in L/D ratio through new aircraft configurations. These all result in a lower energy consumption. However, the level of improvement varies between capacity and mission range. The improvement between different design combinations is minimum at low capacity and short mission range, where BWB/kerosene has the best performance, with 29.4% reduced in energy consumption, followed closely by BWB/biofuel and HAR/LH_2, 28.8% and 26.1% respectively. As the capacity and mission range increase, HAR/LH_2 and BWB/LH_2 start to outperform other design combinations and bring up to 39.3% and 43.9% improvement in energy consumption each.

While reducing GHG emissions is the main goal in order to achieve Net Zero emissions by 2050, alternative fuels have a much higher impact compared to novel configurations. The use of sustainable fuels produced through green pathways, such as biofuel, NH_3 and LH_2, is key to reducing GHG emissions. with a potential GHG reduction of up to 91.5%, and different configurations provide the best platform for these fuels to be used. However, there are a few demerits towards passengers' acceptance, from a longer flight time to a more expensive ticket fee, as compensation for flying sustainability.

9. Data availablilty

The dataset generated during and/or analysed during this study is available at
https://doi.org/10.17862/cranfield.rd.25895443 and from the corresponding author on reasonable requestion.

10. Copyright Statement

References

[1] Unfccc. Adoption of the Paris agreement - Paris Agreement text English. Technical report, 2015.

[2] European Commission. Directorate General for Mobility and Transport. and European Commission. Directorate-General for Research and Innovation. *Flightpath 2050 : Europe's vision for aviation : maintaining global leadership and serving society's needs.* Publications Office, 2011.

[3] Hannah Ritchie. Sector by sector: where do global greenhouse gas emissions come from?, 9 2020.

[4] International Energy Agency. Transport sector CO2 emissions by mode in the Sustainable Development Scenario, 2000-2030, 11 2019.

[5] Bethan Owen, David S. Lee, and Ling Lim. Flying into the future: Aviation emissions scenarios to 2050, 4 2010.

[6] M. Klower, M. R. Allen, D. S. Lee, S. R. Proud, L. Gallagher, and A. Skowron. Quantifying aviation's contribution to global warming. *Environmental Research Letters*, 16(10), 10 2021.

[7] Marty K Bradley and Christopher K Droney. Subsonic Ultra Green Aircraft Research: Phase I Final Report. Technical report, 2011.

[8] Airbus. Airbus reveals new zero-emission concept aircraft, 2020.

[9] Daniel P. Raymer and American Institute of Aeronautics and Astronautics. *Aircraft design : a conceptual approach*, volume 5. American Institute of Aeronautics and Astronautics, 2012.

[10] Denis Howe. *Aircraft conceptual design synthesis*. 1 edition, 2000.

[11] Mcdonnell Douglas. The USAF stability and control DATCOM Volume I, Users Manual. Technical report, 1979.

[12] Public Domain Aeronautical Software. Description of Digital Datcom, 10 2022.

[13] Public Domain Aeronautical Software. PANAIR, 4 2021.

[14] Mark Drela and Harold Youngren. AVL Aerodynamic analysis. Technical report, 4 2022.

[15] Thomas Derbyshire, Kenneth W Sidwell, and N / Sa. PAN AIR Summary Document (Version 1.0). Technical report, NASA, Floria, 4 1984.

[16] NASA. Engine Parameter Interactive, 2014.

[17] Russell W Stratton, Hsin Min Wong, and James I Hileman. life-cycle-greenhouse-gas-emissions-from-alternative-jet-fuels-version. Technical report, 2010.

[18] E. Cetinkaya, I. Dincer, and G. F. Naterer. Life cycle assessment of various hydrogen production methods. *International Journal of Hydrogen Energy*, 37(3):2071–2080, 2 2012.

[19] US energy information Administration. Frequently asked questions (FAQS), 12 2020.

[20] Yusuf Bicer, Ibrahim Dincer, Calin Zamfirescu, Greg Vezina, and Frank Raso. Comparative life cycle assessment of various ammonia production methods. *Journal of Cleaner Production*, 135:1379–1395, 11 2016.

[21] Timothy Chau and David W. Zingg. Aerodynamic Design Optimization of a Transonic Strut-Braced-Wing Regional Aircraft. *Journal of Aircraft*, pages 1–19, 8 2021.

[22] N. Qin, A. Vavalle, A. Le Moigne, M. Laban, K. Hackett, and P. Weinerfelt. Aerodynamic considerations of blended wing body aircraft, 8 2004.

[23] Paul Okonkwo and Howard Smith. Review of evolving trends in blended wing body aircraft design, 4 2016.