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Airliner conceptual design for application of alternative fuels

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This paper investigates the application of alternative fuel in conventional tube-and-wing aircraft configuration. Alternative fuel choice including biofuel, liquid hydrogen, liquefied natural gas, ammonia and methanol. A comprehensive mission range starting from 2000 nautical miles to 8500 nautical mile are explored, designed and analysed using GENUS, an in-house built multidisciplinary design analysis and optimisation platform. It is expected to see a progressive changes for each fuel type and capacity combination over different mission range. The gradient of these trends should be different which potentially demonstrate the additional benefit from using alternative fuel. The aim of this study is 1) to determine how different fuel properties will affect the designs and performance of aircraft, 2) to quantify the reduction of green house gas emission by utilising alternative fuel. The results show the use of hydrogen and biofuel can significantly reduce life cycle green house gas emission if only the fuel is produced in sustainable pathways.

I. Nomenclature

CJF	=	Conventional jet fuel
$IATA$	=	International Air Transport Association
$ICAO$	=	International Civil Aviation Organisation
LH_2	=	Liquid hydrogen
LNG	=	Liquefied natural gas
$LSGRG2$	=	Large scale generalised reduced gradient 2
$MDAO$	=	Multidisciplinary design analysis and optimisation
$MTOM$	=	Maximum take-off mass
NH_3	=	Ammonia
TAW	=	Tube-and-Wing

II. Introduction

Alternative fuels have come to an interest to many in the commercial aviation industry. Especially with the vision of achieving Net Zero emission by 2050. International Civil Aviation Organisation (ICAO) , International Air Transport Association (IATA) and United Kingdom Sustainable Aviation have set their vision and technical road map on how to achieve Net Zero, in which application of alternative fuel plays a major role [1] [2] [3] [4]. The use of alternative fuel can help achieve Net Zero by reduce direct emission during flight and or indirect emission during fuel production.

Potential alternative fuel candidates include biofuel, synthetic fuel, liquid hydrogen (LH_2), liquefied natural gas (LNG) and ammonia (NH_3). Among these fuels, biofuel and synthetic fuel share much the same physical properties to existing kerosene-based conventional jet fuel (CJF). They are also known as drop-in fuel which can be adapted to current aircraft fleets with little to no modifications [5]. On the flip side, most of the other alternative fuel candidates have rather different physical properties in which some of them need to be used as a cryogenic fuel, including LH_2 and LNG. Therefore changes to existing aircraft or new designs are required.

In the mean time, commercial aircraft has adopted “Tube-and-Wing (TAW)" configuration since the beginning of Jet age back in 1940s [6]. TAW configuration consists of a capsule shape fuselage with wings attached in the middle lower part of the fuselage and stabiliser devices attached at the rear of the aircraft [7]. For this configuration, fuel stores

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in wing tanks and center tanks. Yet wing tanks are not suitable for cryogenic fuel mostly because of the insufficient insulation[8] [9].

The design analysis is conducted using GENUS [10], a multidisciplinary design analysis and optimisation (MDAO) platform. GENUS can model and analysis a wide range of designs from conventional TAW to box wing, high aspect ratio wing and blended wing body. There are a number of case studies of aircraft designs using GENUS [11] [12] [13] [10] [14][15].

III. Design aim

Some alternative fuels show potential improvement in performance addition to reduce green house gas (GHG) emission. Take LH_2 as an example, it is a much lighter fuel compared to CJF. Some studies propose that it will be more suitable to use LH_2 for long distance mission [8][16] [17] [18].

The aim of this paper is to explore the application of alternative fuel in conventional TAW configuration for different mission range to 1) determine does alternative fuels bring additional benefits apart from reduction in GHG emissions; 2) an optimum combinations between alternative fuels and mission range exist. This will be evaluate in different design criteria counting maximum take-off mass (MTOM) and fuel consumption.

IV. Design methodology

GENUS consists of multiple parametric design modules where user can input or modify different values to calculate different designs. These modules include geometry, mission, propulsion, mass breakdown, aerodynamics, performance and stability. In addition, it also contains some extra modules like cost and emission.

A. Geometry

The geometry section allows user to model their aircraft by defining body components and lifting surfaces. Body components refers to fuselage, engine nacelle and external tanks if exist. Meanwhile wings, horizontal tail, vertical tail and canard are assign as lifting surface. This allows a very flexible aircraft modelling thus makes it possible to represent both conventional and unconventional aircraft designs.

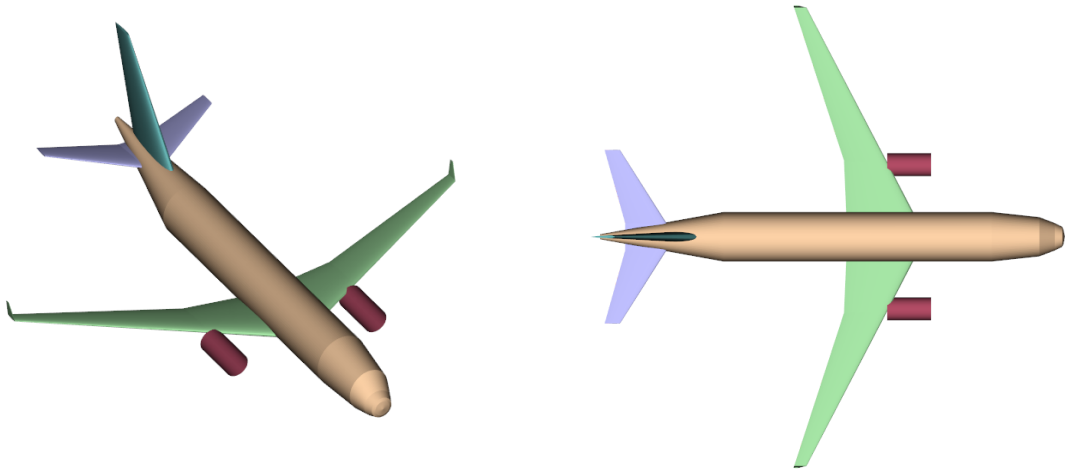

Fig. 1 Geometry generated by GENUS

B. Mission

Mission requirement are define in this modules. Through setting different mission range, flight condition, payload and so on to explore the application of alternative fuel.

Table 1 Mission requirement

Requirement	Value
Take-off distance (m)	1800 ~ 3100
Landing distance (m)	1500 ~ 2500
Passengers	200 / 400 / 800
Range(nm)*	2000 ~ 8500

* In an increment of 500 nautical miles

C. Propulsion system

NASA EngineSim model [19] is used in propulsion module. It can model a rubber engine and calculate the engine performance based on its parameters, incorporate geometry, material, flight condition and so forth. In addition, different fuel can be define here and substitute in to the propulsion system. It is even possible to have more than one type of fuel in a single design.

Table 2 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

D. Mass breakdown

Mass breakdown module uses empirical methods incorporate Daniel Raymer [20], Denis Howe [21] and Cranfield mass prediction method, to provides an estimation towards different components of the aircraft. It starts the calculate with an estimated MTOM.

E. Aerodynamics

Aerodynamic performance can be calculated by three different algorithms, DATCOM, PANAIR and AVL. DATCOM is a robust aerodynamic solver which can provide a rapid and economical calculation on the aerodynamic of the design.

F. Performance

The performance modules is composite with multiple preset flight segments, for example, take-off, climb, cruise, descent, landing and etceteras. User can compose the needed mission requirement with the preset segments with a high level of freedom.

G. Stability

The stability and control module uses centre of gravity calculated in mass breakdown module. The aerodynamic centre is calculated through DATCOM while thus static margin[22].

Table 3 Mass breakdown methods

Component	Raymer's method(kg)	Cranfield methods (kg)
Fuselage	5637.279	7674.273
Wing	4603.136	5275.282
Vertical tail	413.671	565.428
Horizontal tail	541.541	648.732
Engine	1907.145	2829.41
Nose landing gear	294.952	337.8
Main landing gear	1690.103	1773.452
System	7306.08	5892.418
Wing tanks	221.056	221.056
Fuel	9254.313	9254.313
Crew & passengers	17380	17380
Payload	6400	6400

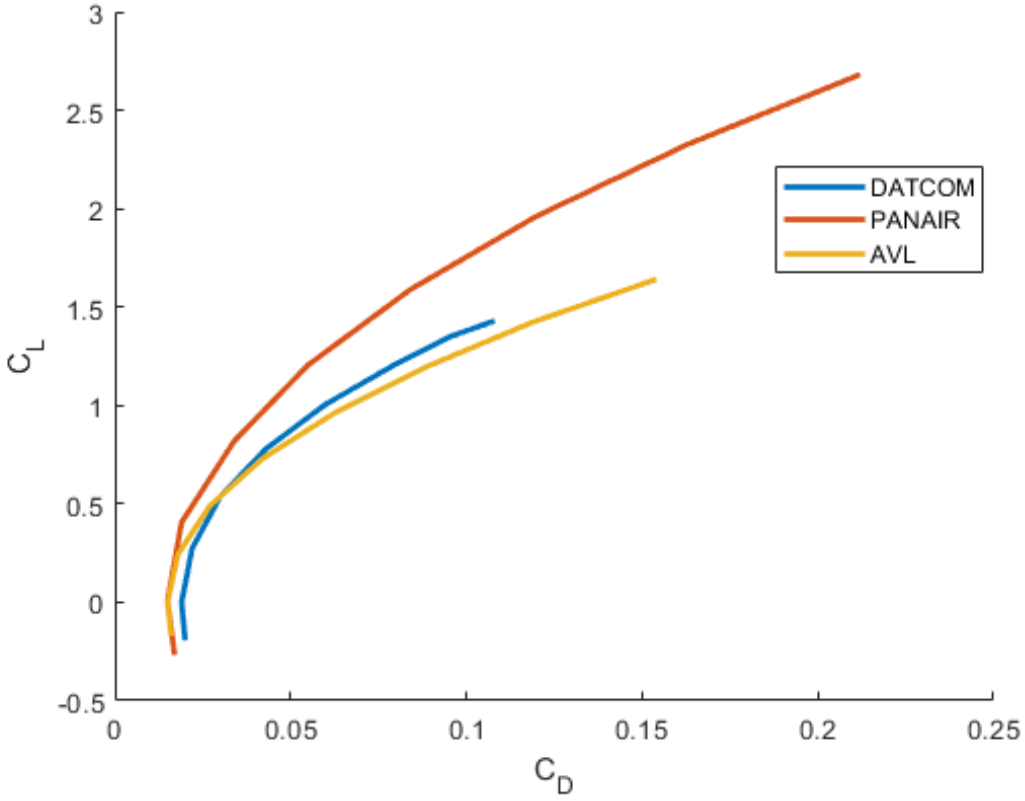

Fig. 2 Drag polar of using various aerodynamic models

H. Emission

In the emission module, a simple emission model is construct with preset GHG emission factors collected from various research paper [23] [24] [25] [26]. It calculates the CO_2 emission of each flight by the fuel type and the amount of fuel used. Indirect CO_2 emission can also be estimated.

I. Optimisation

GENUS includes a built in optimisation platform which uses genetic algorithm and large scale generalised reduced gradient 2 (LSGRG2) algorithm. Once the objective, variables and constraints are set, a multidisciplinary design optimisation can be performed and return with an optimum design. An optimisation is performed at each point over the mission range.

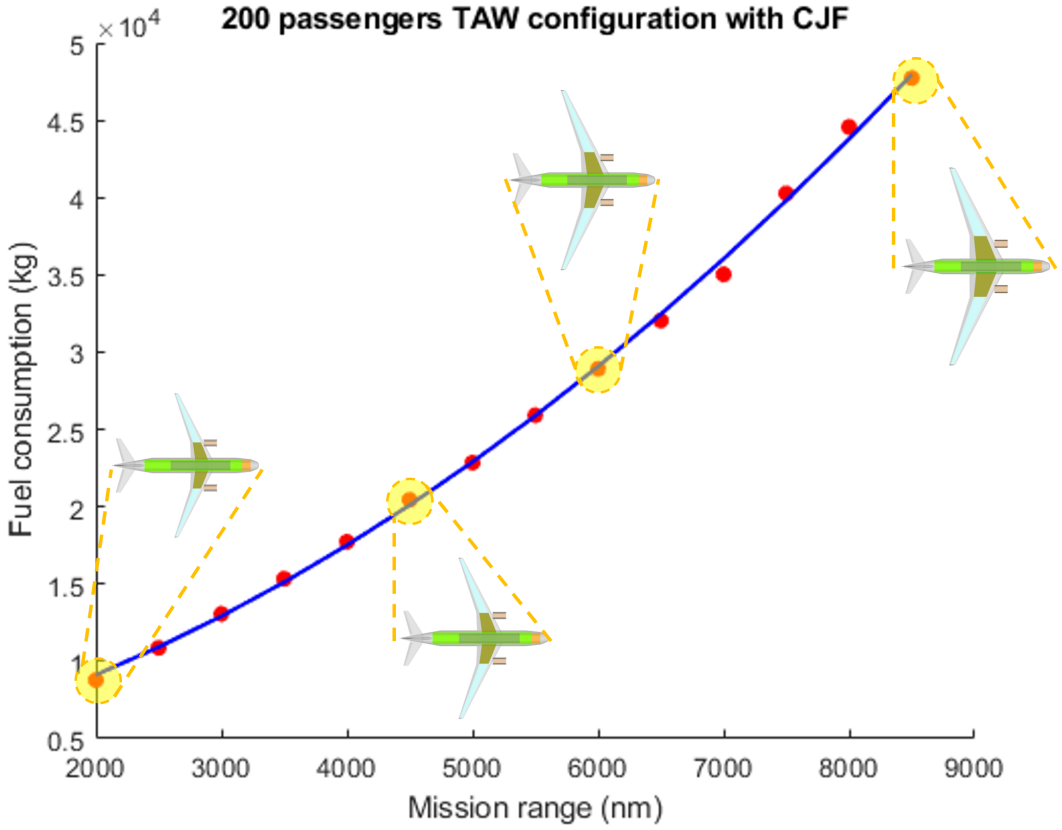

Fig. 3 Optimised designs of 200 passengers capacity over different mission range

V. Case study: 200 passengers TAW configuration

A. Geometry and packaging

The geometry and packaging of each design is being modified and optimised based on different mission range and fuel selection. One of the driving factors for the changes of the geometry is the fuel tank volume. The required fuel tank volume changes based on the mission requirement and on top of that different fuel candidates have different fuel tank requirement. Conventional wing tanks are not suitable for cryogenic fuels such as LH_2 or LNG, therefore capsule shaped fuselage fuel tank or external tanks are added to the design.

1. Jet A fuel and drop-in fuel

Since the early days of jet-age in 1940s, kerosene-based jet fuel is already one of dominating fuel in the market. This has been defining the geometry of the model aircraft. Conventional Tube-and-wing configuration has been designed around kerosene-based fuel, namely having wing tanks. Meanwhile drop-in fuel refers to any fuel that can either blended with or directly replace current jet-A fuel without the needs of modifying the fuel system or the design of aircraft[5]. Biofuel fuel and synthetic-kerosene are two examples of drop in fuels. Figure 4 shows the geometry and packaging of kerosene-based fuelled designs. It is clear that all the payload, counting cockpit, cabin and cargo are within the fuselage

while fuel tanks are mainly distributed over the wings. Moreover, the figure demonstrate the changes as designed mission range increases. One of the most significant changes is the size of the wing. This is primarily consequence of increase fuel tank volume.

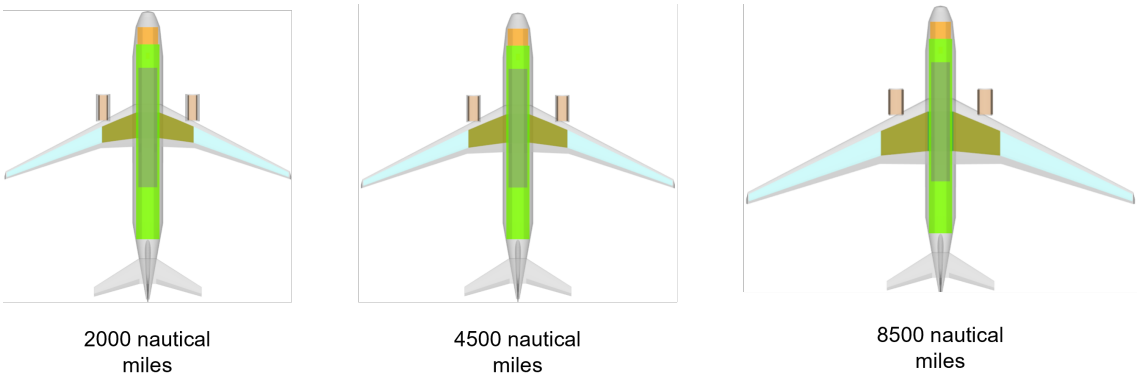

Fig. 4 Geometry and packaging demonstration of designs over different mission range

B. Cryogenic fuel

Cryogenic refers to the study of materials at low temperatures, normally ranging from 0 k to around 123 k[27]. Liquid hydrogen and liquefied natural gas are two examples of cryogenic fuels. One major difference between cryogenic fuels and jet-A fuel is the fuel tank requirement. Unlike Jet-A or drop-in fuel, cryogenic fuel cannot be stored inside wing tank due to insufficient insulation. Therefore, cryogenic fuels are designed to be stored within fuselage fuel tank or external drop tanks which is presented in Figure 5. There are different design constraints for these new fuel tanks, especially fuselage fuel tanks. Fuselage fuel tank in Figure 5 is fitted by extending the length of fuselage so as to keep the designed capacity. The main constraint of this approach is tail scraping angle and storage of main landing gears. There are other approaches such as reducing number of passengers to increase the fuel tank volume which will be explained in section VII.

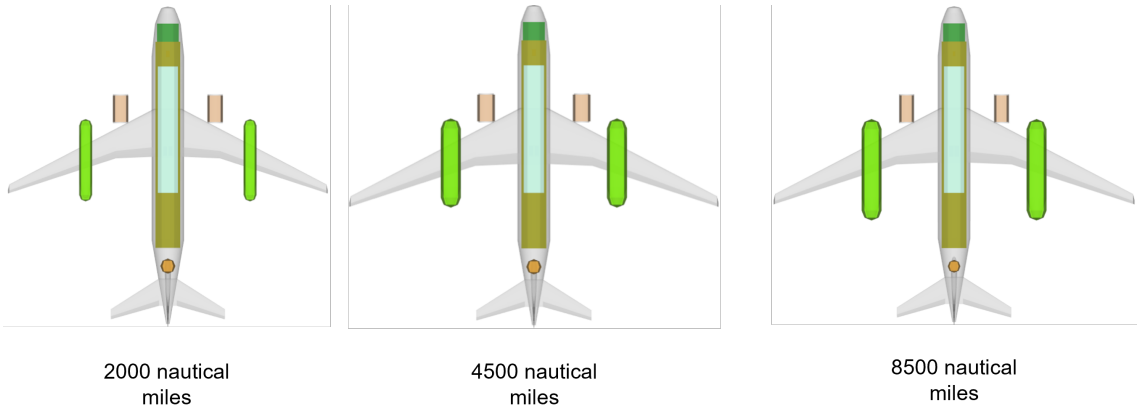

Fig. 5 Geometry and packaging demonstration of designs over different mission range

VI. Fuel tank configuration trade-off

For different fuel tank configurations, there are different trade-off between fuel tank volume, weight and aerodynamic performance. Each aspect is analysed between different fuel tank configurations with given fuel requirement.

A. Fuel tank volume

For the three tank configurations, each has different constraints over the fuel tank volume. Volume of wing tanks is heavily constrained by the size of the wing, which makes it inflexible, especially scaling down. As a consequence the fuel tank will not be fully optimised when required fuel is low. On the flip side, fuselage fuel tank struggles to scale up due to the physical limitation of tail scraping angle, main landing gears length and lateral stability.

B. Weight

As presented in Figure 6, the mass of three different fuel tank configurations weight very similar initially however as the size of the tank increases, the weight of external tanks increase more significantly compared to both fuselage fuel tanks and wing tanks.

C. Aerodynamic

Figure 7 shows the changes in coefficient of drag as the volume of fuel tanks increase. For fuselage fuel tank and extended tanks, drag increases as fuel tank volume increases. Worth noting, fuselage fuel tank has a lower initial coefficient of drag but with a higher rate of increases compared to extended tanks. On the contrary, coefficient of drag decreases as wing tank volume increases due to increase of AR which reduces induced drag. Increase of total wing surface will also reduce wing loading, as a consequence the aircraft would have to either travel in a slower speed or higher altitude.

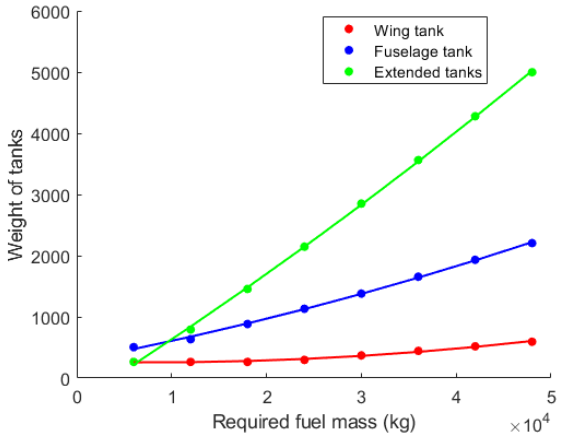

Fig. 6 Fuel tank weight

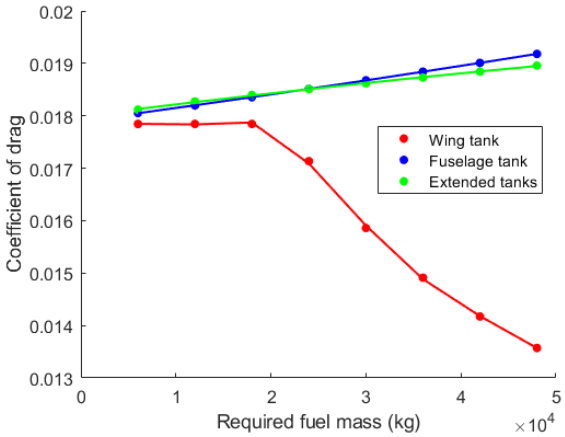

Fig. 7 Additional drag from different fuel tank layouts

VII. Case study: Fuselage fuel tanks and stability trade-off

As mentioned in previous sections, there are few unique constraints for fuselage fuel tanks, especially the location of the tanks. One of the most designs is having a front and aft tank as shown in Figure 8. This layout allows a better stability control however this potentially limit the accessibility of the cockpit in the event of emergency. Therefore some proposal the idea of having a single aft tank. Only problem is the lateral stability as the mass of the fuel and fuel tank is now located at the rear of the aircraft, this will shift the centre of gravity backwards and leads to a unstable aircraft.

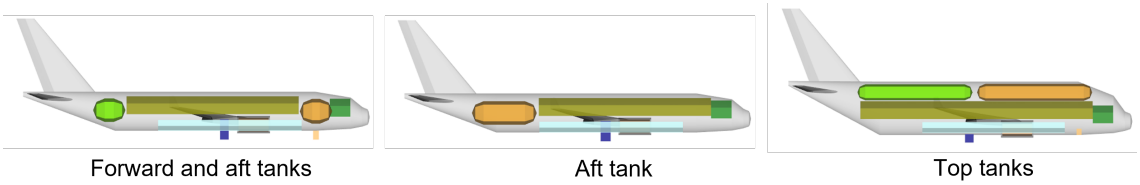

Fig. 8 Different fuselage fuel tank layouts

To investigate where is the limit to the tank size, a trade-off study is performed. Given a fixed fuselage length and by reducing the number of passengers and convert the extra space to fuel tank as illustrated in Figure 9.

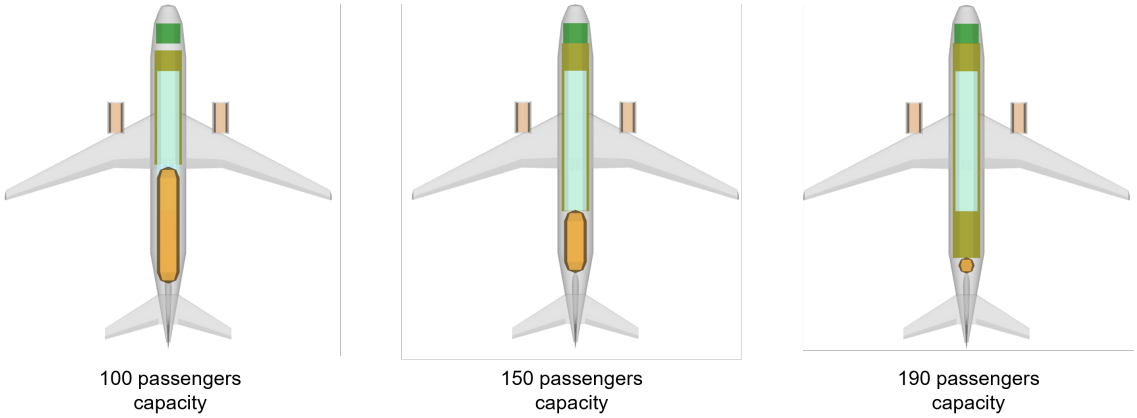

Fig. 9 Stability trade-off study

From the calculate, it shows the stability depends on the weight and the centre of gravity position of the fuel system. In general, if the total mass of the passengers and payload is higher than the fuel system, the aircraft will still remain stable. There are some exceptions when the passengers payload and fuel systems are at similar weight, then it will more depends on cg position. Stability is easier to achieve for fuel with low density such as LH_2 or LNG.

Passengers capacity	100	110	120	130	140	150	160	170	180	190
Payload (kg)	8300	9130	9960	10790	11620	12450	13280	14110	14940	15770
Fuel system (Kerosene)	50103.3	43958.5	40885.5	34738.4	28604	25543.9	19423.7	13303.4	10409.5	2726.48
Stability	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable	Stable
Fuel system (LH_2)	10792.6	9521.2	8885.49	7614.08	6342.66	5706.96	4435.55	3863.27	2528.44	1116.8
Stability	Unstable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable	Stable

Figure 10 and 11 illustrate the centre of gravity and mass of the cabin and fuel tank. It also shows the centre of gravity position when the aircraft has a full and empty fuel tank which both needs to be in front of the neutral point, indicated by the vertical line, to become stable.

VIII. Results

After substituted all these different potential fuels to the aircraft. The total energy consumption, total in-fight emission and total life cycle emission are calculated and presented as follow.

A. Emission

1. Total energy consumption

Ammonia has the most standout energy consumption compared to the other fuels. The higher energy consumption is a direct consequence from the weight and drag penalties for using fuselage fuel tank and extended tanks, which cause by the high energy density and low energy density. Similar situation applies to liquefied natural gas which energy consumption is still noticeably higher than the remaining fuel options.

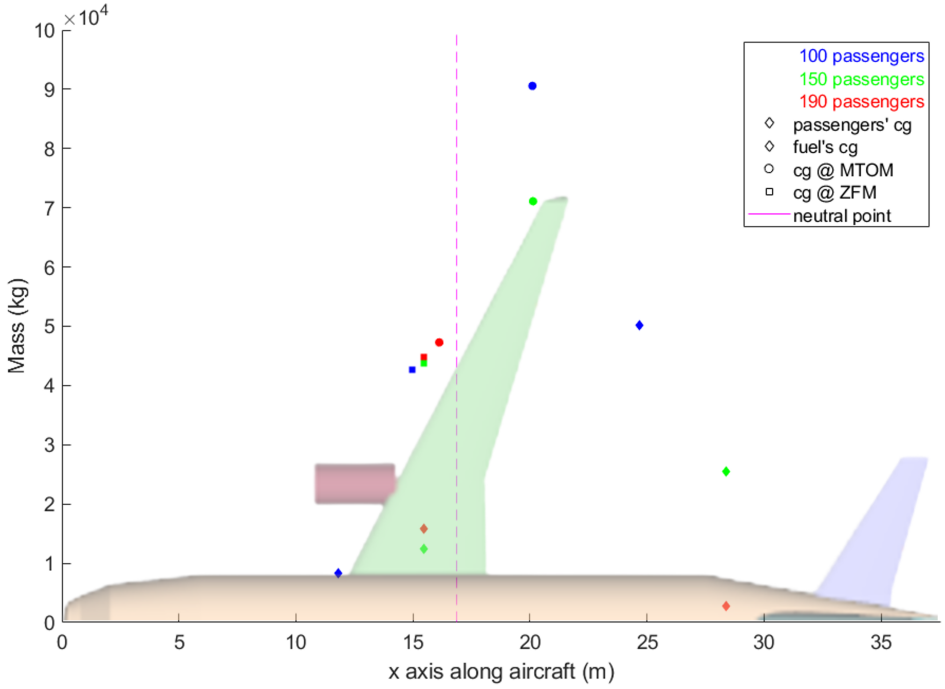

Fig. 10 centre of gravity

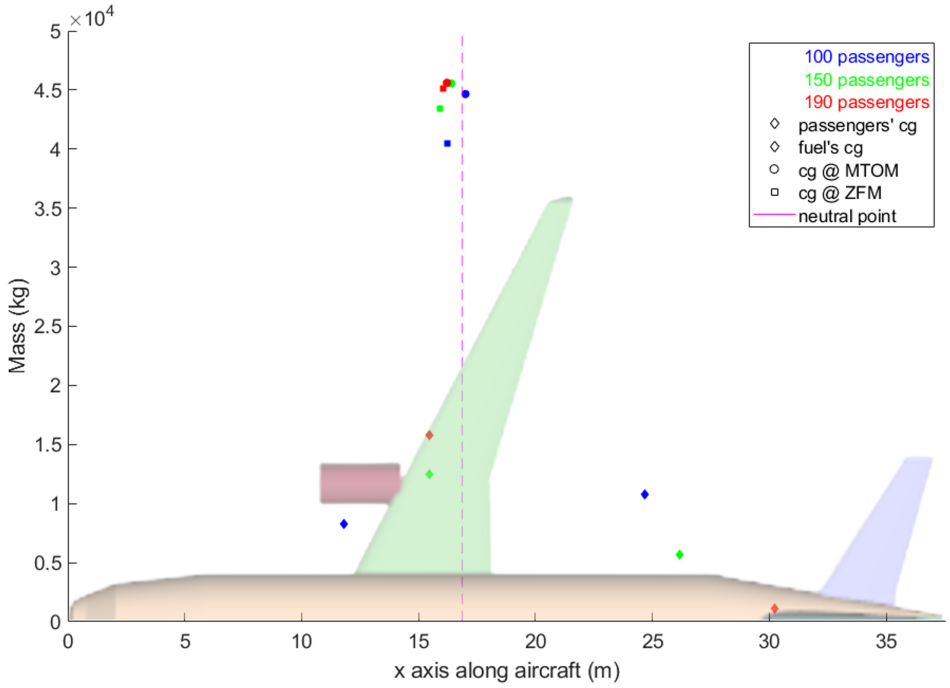

Fig. 11 centre of gravity

Table 4 Emission factors

Fuel	Well-to-Wing emission	Combustion
Kerosene	97.33	72.9
Biofuel	–25.3 ~ 102.2	70.4
LH_2	42.11 ~ 221.64	0
LNG	430	57.29
NH_3	21.21 ~ 119.97	0

2. Total in-flight emissions

Total in-flight emission is calculated based on the GHG emitted during combustion. The emission factor of combustion is listed in Table 4. From Figure 13, it displays the in-flight emission where kerosene, biofuel and LNG shared very similar level of emission in which biofuel has a slightly higher emission compared to the other two. On the other hand, LH_2 and Ammonia does not emit any CO_2 in-flight.

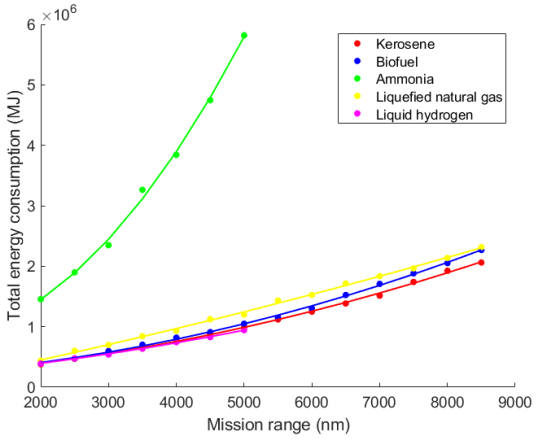

Fig. 12 Total energy consumption of TAW configuration

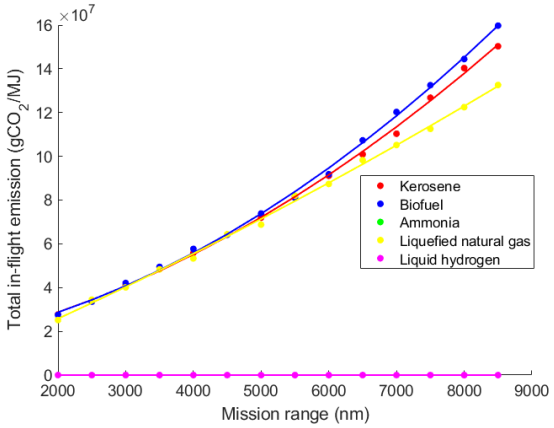

Fig. 13 Total in-flight emissions

3. Total LCA emissions

For the total life cycle emission (LCA), fuel production is also taken into consideration where the results are demonstrated in following figure.

Emission factor during fuel production varies based on different assumptions and production methods, which can significantly affect the results. Figure 14 exhibits realistic estimation which is based on current technological level and industry practice. On the flip side, Figure 15 demonstrates an idealistic estimation which is based on the most sustainable production method possible.

It is clear that given current industry fuel production methods, the use of alternative fuel will not actually provide any improvement in a sustainability prospective. Having said that, nearly all the potential fuel candidates show the potential to achieve a better overall GHG emission compared to conventional kerosene based jet fuel.

IX. Conclusion

The ambition of this study is to model conventional TAW configuration with the application of different alternative fuels, including biofuel, LH2, LNG and ammonia, in different mission range to determine if there is any additional improvement towards the performance and is there an optimum combination of alternative fuel and mission range. The results present a progressive changes in the design when the mission range increases, which include MTOM and fuel consumption. The rate of changes vary depends on the fuel properties.

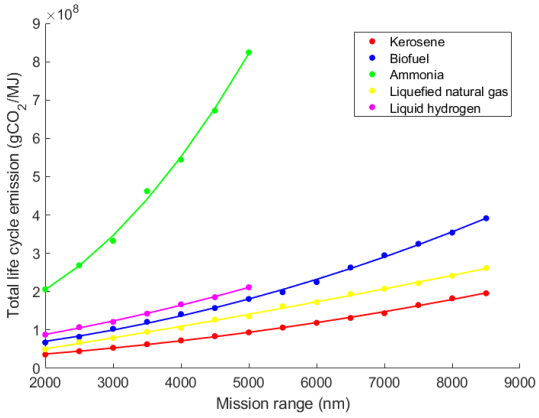

Fig. 14 Realistic estimation of total life cycle emission for TAW configuration

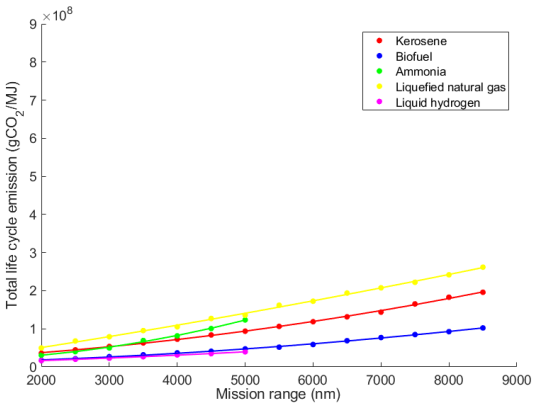

Fig. 15 Idealistic estimation of total life cycle emission for TAW configuration

By comparing these trends, it clearly shows fuels which require extended tank or fuselage fuel tank will noticeably increase energy consumption due to drag and weight penalties and as a consequence increase energy consumption and emissions. Moreover, from the results, it clearly shows that fuel production methods heavily affect the overall emission level and should be taken into consideration instead of just focusing on in-flight emissions. On the flip side, biofuel and hydrogen show a good potential to out perform conventional kerosene based fuel in regards to sustainability given the fuel is produced under sustainable pathways.

X. Future work

Next step of this project is to look into the application of alternative fuels in other novel configurations, such as high aspect ratio wing (HAR) aircraft and blended wing body (BWB) aircraft. These novel configurations provide different fuel tank packaging naturally which possibly to be more suitable for cryogenic fuels and reduce the penalties from extended tanks and fuselage fuel tanks.

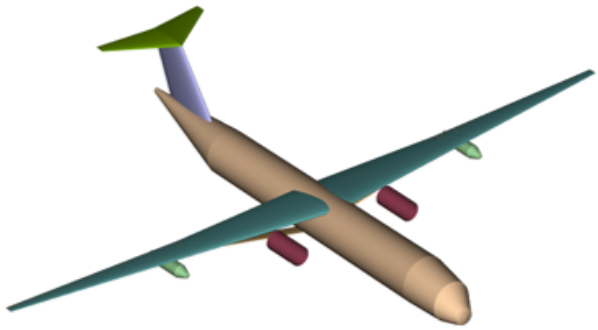

Fig. 16 High aspect ratio wing configuration

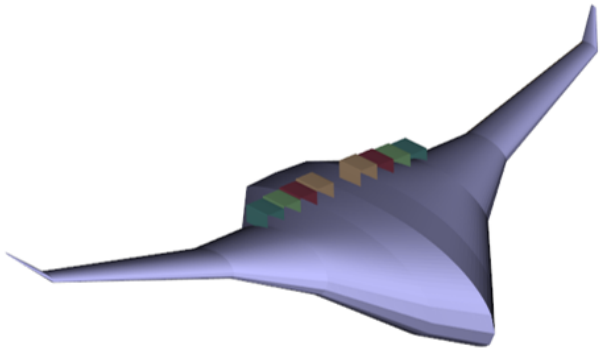

Fig. 17 Blended wing body configuration

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