JUMBO CITY FLYER

Arvind Gangoli Rao
Associate Professor
Faculty of Aerospace Engineering, Delft University of Technology
The Netherlands
A.Gangolirao@tudelft.nl

Director Georg Eitelberg

DNW- German-Dutch Wind Tunnels, The Netherlands
georg.eitelberg@dnw.aero

ABSTRACT

Aviation is forecasted to grow at around 5% every year for next few decades. The internal air traffic within Asia has increased substantially and is driving the growth in aviation. With the increasing urbanization, a substantial part of the air traffic within Asia and around the world is marked by travel between mega cities (with population of around 10 million or more). At present large passenger capacity aircraft (like Boeing 747 or Airbus A330 & A340) are being used to carry passengers between several of these cities which are separated by less than 2000 km. However these large aircraft are optimized for long range missions and are thus inefficient when used on these short range missions. Apart from being expensive in terms of operating costs, these aircraft also produce more emissions per passenger km.

The present paper discusses the proposal for a short range aircraft capable of carrying around 500 passengers in the year 2030. The proposed aircraft called the "Jumbo City Flyer", has payload characteristics similar to Boeing 747-400 but the fuel efficiency of a turboprop. The proposed aircraft can help in cutting down the emissions from aviation to a significant extent. The proposed aircraft is a new concept in civil aviation that has the potential to meet the future energy demands in aviation as well as being sustainable.

1 INTRODUCTION

Aviation is a major player in the world economy and it is growing steadily. It is expected to grow at a rate of 5% annually for the next couple of decades [1]. Add to this the rising fuel costs and the growing global pressure on the aviation industry to reduce its environmental impact, and it becomes obvious that we need better and efficient aircraft in the future.

The anticipated reduction at various fronts (noise, air pollution and fuel consumption) required to meet the future challenges, as envisioned by the Advisory Committee for Research in Aeronautics (ACARE) is shown in Figure 1. It can be seen that from an emission

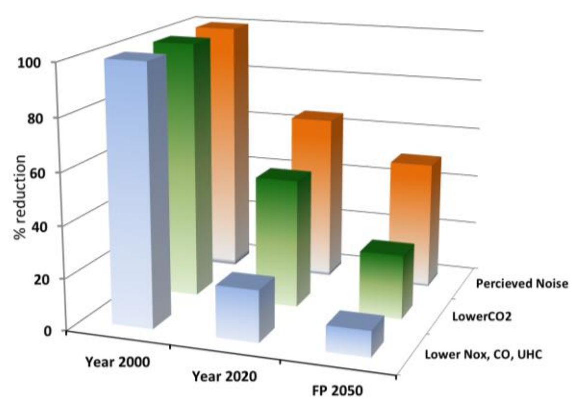


Figure 1. The ACARE goals for civil

reduction point of view, reduction in CO_2, noise and NOx emissions are the most prominent. The aim is to reduce the CO_2 and NOx emission are reduced by 75% and 90% respectively by year 2050 when compared to an typical aircraft in year 2000 [2].

2 MARKET ANALYSIS

With the increase in Asian GDP, the internal air traffic within Asia has increased substantially and this increased demand from Asia is driving the current growth in aviation. The figure 2 below shows the major population & economic centers in South Asia. Most of these population centers are within a range of 2000 km from each other. Due to rapid urbanization in Asia, it is expected that these population centers will grow even further in the coming years.

Figure 2. Major population and economic hubs in South Asia (obtained from Google Maps)

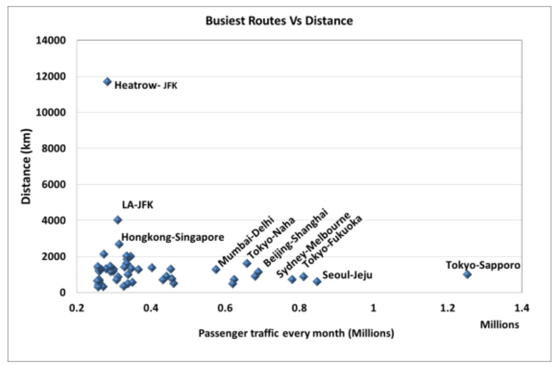


Figure 3. The 50 busiest intercity routes in the World.

The figure 3 shows the distance and passenger traffic for 50 busiest intercity routes in the world and it can be seen that a majority of those routes are in Asia. Thus a new market segment is emerging for aviation. This market is quite different from the short range market in the west which is primarily catered by aircraft like B737, A320, A319, Bombardier C series, etc. With substantial growth in the Asian aviation sector, there might be enough market to design a new kind of specialized aircraft for short range intercity air traffic.

At present, large passenger capacity aircraft such as the Boeing 747 or the Airbus A380 are designed for an entirely different mission, positioning them in the upper right-hand corner of the capacity vs. range diagram shown in figure 4. Currently there is no aircraft designed for a short range high passenger capacity. Therefore an aircraft catering this newly emerging market segment is proposed, called as the "Jumbo City Flyer" (JCF).

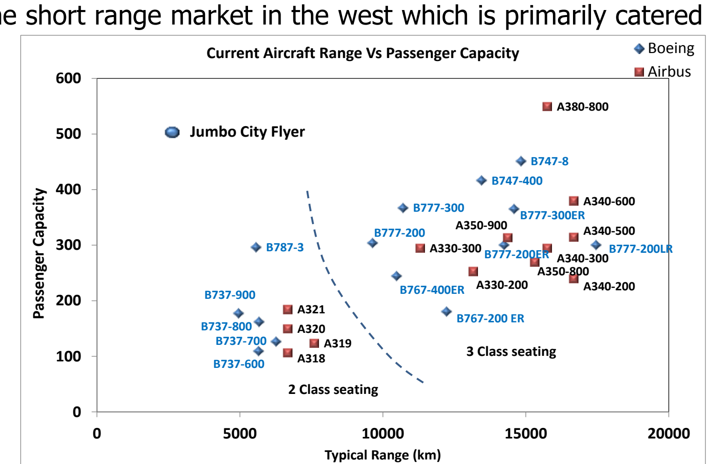


Figure 4. Passenger capacity Vs range for widely used civil aircraft.

In addition to the development of the market, due to the developments in the supply of kerosene, fuel prices are increasingly a major portion of the operating costs. At present the fuel cost in general for all major airlines in the world is around 33% of the total operating costs. However for the Asia pacific region, the fuel cost is approximately 38% of the total operating cost due to the lower labour charges [3]. Using non-optimized aircraft contributes to the fuel cost and emissions per passenger-km substantially. This also means that there would be a huge market for a more fuel efficient aircraft, albeit slower than the current turbo-jets.

The design flight mission of the proposed JCF aircraft (including the reserves) is shown in figure 5. Another operational aspect of such short range aircraft is that the cruise Mach number can be lower than that of current jet aircraft because the decrease in cruise Mach number has little influence on the total time of the flight time (gate to gate), even more so when compared to the door to door time required. Therefore for the design of the JCF, a cruise Mach no. of 0.62 is chosen.

The fact that the JCF is designed to fly slower than current jet aircraft is because this decreases the drag and removes the need for swept wings. An advantage of the straights wing is that a straight wing provides more lift and has a lower structural weight compared to a swept wing of the same span. The lowered flight speed also means turboprops are better suited for the mission than turbofan engines, as turboprops operate more efficiently at Mach 0.62.

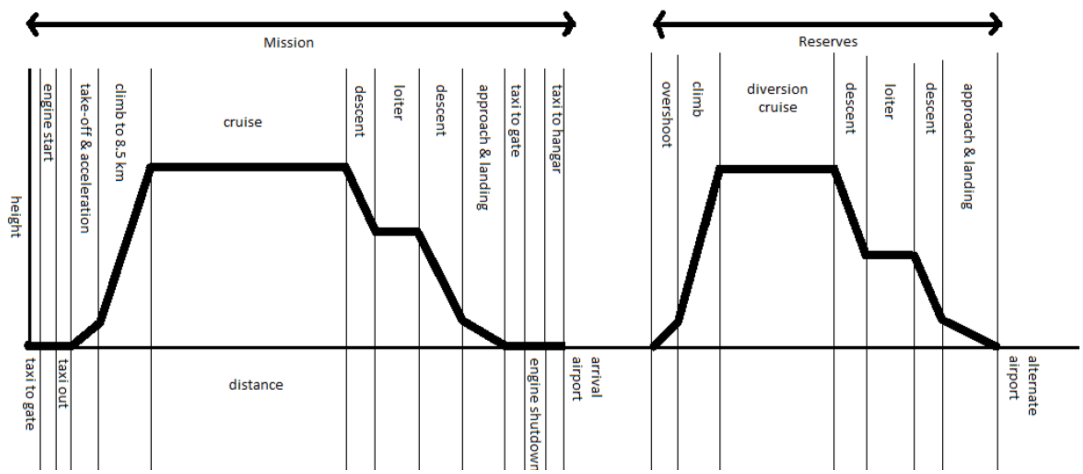


Figure 5. The Flight Mission for Jumbo City Flyer.

3 THE AIRCRAFT CONFIGURATION

For the JCF mission as described above, a conventional fuselage-wing aircraft configuration is most suitable. Classical methods of designing aircraft as mentioned by Raymer [4] and Torenbeek [5] have been used. The general aircraft characteristics are shown in Table.1. The general planform of the JCF is shown in figure 6. It has been designed to carry 500 passengers in a double deck configuration. As can be seen, is the configuration fits well within the 80×80 m box limits. The comparison of JCF with Boeing 747 is shown in figure 7. As can be seen, the fuselage has a lower length but the wingspan is the nearly the same.

Table 1. General Characteristics of the Jumbo City Flyer

Feature	Jumbo City Flyer
General	
Fuselage height [m]	*7.2*
Fuselage width [m]	*6.2*
Total length [m]	*58.3*
Total height [m]	*21.9*
Passengers [Eco/Bus]	*418/96*
Cargo	*32 LD1 containers*
Performance	
Design range [km]	*2500*
Stall speed [m/s]	*76.6*
Cruise speed [m/s]	*190*
Cruise altitude [m]	*9000*
Minimum take-off length [m]	*2300*
Minimum landing length [m]	*2200*
Propulsion	
Fuel Type	*LNG (Liquefied Natural Gas)*
Reference engine type	*Turboprop*
Thrust per engine [kW]	*13,300*
Number of engines	*4*
Wing	
Span [m]	*62.5*
Area [m2]	*391*
Aspect ratio [-]	*10*
Airfoil type	*Updated version of NACA 63A-613*
Incidence angle [deg]	*3*
Dihedral [deg]	*6*
Weight	
MTOW [tonne]	*239*
EOW [tonne]	*114*
FW [tonne]	*56.7*
Payload weight [tonne]	*68.7*
Aerodynamics	
Cl,max,clean [-]	*1.7*
Cl,max,land [-]	*2.3*
Cl,max,take−off [-]	*2.1*
Cd,0 [-]	*0.0165*
Stall Speed	
$V_{stall,clean}$	77
$V_{stall,take\text{-}off}$	68
$V_{stall,landing}$	65

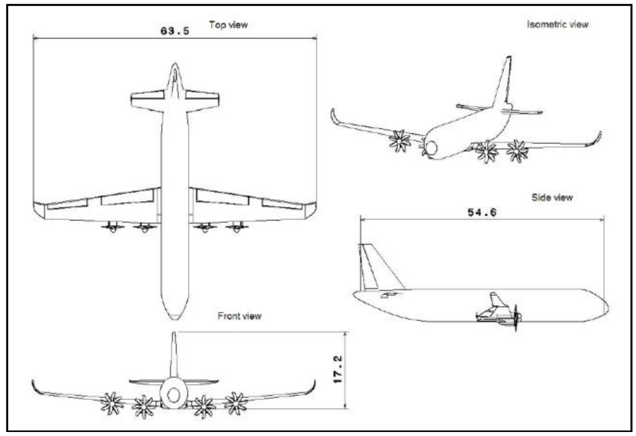


Figure 6. Planform of the Jumbo City Flyer.

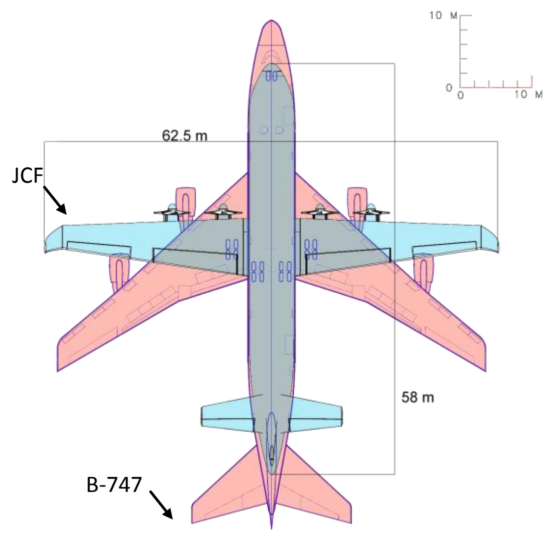


Figure 7. Comparison of Jumbo City Flyer with Boeing 747-400.

4 THE CLASS II PERFORMANCE ANALYSIS

The method used as well as the results from the Class II performance analysis is explained in this section. Since the aircraft configuration fits well within the realms of the existing aircraft technology and design methodology, the procedure of aircraft design as described by Roskam has been utilised [6]. The results from the Class II weight estimation can be found in Table 1.

4.1 Stall

The stall speed is the first characteristic for which the Class II performance analysis has been conducted. The results of the calculations are summarized in Table 1. Similar to the Class I performance analysis, three stall speeds were calculated. These are the stall speed in clean, take-off and landing configuration. As stated in CS-25 [18] and FAR 25 [16], these stall speeds are determined at most forward c.g., while assuming MTOW. Note that the stall characteristics given in Table 1 were determined at sea level in ISA.

4.2 Take-off performance

The take-off distance is the second parameter for which the Class II performance has been investigated. The runway lengths for airports on the 50 busiest routes were determined, resulting in the conservative requirement that the total take-off length should be below 2200 m. In the Class II performance analysis the length of the ground run for the Jumbo City Flyer was calculated to be 2180 m. The aircraft still needs approximately 200 m to climb to the screening height of 15 m. As most airports have a clearway and since the requirement was taken to be conservative, it is assumed that this will not be a problem. Several assumptions have been made for determining the ground run length as listed below:

- FAR 25 is used and verified to be coherent with CS-25.
- Only concrete and asphalt runways are considered.
- Take-off power is assumed to be the maximum available power.
- Density ratio is 0.78, corresponding to an airfield elevation of 2300 m.

4.3 Climb performance

The Class II maximum rate of climb at sea level for the Jumbo City Flyer was determined to be 19.32 m/s (3800 fpm). This climb rate was determined for sea level in ISA. Additionally, the aircraft was assumed to fly in clean configuration at the cruising lift over drag ratio. Since the proposed JCF aircraft uses turboprops for propulsion, the higher thrust lapse rate of turboprops make them ideal for higher climb rates. This is essential to reduce the noise footprint of the proposed aircraft when compared to other conventional aircraft using turbofan engines.

4.4 Payload-range diagram

The requirement for the JCF's range when fully loaded was set at 2500 km. The payload-range diagram for the JCF can be found in figure 8. The point "A" indicates the maximum range for the aircraft loaded with 514 passengers and 20 tonnes of cargo. From point "A" the range increases as the payload is reduced until it reaches point "B". This point indicates the maximum range of 4459 km for the aircraft transporting 100 passengers and 20 tonnes of payload. Finally point "C" indicates the ferry range of 5567 km. The ferry range is important when transporting the aircraft from the manufacturing plant to the customer. A ferry range of 5000 km ensures that the aircraft can be delivered to the corners located around the globe.

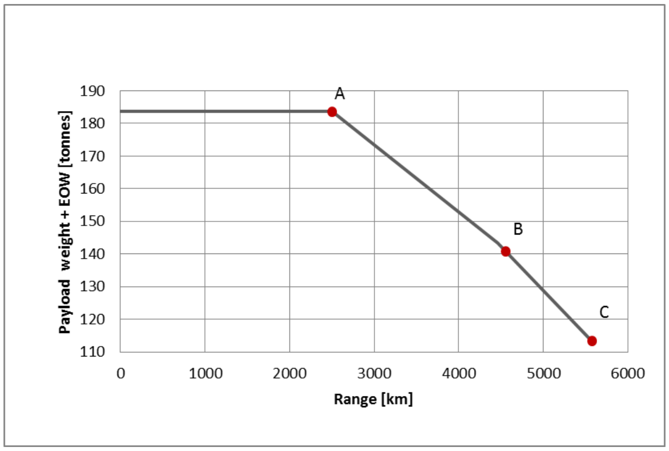


Figure 8. Payload Range Diagram of the proposed Jumbo City Flyer

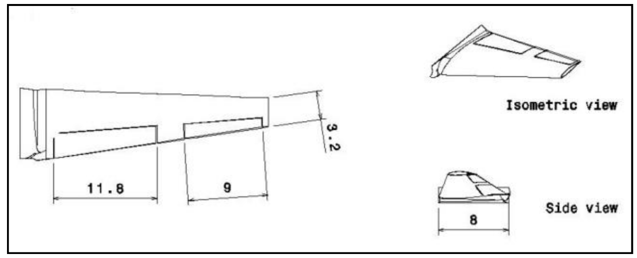


Figure 9. Overview of the Wing Planform.

4.5 Landing Performance

The final performance parameter for which a Class II performance analysis was carried out is the landing distance. It was calculated that the JCF requires a maximum landing field length of 2241m. To determine the landing distance, the following assumptions were made:

- The average flight path angle is assumed to be 0.1 radians, an average value for commercial aircraft.
- The average deceleration in the ground run is assumed to be 0.4, an average value for turboprops.
- It is assumed that no reverse thrust is available. The availability of reverse thrust due to variable pitch propeller can substantially decrease the above mentioned landing distance.

5 THE AERODYNAMIC DESIGN

From the design point, a wing loading of 6000 N/m2 was selected which resulted in a wing area of 391m^2. An aspect ratio of 10 was selected for the Jumbo City Flyer wings, resulting in a wing span of 62.5 m. As mentioned earlier, there is no need for sweep when flying at a Mach number of 0.62. An overview of the wing planform is shown in figure. 9.

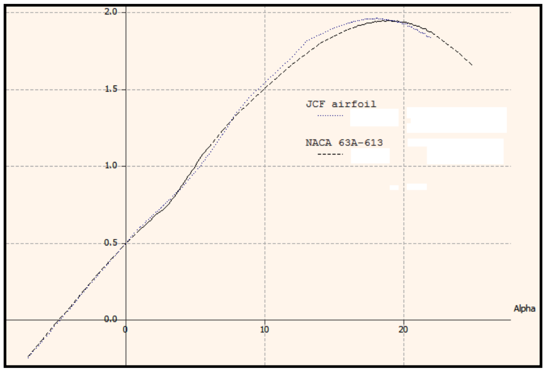


Figure 11 (a). Cl Vs α curve for the JCF airfoil. Re = 35 million

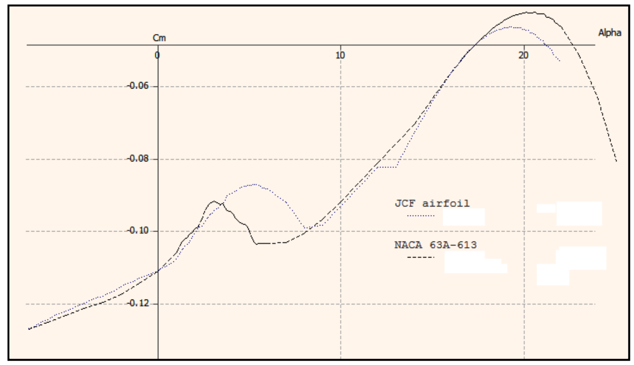


Figure 11 (b). Cm Vs α curve for the JCF airfoil. Re = 35 million

The maximum lift coefficient during take-off and landing (2.1 and 2.3 respectively) are obtained from the design point. Analogous to the clean configuration, the wing should again provide for 1.05 times that value, meaning the maximum lift coefficients should be 2.21 and 2.42 for take-off and landing, respectively.

To size the high-lift devices, the method presented in chapter 12 of Raymer [4] is followed. The high lift device used is the single fowler flaps as this was found to be sufficient. The use of single fowler flaps simplifies the design and minimizes the structural weight substantially. The lift curve for the JCF is shown in figure 11.

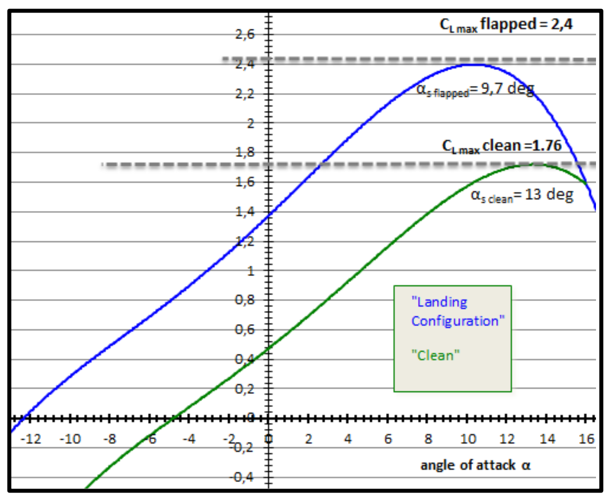


Figure 12. The lift curve for Jumbo City Flyer.

6 THE FUEL AND THE PROPULSION SYSTEM

One of the main challenges of civil aviation is the fuel/energy source in the future. With the increasing demand for global oil usage and limited petroleum resources, it is obvious that the oil prices would increase in the coming years/decades. One of the ways to combat this increase in the oil price is by using alternative fuels which are cheaper than the current fuel. There are several criteria that need to be taken into account while looking for an alternative fuel source for aviation. The figure 13 below shows some of the alternative fuels/energy sources for aviation classified according to terms of both specific energy density (MJ/kg) and volumetric energy density (MJ/lt). Liquid hydrogen (LH2), a cryogenic fuel which is attractive from a sustainability point of view, has a high specific energy density but suffers from a low volumetric energy density and therefore is difficult to be stored in an aircraft.

Liquefied Natural Gas (LNG) is an attractive alternative. It is in between kerosene and LH2 in most of the aspects. The vast natural gas reserves and shale gas reserves would imply a steady supply of LNG for a long time to come. Moreover LNG can also be produced by using renewable energy sources [7].

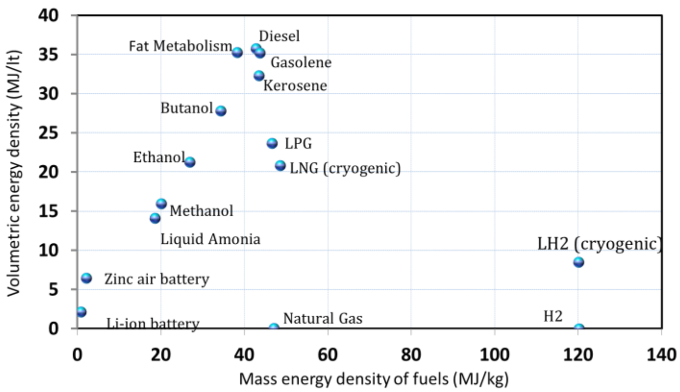


Figure 13. Various fuels/energy sources for aviation [8]

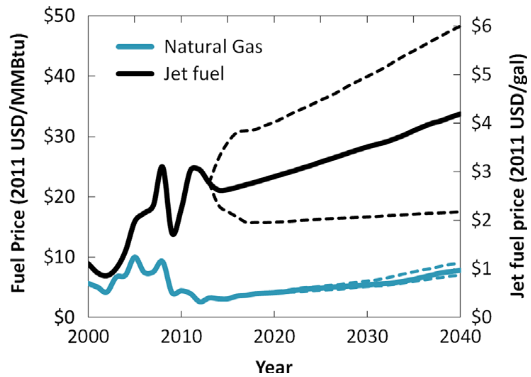


Figure 14. Variation in the price of Kerosene and Natural Gas

The LNG has 15% higher specific energy content than kerosene and the CO2 emission due to its combustion is 25% less for the same energy content. Both these features are attractive for reducing the CO2 footprint of aviation. The natural gas is cheaper as compared to kerosene; the expected variation in the price of both fuels is shown in the figure 14 below [9].

Based on the above mentioned considerations, it was decided to use LNG for the proposed JCF aircraft. The use of LNG as a fuel means a special fuel system is required, as LNG is stored at -162 °C. The specific energy and energy density of LNG lead to a higher fuel volume, but a lower fuel mass, compared to conventional jet fuel. Regular fuel tanks are not designed for these temperatures, so specialized insulated tanks are required. This will increase the weight of the aircraft. However, the advantages offered by the use of LNG were found to offset the possible disadvantages.

Advantages of LNG

- Lower fuel weight compared to kerosene.
- Approximately 25 % reduction in CO2 emission per unit of heat released.
- Approximately 80% reduction of NOx-and particulate emissions.
- Usage of cryogenic heat sink can increase engine thermal efficiency [10].
- The LNG is substantially cheaper than conventional jet fuels.

Disadvantages of LNG

- Requires pressurised tanks for storage resulting in increased aircraft OEW.
- Requires insulation to keep the fuel cool thereby increasing the aircraft OEW further.
- Increased storage space for LNG compared to conventional jet fuels.
- Airport facilities and logistics for tanking LNG are required.

Using natural gas as a fuel is not a problem for the engine as natural gas is a clean fuel which can reduce the NOx formation substantially when compared to kerosene. However an additional heat exchanger has to be used for evaporating the LNG to natural gas. Since LNG is a cryogenic fuel and therefore a good heat sink, it can be used in a beneficial manner to enhance the thermodynamic efficiency of the engine for intercooling, bleed cooling, air-conditioning, etc. This has been discussed in detail in [10] and using the cryogenic fuel for cooling the bleed air used for turbine cooling was found to be most beneficial with SFC reductions in the order of 5% or more.

Since the cruise Mach number for JCF is low, therefore it is attractive to use turboprops as a propulsion system due to its higher propulsive efficiency and consequent lower specific fuel consumption. For the JCF to take off a total of 53,300 kW of power is needed. That means that each of the 4 engines should provide around 13,300 kW of power. No turboprop currently exists that can provide that amount of power, but looking at how the power available for turboprops has developed over time, it is expected that an engine can be developed that is capable of providing the required power by 2025. It is expected that an engine capable of providing the power required for the JCF will be one of the most powerful turboprop of its time. Currently, the Europrop TP400 is the most powerful turboprop in Western world and therefore it is used as a reference for engine parameter calculation purposes. The required engines for the JCF should produce 37 percent more power compared to the Europrop TP400, however this is not a problem as the TP400 can be scaled up to enhance its performance.

Since the mission is a short range mission, the amount of total fuel required for JCF is much less than B-747 or other similar aircraft. Most of the fuel is stored in a multi-bubble insulated centre tank with a volume of 49 m3. Rest of the fuel is stored in the 2 inboard units. All the fuel lines are insulated double pipes with LNG in the inner pie and Nitrogen in the outer shell. This type of construction makes sure that there is no condensation on the pipes and that the pipes remain safe even in case of a fuel leakage.

7 MATERIALS AND STRUCTURE

The structures consist of multiple elements like the wingbox, ribs, frames, stringers or stiffeners and skins. Since different loads are carried by these components, they are split up in two groups: plates/skins and stringers/stiffeners.

A service life in terms of flight cycles has been determined based on reference aircraft. The FAR recommends that on an average commercial aircraft are designed for 20,000 flight cycles [11]. However, a higher number of cycles are considered for the JCF due to its short range mission. To maintain the same service life in years, the JCF is designed for 60,000 flight cycles.

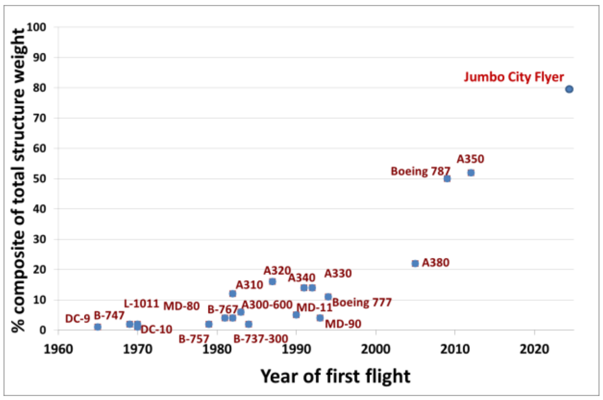
Table 2: Loading conditions per structural part

	Plates / Skins	**Stringers/ Stiffeners**
Type of loading	Axial, bending, torsion	Axial
Mode of loading	Static, fatigue, impact	Static, fatigue
Service life	60,000 flight cycles	60,000 flight cycles
Operating environment	Temperature: 203k–313k; humidity conditions : 0 – 100%	Temperature: 203k–313k; humidity conditions: 0 – 100%

Composite materials have relatively low density while maintaining high Young’s modulus compared to metals and alloys. This also applies for other important material properties. Better fatigue resistance is an important feature of composite materials, since many load cycles will occur during the service life of the JCF. Other properties like resistance to acoustic environment are also important factors, since the use of turboprops will cause more noise and vibrations.

The epoxy HS/carbon fibre composite came out of the selection process as the best material for both the plates/skins as the stringers/stiffeners. For the stringers/stiffeners a different laminate structure of the composite material will be used than for the plates/skins, since stringers and stiffeners will mainly carry axial loads, compared to combined loads for the plates and skins.

As shown in figure 15, there has been a substantial increase in the use of composite materials since the year 2000. Introduction barriers like cost-intensive testing of composite materials in structural parts of the aircraft have now been breached, allowing the usage of composite materials to grow even more in the coming years.



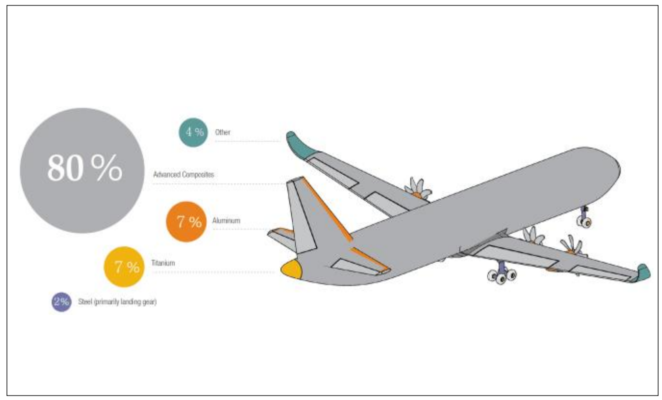


Figure 15. Use of composite materials in commercial aircraft.

Figure 16. Composition of materials used in the Jumbo City Flyer.

Following the trend as shown in figure 15, it can be expected the entire fuselage and wings of the aircraft will be made up of composites. Thus it can be anticipated that by the year 2025, a large part of the aircraft structural mass can be made up of composite materials. It is estimated that approximately 80 percent of the Jumbo City Flyer's total structural mass can be made of composite materials as shown in the figure 16. However it should be noted that even if the percentage of composites used is reduced, the effect on the aircraft OEW is not significant.

Material properties for composite materials are only given for laminates with a 0 fibre orientation. Fibre orientation in each layer as well as the stacking sequence of various layers in a composite laminate can be controlled to generate specific physical and mechanical properties for the composite laminate. Using methods described in Baker [12] and Mallick [13], optimised laminate configurations have been calculated. For the stringers/stiffeners a 0 laminate angle is the best option, since it is assumed that only pure axial loads are carried by these components. For the laminate design of the plates/skins it is determined that a laminate where half of the plies are +45 and -45 fibre angles, while the other half of the plies are unidirectional with 0 fibre angle.

The class II weight estimation method applicable for commercial transport airplanes is used for the JCF. This process consists of averaging results from two separate methods: the General Dynamics (GD) and the Torenbeek methods for each airplane component and summing up these values to get the total maximum take-off weight. Table 3 shows weight major breakdown of the JCF aircraft. Table 4 compares the weight breakdown of JCF with other aircraft.

Table 3: Weight break-up of the Jumbo City Flyer.

Aircraft Component	Weight [tonne]	% of total weight	Position of c.g. [metre]
Structures	60.7	25.4	35.48
Powerplant	15.4	6.4	32.20
Fixed equipment	36.2	15.3	30.34
Payload	68.7	28.7	25.25
Crew	1.17	0.5	30.00
Fuel	56.7	23.7	34.00
Total	239	100	31.18

Table 4: Typical average empty weight fractions in comparison with JCF.

Aircraft Category	**Percentage of MTOW**			
	Structure	**Propulsion**	**Fixed equipment**	**OEW**
Short haul turboprop	**32.0**	**12.5**	**13.5**	**58.0**
Long haul jets	**24.5**	**8.5**	**9.0**	**42.0**
Long haul turboprops	**27.0**	**12**	**12**	**51**
Jumbo City Flyer	**25.5**	**6.5**	**15.4**	**47.9**

It can be seen that the JCF is within reasonable limits in terms of structural and fixed equipment, and OEW in comparison with the passenger transports, according to data obtained from Torenbeek [5]. However, formulae for these methods are derived from statistical data of reference aircraft of similar size and type, of which it can be assumed that aircraft data is relatively old and does not take into account the technological advances in structural and material weight savings for the respective aircraft systems. It is assumed that the lower structure, propulsion and fixed equipment weights is due to technological advancement.

8 THE SEATING ARRANGEMENT

For short range mission, a two class configuration is preferred; therefore the proposed JCF has two classes, the business class and economy class. The business class is positioned at the front of the upper deck, the remainder of the upper deck and the lower deck is economy class. The business class is composed of 16 rows in a 2x2x2 configuration, which results in 96 business seats. The economy compartment on the upper deck is composed of 15 rows, the first 10 rows are in a 2x3x2 configuration resulting in 70 economy seats on the upper deck. The last 5 rows are in a 2x2x2 configuration, resulting 30 economy seats. The lower deck has 37 rows installed. The first 32 rows are in a 3x3x3 configuration and the last 5 in a 2x2x2 configuration, resulting in 318 economy seats. The seating arrangement is shown in figure 17.

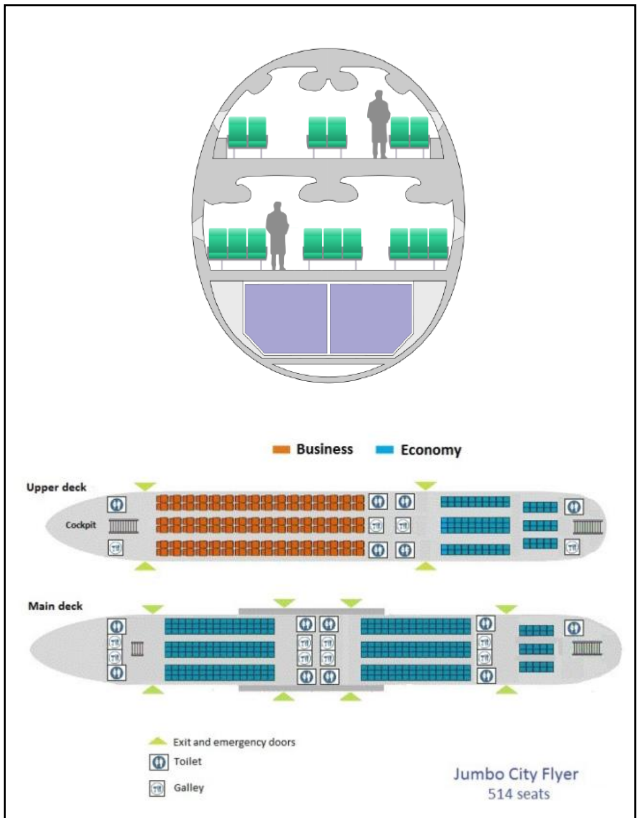


Figure 17. Fuselage Cross section and Passenger Seat Configuration of JCF.

In total 96 business and 418 economy seats are placed. The fuselage includes room for 15 toilets and 12 galleys. The emergency exits are type A doors as required by regulations [14]. For aircraft that can transport more than 299 people all exits must be type I or A. In this case type A is used and for every 110 passengers. The complete aircraft configuration of the proposed JCF aircraft is shown in figure 18.

9 EMISSION COMPARISONS

It is important to compare the emissions from the JCF to Boeing 747-400 for the same mission in order to evaluate the potential reductions in emissions and the potential savings in the operating costs. One of the reasons for using LNG as a fuel was to reduce the CO2 emissions of the JCF. Based on emission factors [15] and the fuel weight, the amount of CO2 that is emitted for a flight by JCF was calculated and the same was done for the reference aircraft Boeing 747-400.

The method used to compare the performance of the JCF with that of a Boeing 747-400 was to use the Breguet formulae to calculate the fuel used on a mission with a fully loaded aircraft carrying enough fuel to fly the mission and loiter for 45 minutes. The unknowns for the Boeing 747-400 were the amount of passengers, empty weight, payload weight, take-off weight and the lift over drag ratio. These data were all found via different sources [16, 17, 18] and implemented into the Breguet formulae, with the range changed for each route of the 50 busiest routes the JCF could perform. This was compared to data found from Fuelplanner [19] and an error margin of about 20 percent was found. This falls within the error range as expected from the Breguet formulae. The error margins are shown in figure 19

Figure 18. The Jumbo City Flyer.

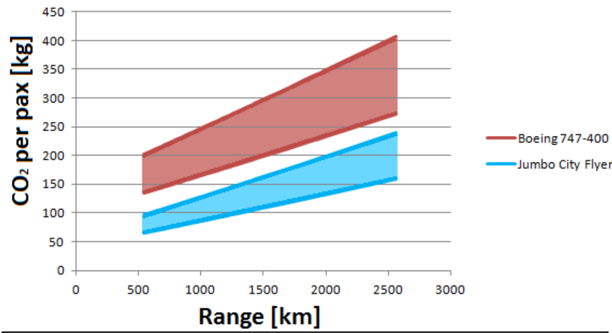


Figure 19. CO2 emission including uncertainties.

Combined with the emission factors for both fuels, this resulted in the CO2 emitted by the Boeing 747-400 and JCF. This allowed the savings on emission to be compared. These range from 43% for a flight from Beijing to Hong Kong up to 52 % for a flight from Los Angeles to San Francisco and can be seen in Table 5, along with the route closest to the average distance of 1250 km as weighted by the amount of passengers.

Table 5: Expected reduction in CO2 emission on various routes.

Flight	Distance [km]	Emitted CO2/pax [kg]		
		B747-400	JCF	Reduction
L.A. – San Francisco	543	169	81	52%
Narita – Incheon	1256	228	122	47%
Beijing - Hong Kong	1991	290	165	43%

There are several reasons why the emission from JCF is lower when compared to B747-400. figure 20 shows four important contributors to the reduction of CO2 emissions. The method of calculation is to take the Boeing 747-400 as a starting point and each parameter subsequently to see how this would change the emissions.

Important to note is the fact that the individual reductions do not show directly in figure 20. For instance, reducing the flight speed from Mach 0.85 to 0.62 would reduce the emissions per mission by 30%. The reason that the reduction shown in figure 20 is less is due to the effect of diminishing

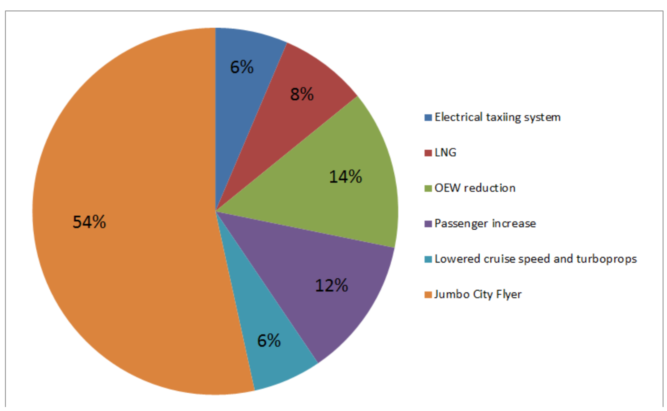


Figure 20. Breakdown of emission reduction as compared to B-747.

returns when calculating percentage reductions, e.g., two reductions of 40% do not mean a total reduction of 80%, but 64 percent. The reduction caused by either is then 50 percent of the total.

10 CONCLUSIONS

A new segment in air transport has been identified. This segment is primarily being driven by the intercity travel between the major population and economic hubs of Asia. The expected growth of this segment is more than the average growth of global aviation due to the growing Asian economy.

The specifics of the segment have been used for designing an aircraft. The simplified geometry with turboprop propulsion system and LNG as fuel were identified as the most suitable option for satisfying the mission requirements. The new aircraft, Jumbo City Flyer, has the potential to reduce the CO2 emissions by around 50 % and operating costs substantially when compared to reference Boeing 747-400.

The JCF concept is based on the technologies which are available within the current generation of aircraft development and have achieved high TRL levels. Therefore the proposed concept is realistic and presents a feasible aircraft for the near future.

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