CHALLENGES IN EUROPEAN AEROSPACE
5TH CEAS AIR & SPACE CONFERENCE

CEAS

Delft, NLD, 7-11 September 2015

Introducing Air to Air Refuelling (AAR) into Civil Aviation – Why & How

Dr. R. K. Nangia
Consulting Engineer, Bristol, UK

ABSTRACT

Over the last decade, the Air-to-Air Refueling (AAR) ideas are being explored towards civil application. There is now renewed confidence that AAR has the potential to bestow a step change towards higher efficiency in civil aviation.

AAR origins, of course, are from Military circles where for last 80+ years. Aircraft are designed, taking for granted, that AAR is available on demand. The military tankers essentially operate like "garages" in sky. The missions need to be successful rather than be overly concerned about fuel usage. Often tankers accompany and refuel shorter range aircraft over longer missions. However, the civil operations are aimed at saving fuel and the tankers will operate over shorter radii.

An overview of metrics provides the understanding of the sensitivities involved in aircraft design and setting up the operational concepts for an AAR-system. This yields the study cases on anticipated aircraft performance and missions. Operational issues and constraints e.g. Turbulence, Air Navigation Services and environmental impact are discussed.

The AAR system. introduced as replacement for today´s Inter-Continental air travel system would give fuel savings and CO_2 emission reductions 15-30% (depending on mission range). Additionally, there are 30-40% weight savings.

To maintain transport capacity, more AAR cruisers may be needed. However, the total flying mass (metal) in the is lower.

The highest benefits from AAR in civil air traffic as the system transforms towards point-A to B rather than the "hub-spoke" solution. The smaller AAR-cruisers inherently give the opportunity for smaller airports to make new connections compared with the larger baseline cruisers.

For a sustainable growth of aviation and meeting the demands from continued urbanisation, there is a clear need to mitigate short flights to other transport modes. The relief in capacity from reducing number of short flights can then be used for long flights, where aviation transport, for the foreseeable future is the only viable solution.

1 INTRODUCTION

The World-wide aviation shows a resilient growth (e.g. Airbus or Boeing www). **Figs. 1-2** interpret this in terms of global "work done" and fuel burn trends for Cargo, Passenger and Total payloads. It is estimated that in 2010, passenger transport represented 75% of global "work done" with cargo making up the other 25%. These ratios are not likely to change significantly over the next 20 years assuming constant growth rates of 5.9% p.a. cargo and 4.5% p.a. passengers.

This means a doubling of the air traffic demand every 15 years. Even if the continued efforts on improving aircraft and engine efficiency are accounted for it will be impossible to meet the increased demand without increasing emissions if the mode of operations is as it is today. Following IPCC, **[1]**, high speed rail can substitute short-distance air travel up to 800 km and in limit to 1500 km (e.g. Beijing – Shanghai). This is one way of mitigating greenhouse emissions and alleviating noise and air pollution that characterise the world's megacities.

The congested airspace over Europe, US and Asia already limits the availability of slots at the big hubs. With continued urbanisation - more megacities on the earth, air transport could be reserved for long distance (intercontinental) travel, where no other viable options exist. Reduction of short flights will allow increased availability of slots for longer flights between city pairs.

The promising ideas that require relatively small changes to aircraft and offer significant fuel benefits

are: Staging flights (hopping), formation flying and Air to Air Refuelling (AAR). Intimately connected with AAR is need for efficient tankers, their design and system logistics.

In **Fig. 2,** fuel burn data has been tentatively extrapolated for estimation of overall Payload Range Efficiency (PRE) values (Cargo, Passenger and Total) for that year. These data include all flights whether they are at full capacity (100% load factor) or wholly inefficient re-positioning flights at zero load factors. We expect current passenger aircraft to have PRE of about 2000 nm at design point with freighter aircraft achieving higher values, approaching 4000 nm, when operating at max load Point A. The low global values indicate an inefficient operation of large aircraft.

Within the EEC FP7 "RECREATE" programme (2011-15), **[2-3]**, a focus was on determining how Cruiser – Feeder option i.e. using AAR, will benefit the fuel efficiencies in near and distant future. A goal was to come up with viable operational concepts and designs where safety considerations, as always, rule over the other areas. The operational set-up depends on the mission flown and on the methodology chosen for how feeders intercept the cruisers. Operational constraints like air traffic management, weather and environmental impact are assessed at all times. Consideration was given to details of operations and the success of certifying aircraft, fuel transfer systems, methods and procedures in order to reach the civil market. So far, no real showstoppers were identified for civil certification of AAR.

2 EMPHASISING SENSITIVITIES FOR DESIGN, METRICS

We summarise the metrics and design sensitivities from the Breguet range equation, following **[4-8]**. These metrics have a strong bearing on consideration and evaluation of AAR aircraft and tankers.

We define WFBS as the fuel used during climbing to cruise altitude approximately 2.2% MTOW over about 100nm range. X is defined as V L/D/sfc, where V is the velocity and L/D, the Lift to Drag Ratio. Strictly, the X factor applies during the cruise phase. However, an equivalent X factor can be obtained by assuming that W2 is the landing weight (ignoring the flight descent phase properties) and W1 is the weight when cruise starts. Using the weight of the fuel burnt during cruise (WFC), we write the weight of the entire fuel block (WFB) for the flight as:

W1 = MTOW – WFBS, W2 = W1 – WFC & WFB = WFC + WFBS

$PRE = R*WP / WFB = WP/WFB * X . \log_e[W1/(W1- WFB)]$

$PRE/X = WP/WFB . \log_e[W1/(W1-WFB)]$

PRE/X is effective correlation parameters for relating different aircraft with varying X factors. For example, small PRE and small X for a given aircraft may lead to similar value for another with large PRE and large X. The real Efficiency parameter is PRE by itself.

The peak value of PRE/X with respect to Z is somewhat difficult to ascertain from practical data because WFBS is not known accurately. This PRE/X character can be more easily explained on basis of theoretical model introduced in **[4]** where the weight of the payload (WP), fuel reserves (WR)

MTOW = c1 MTOW + c2 WP + WOE + WFR + WFB

WOE + WFR = c1 MTOW + (c2 - 1) WP

Point A, Typical value for c2 is 2.0 (c2A), Point D, c2D = 1 + (c2A - 1) WPA / WPD

The ratio WPD/WPA is about 0.85 for short-moderate range aircraft. For long ranges, it is near 0.5.

WFR is near 4.5% MTOW in present day. It depends on sfc and it should reduce to 3.5% MTOW for new aircraft generations.

There is a strong "gearing" between WFBS, WFBR and WPR

	small R	large R	small R to large R
WPR	0.22	0.11	double
WFBR	0.2	0.45	less than half
WFBS/WP	0.1	0.2	twice

We can show that as WFBS reduces the peak value of PRE/X increases. Also, peak PRE/X moves to lower Z.The factor Z has a bearing on consideration and evaluation of designs for AAR. This knowledge is extremely important in comparing short and long range aircraft. We need to ensure that short range aircraft is chosen to be near the peak of the PRE/X ~ Z curve.

To a first approximation, OEW/WP gives a measure of the aircraft structure per unit payload. This factor is an increasing function as range R increases. At R = 3,000nm, the factor is about 2.7 whilst at R = 7,000nm, the value is about 4.8.

"Nangia" Value efficiency parameters have been introduced to relate PRE with MTOW and WOE.

The factor OEW/WP is related to the cost of ownership per unit payload. Relating the non-dimensional fuel efficiency PRE/X and the factor OEW/WP, we define a non-dimensional "Nangia value efficiency" VEOPX = (PRE/X) / (OEW/WP) = (PRE/X)*(WP/OEW).

In dimensional terms, a simpler expression can be envisaged: VEO=PRE/WOE

VEOPX also serves a measure of approach and landing noise. Higher value is better for lower structure weight, costs (acquisition and operating) and landing noise.

Similarly using MTOW as a measure of take-off noise and emissions, we define the "Nangia Value efficiency" VEMPX = (PRE/X) / (MTOW/WP) = (PRE/X)*(WP/MTOW)

In dimensional terms, we use: VEM=PRE/MTOW. VEMPX denotes the fuel efficiency per total weight per unit payload. This also serves a measure of airport and other fees. Higher value is better for lower noise emissions and operating costs.

3 OPERATIONAL CONCEPTS SELECTION, CRUISERS & TANKERS DESIGN

Even if long flights only make up for the smaller fraction of all flights, they do burn a large proportion of fuel in air transport. Hence, focus is on long range intercontinental transport where the potential for fuel saving is high and no other real option to air travel exists.

Based on efficiency and AAR considerations in **[4-8]**, the non-dimensional metric w r t to Z=R/X has allowed incorporation of realistic near-future technology levels in the design space. The Cruiser and Tanker AAR concepts are set as follows:

Cruisers

- 250 passenger capacity, Design Range 2500-3000 nm
- Max Take Off Weight 240,000 lb
- Specific Fuel Consumption (sfc) 0.525

For comparisons, a long-range cruiser needs to have a double the range.

For the Tanker

- Offload capability – 35,000 lb per each refuel of a Cruiser, up to three operations
- Flight profile – Two to Three hours total flying time. Least the better
- AAR procedure - 20 minutes including a wet contact for five minutes
- Examine different formations. Tanker at rear prefered

4 METRICS & EFFICIENT CRUISERS

The importance of X-factor is to be emphasised. **Fig. 3** shows that current aircraft demonstrate a very wide range of X factors. Short range aircraft between 12 –13,000 nm, Moderate range aircraft between 12,500 -14,000, Long range Aircraft are touch 17,500. A 30% spread is seen.

Fig. 4 reflects the understanding on typical X factor values and how it can be interpreted and improved. The cruise speed enhancement is somewhat limited. However L/D and sfc continue to evolve with technology albeit at a very low rate. This also indicates scope for novel configurations.

Fig. 5 emphasises the importance of X factor via L/D in the AAR context **[4]**. Assume a total range of 6000 nm, and employ a short range aircraft (A) with AAR at 3000 nm to fulfil the mission and compare with an aircraft (B, L/D=20) for the whole mission without AAR. The short range (A) with L/D of about 12 will be just as heavy as the aircraft (B). So AAR does not benefit the situation. On the other hand, (A) - L/D of 20 saves 45% in weight compared with aircraft (B) with associated fuel savings.

We emphasise that in any analyses for AAR, we need to ensure that X factors for the shorter-range and longer-range aircraft are equivalent. There have been several studies, in which this rigour has been overlooked and therefore, less than optimum figures (even misleading ones) have been found.

For 250 passengers, **Fig. 6** shows the effect of X-factor on MTOW variations with range up to 9000 nm. **Fig. 7** refers to the effect of X on WFB variation with Range up to 4000 nm. Note selected points for

existing aircraft. With X-factor at 17,500 nm, we note that for 2500 nm range, the block fuel is of the order of 35,000 lb

Fig. 8 shows WFB ~ range relationships for X varying between 13000 to 18500 nm.

Fig. 9 shows PRE variation over Design Ranges from 1,500 nm to 6,000 nm, at X values from 13,000 to 18,500 nm. The design range has been extended, beyond that anticipated for a short range Cruiser using AAR, to include current, efficient long range aircraft e.g. the A330-200. We emphasise that this is not PRE variation with Range for any one aircraft.

It is significant that at their design points, the current civil aircraft have similar PRE (2000 to 2300). This implies that a B737-700 could be refuelled once at 3000 nm and achieve the same PRE as an A330-300. The B737-700 has relatively low efficiency (X = 12,300 nm) and MTOW of 154,500 lb. The A330-200 has higher efficiency (X=17,000 nm) and weighs over three times the B737-700. If the B737-700 were to be "re-designed" for the same design range but achieving modern efficiency levels of X=17,000 nm, its PRE would rise to near 3,500 nm, an improvement over the A330-200 of over 50%. This can be directly related to fuel burn saving with an allowance for tanker fuel.

Peak PRE occurs at increasing Design Range as X increases (near 1,500 nm for X=13,000 nm to 2,200 nm for X=18,500 nm). Such effects need to be taken into account for selection of the Design Point for the Cruiser aircraft at the estimated achievable efficiency level.

Fig.10 shows PRE/X ~ Z relationships. Large values of X need to be accompanied by large values of PRE to fall on the curves. If the short and long range aircraft lie either side of the peak PRE/X ~ Z curve and the differences in PRE become smaller. There is an important inference: to ensure that PRE/X for the smaller range cruiser should be at the peak or just to the right of the peak on Z base.

Fig.11 shows "Nangia" value efficiencies. Note how quickly these drop as Z increases. Long-range cruiser is only at 1/3rd of the value for the shorter range cruisers.

4.1 Inferences towards AAR

It is important to appreciate the fuel and weight efficiencies from airline perspective. **Fig. 12** shows the interpretations of the Weight, Payload and derived PRE/X for 3 designs for different ranges (2500, 5000 & 7500 nm). In **Fig. 13**, note the high gains in Value efficiency for using the 2500nm cruiser over longer ranges. **Figs.12-13** enable a confident judgement of targets for the design work. Although most of the analysis is for point D operation, there are possibilities for point A operations for increasing gains as mentioned in **[5]**.

5 MILITARY & CIVIL AAR TANKERS - DIFFERENCES

The military tankers are often multi-role with long operation radii (range capabilities), **Fig. 14**. The offloads decrease as the range increases. Often several support tankers are needed in a military operation. The dedicated Military tankers e.g. KC-135 are capable of carrying a fuel load of 65% of MTOW. For the civil scenario we need smaller ranges (about 1000 nm) and a similar fuel capability of 65% MTOW can be assumed. Each tanker mission is capable of refuelling 2 to 4 cruisers, **Fig.15**. Military refuel operations are usually at lower altitudes nearer 20,000ft, avoiding civil flights. In civil context, if the tanker has sufficient thrust, such limits need not apply. The foregoing considerations essentially differentiate between civil and military tankers.

Fig.16 shows an example of how a tanker, the size of B757 in weight could be envisaged as a flying wing layout or one with a "pencil" fuselage. This would imply lightness and efficiency (high L/D).

Fig.17 shows an example of fuel burn and MTOW advantages afforded by AAR over 6000 nm route, using 3000 nm cruiser. Tanker fuel at RT=4 is included. The effect of X is emphasised. If the short range aircraft has smaller X. then we always get a MTOW advantage but fuel burn reduces. Such graphs need to be studied for 5000 nm range also.

Fig.18 & 19 emphasise the need for smaller tankers as X-factors increase or number of refuel operations decrease per tanker. Even an A321 could be modified into a very effective tanker, capable of 3 refuel operations. However, we can imagine newer efficient tanker types, with very much slimmer fuselages and low drag. Li **[9]** has studied small Joined-wing Tanker.

5.1 Range Variations for AAR, Transporting a Block of 3000 pax in a day

For 250 pax over 2500 nm, **Fig.20** compares non-stop long-range flights and refuelled flights. Note the fuel burn figures. Similar numbers from other ranges lead to **Fig.21**, assuming a block of 3000 passengers travelling in a day over different route lengths. Note the substantial fuel burn and TOW advantages afforded by AAR using cruisers capable of 2000, 2500 and 3000 nm lengths. Shorter service routes require one refuel operation. The longer routes may require 2 refuels.

In a wider context, with the Aviation scene growing and the need for point-to-point flights, there is room for different capacity Cruisers, say 150 to 350 pax with ranges from 2000 to 3500 nm. This way, "thin" or "thick" routes can all be catered for.

This analysis has given the confidence and allows consideration of a realistic World-wide scenario.

6 OPERATIONAL TRAFFIC NETWORK CONCEPT WITH AAR

The current Traffic system for longer ranges is based on (Feeder - Hub – Hub - Feeder) principles. allowing large aircraft flights between major International hubs. This implies that passengers arrive at the hubs, via other transport means, surface or air. The hubs serve a considerable proportion of connecting and in-transit pax in relation to total pax. At LHR in 2012, 37% of total passengers were in transit i.e. flying in to fly out. The most popular destinations e.g. New York, Dubai, Dublin, Frankfurt and Amsterdam are all hubs. Further, passengers transferring to a "sister" airport for continuing their onward journeys are not listed as transfer passengers from Heathrow. As a continuing example, Heathrow has at least four "sister" airports: Gatwick, Stansted, Luton and London City. Numbers & Statistics games!

AMS (Schiphol) figure for transit passengers is higher at 50+% and it may possibly include LHR as a popular destination. Hong Kong airport handles aircraft operations (cargo and pax), one every minute.

Infer that a typical large hub-to-hub flight, **Fig.22**, may well have close to 50% of passengers arriving via smaller feeders or connecting flights. Similarly at the destination, 50% of passengers will need feeder and connecting flights. In the nature of things – some passengers are "re-tracking", over regions close to their original or final destinations. So all this implies major time delays and inconvenience for a very significant proportion of passengers.

Today the hubs are large cities (or megacities) with a population over 4 million. Inherently, the megacities are the popular destinations and the increasing number of persons on the Earth will continue the urbanisation trend and many airports will be on the edge of their capacity. LHR is at 99% capacity. The operating slots are at premium. Most take-offs involve a wait of 15-20 min. on the tarmac. Arriving flights stack up, loitering, wasting fuel – 20-30 min.

The hub-spoke design may be economically efficient for airlines as the focus is on intercontinental infrastructure to a few locations. However from an environmental perspective it makes little sense to fly people via a hub, if with AAR, they could be flown directly.

To open up a new intercontinental " point-to-point connection" from an airport in a "mid-sized city" that today has no (or few) intercontinental connections, will of course only be introduced if there is a business case (passenger demand) for that connection.

A complete removal of the hub-spoke system is not realistic in the near term, but for the future the system has to be pushed away. According to Eurocontrol, there were 9.55 million controlled (IFR) flights in Europe 2012. About 70% were shorter than two hours. If only 10% of the short flights were mitigated to other transport sectors and it represents close to 700,000 flights which, as a comparison, is more than the 500,000 flights Heathrow handles in a year.

Apart from major fuel and weight savings, AAR offers will reduce pressure on the large hubs - a relief in the systems immediately; Pt A to B routing is encouraged straight away. Additionally time is saved – connecting flights are minimised. To emphasise this with an example, consider 3000 passengers travelling via say 6 large aircraft (500-seaters) from a hub over longer ranges.

At departure, 1500 pax would have arrived via feeder connecting flights. The question of how many such flights is intrinsically difficult to assess. In "dribs and drabs", many such flights would be included over a period of time and transit time allowed. In minimum terms and with least transit delays, for a 500-seater, 250 transit pax could arrive from 2 to 3 feeders or short-range aircraft. So, for 3000 pax, an

answer is 12 to 18 connecting flights. These serve 6 large aircraft – 500 pax each, imply 6 hub pairs being served. At arrival, 1500 pax will connect for their final destination via feeders, 10-20 flights.

With AAR, we infer that 12 aircraft carrying 250 pax each connect 12 city pairs. Of course, many scenarios can be visualised and in a more realistic sense, there will be many thousands of pax flying from a hub per day. So several city pairs will be facilitated with AAR.

Total number of flights may well decrease with AAR. The amount of "metal" in air will be less as Payload fractions of AAR aircraft are close to 22% c.f. conventional long-range aircraft with about 10%. This really constitutes a step change and departure from current thinking. There remains a need for modelling such aspects in greater detail.

7 TANKER BASES NETWORK & LOCATIONS

Fig.23 shows that city pair network can be established, using AAR zones conveniently located. Besides fuel savings, this will also ensure time savings. Despatch Reliability improves.

AAR Safety considerations (weather, availability etc.) will imply that fail-safe operations exist at all times. A favourable approach is to start with tankers and convenient bases and work outwards to include flights from many city pairs. This is in contrast to prevailing ideas that we begin with existing airlines network patterns and then site intermediate tanker bases on popular routes. The existing route network will naturally alter as AAR becomes established.

Consider a twin tanker base network, **Fig.24**. set up 800 – 1000 nm apart (representing tanker flight of 2 to 3 hours). The tankers can perform 2-4 operations, becoming lighter after every operation (increasing the distance and time capabilities).

This allows a greater coverage of airports within 2500 - 3000 radius of each tanker base. Further the tankers could fly mostly on straight tracks between the bases. However, tankers could still be based on one airport depending on the demand. This system then enlarges the refuelling domain of the tankers to be in the region of 1500 to 2000 nm.

As the traffic builds up on dense routes, the ideas could be extended to locating three tanker bases (nearly equally spaced). This will add to safety and despatch reliability.

Fig.25 shows how the tanker range extends during the process of a number of refuel operations. Additionally high T/W is available for 2nd offloads onwards. This may allow longer relative spacing's between the "cluster" of tanker bases. Can we exploit such incidental benefits!

There are several other benefits that arise as the system matures and aircraft become smaller: MTOW near 250,000 lb and Regional airports become truly "International".

- Less noise - less night flying restrictions
- Less congestion into airports. Cost Savings again!
- Less need for Terminals and Buildings at hubs
- Less Fuel storage at airports 30-50%. Less ground tanker movements or pipes 30-40%

8 COSTING IMPLICATIONS

Predicting costs and then comparing them remains an "art form" with a strong element of subjectivity in any method: assumptions made and complexity introduced. In terms of Nangia "Value efficiency parameters", we can infer the underlying delta trends much more clearly and readily.

With our costs prediction based on updating of AEA method, **Fig.26** shows the COC trend in terms of units of $/hr/passengers with Range and Z. A trip of 5000 nm implies 28% cost increase over a trip of 2500 nm. This type of basic information relating finance and flight parameters underpins the more detailed studies to be followed in due course for AAR.

9 OPERATIONAL CONSTRAINTS FOR AAR

9.1 Tanker Operation

We refer to **Figs.27-28**. For good aerodynamic control over the refuelling boom, higher manoeuvrability for the aircraft, and also lower probability of turbulence the refuelling height and speed limits are set near 26,000 feet at Mach less than 0.8. This is based on work with conventional (centre-

line) tanking formation - tanker ahead and downstream downwash effects on the Cruiser in **[2]**. One reason for military AAR being at lower altitudes nearer 20,000 ft is to avoid civil flights.

Unconventional tanker layouts can be proposed, allowing downwash effects to be ameliorated (by moving away from centre-line restrictions). Some "new Unconventional" configurations envisaged work for moderate ranges (allowing small fuel capacity). So that blends in well with future aircraft design. Further work is needed with tanker behind the Cruiser. Tanker will have higher T/W capability and a higher altitude ceiling. The boom will be in lower dynamic pressures.

9.2 Capacity Aspects

We emphasised a scenario with pre-selected design parameters to maximise fuel savings. In real life, cruiser size will vary. One size, would not fit all operations and routes. For an airline, the available capacity per unit time is the product of seats and the average speed. Naturally, reducing speed or the number of available seats will lead to reduced transport capacity per unit of time. Airlines operate globally - in the air 24/7. The transport capacity and scheduling are real constraints, **Figs.29-30**.

With AAR to maintain capacity means smaller cruisers. The increase in LTO's depends on the payload capacity ratio (n) between the baseline Cruiser (B) and the intended AAR Cruiser. The number of refuelling operations each tanker performs per mission (f) also affects the LTO's in an AAR system:

$$\frac{LTO_{AAR}}{LTO_B} = \frac{n_B}{n_{AAR}}\left(1 + \frac{1}{f}\right)$$

At first sight, it might appear that by just replacing today´s system with AAR would need more aircraft in total! However, it is very important to remember the Payload to MTOW ratio for the cruiser (with refuelling) is nearly double that for the conventional long range aircraft. With AAR, fuel savings are accompanied by weight savings. In a properly evolved traffic scenario, there will actually be less "aircraft metal" in the air. In the longer term, the increase in LTOs with AAR will lead to a system with more city pairs. Using smaller cruisers, it will also be easier to justify new point to point connections. In the long run, the use of smaller AAR cruisers is a "win-win" solution.

Fig.31 summarises and acts a reminder for Tanker strategy trade-offs studies needed for AAR.

10 INFERENCES ABOUT ENVIRONMENT (WITH REFERENCE TO FIGS.33-34)

10.1 Weather Considerations

The role of weather is important. The forecasts allow route planning to avoid natural phenomena hazards (**Fig.32**) e.g. lightning, turbulence, in-flight icing, volcanic ash and hence the fuel reserves needed **[6-12].**

The AAR operation implies contact in mid-air. Hazards en-route during flight can make fuel transfer impossible to perform in a safe way. The military AAR, is conducted 24/7 but always visually (free from clouds) and in areas free from lightning, icing or turbulence. In future, we can see the operations becoming completely automatic (US Navy has flight-tested UCAV's).

A future civil AAR system will use a similar forecasting system as the military does today (on a daily basis) to identify safe AAR refuelling areas.

10.2 Climate Impact

The impact of Aviation on climate remains a controversial topic. Assuming continued use of traditional carbon based fuels in combination with the predicted growth of the sector poses sustainability question for future. However, the AAR concept is an option in the right direction.

Contrails produced are of concern. A system with AAR will be no different from today´s baseline. The tankers with the proposed refuelling envelope generate very little contrails since the temperatures needed for contrail formation (below -40°C) are very rare on 26,000 ft.

The emitted sulphate aerosols and the methane reductions caused by NOx are the only processes having a negative (cooling) impact on the radiative forcing. All the other aircraft induced emissions CO2, water vapour, soot, and contrails have a positive (warming) impact on the radiative forcing and the total net contribution is on the order of 0.05 W/m^2 **[12]**. This excludes aviation induced cirrus clouds.

Compared with the baseline (today) an introduction of AAR will have a major favourable impact on the direct CO_2 emissions (reduction) but for the non CO_2 emissions will be at about the same level.

10.3 Noise Considerations

The "Nangia value efficiency" is a good first order approximation of the noise impact from aircraft. The envisaged AAR Cruisers with high payload range efficiencies will have a positive favourable impact on noise around airports, **Fig.33**.

Using typical current-day aircraft types, transitioning towards an AAR-system is likely to result in a reduction of the noise-exposed area, as far as high-intensity noise is concerned. For low-intensity noise levels, it is not clear that AAR will improve the situation since there may be more Landing and Take-offs (LTO) albeit with smaller aircraft to cope with a greater demand.

In a fully evolved AAR system (reduced pressure at hubs), the number of LTO's might be comparable. The AAR-cruiser would benefit from any noise reduction techniques being developed.

10.4 Local Air Quality LAQ

Aircraft engine emits NO_x, CO, HC and particulates (soot) which can be hazardous to people and the environment. Larger engines emit more than smaller engines so AAR would be beneficial, **Fig.34**. However, there is no simple proportionality between the emitted substances.

Preliminary studies **[2]** based on Schiphol emissions data showed that for the current turbofan engines, the amount of carbon monoxide (CO) produced by all aircraft during a year, decreased only slightly. However, the production of hydrocarbon (HC) and NOx decreased very significantly.

Fig.35 summarises the estimated Environmental impact of AAR in a more graphic way. Note the benefits in noise, CO2 and LAQ.

10.5 Air Traffic Control & Navigation Service

Apart from developing Air Traffic Control regulations allowing for in-flight refuelling, no fundamental new issues for Air Navigation Service can be envisaged, **Fig.36**. The airspace is already congested in many parts of Europe, US and Asia. Note a day-plan at NATS, Prestwick (19 Jan 2015). The Oceana Traffic is arranged to fly in "Tubes spaces" 60nm apart. Longitudinal Separation is maintained at 10 mins to allow for aircraft at different speeds and heights. Similar situation would exist in Far East space. The increasing demand for air transport will be, with or without AAR, a major challenge around the world.

There are several Air Traffic Management projects aiming for the "the perfect trajectory" where capacity will be high and the environmental impact low. However, trade-offs between capacity and environmental impact in a complex traffic environment are a non-trivial issue.

Shortening the time between take-offs and landing at airports in another way to increase capacity. This is also a subject under research and some improvements can be expected, however, the wake vortices produced during take-off runs and landings will maintain a flight safety hazard and will set a limit for the attainable capacity.

10.6 Certification Issues, Conversions

Following **[10-11]** and **Figs.37-38**, AAR operation needs to be automatic and maintain civil safety standards i.e. 1 in10^{-9} rather than being autonomous. Autonomous AAR is beyond the scope of current civil certification. With recent experience on A400M certification background, automatic civil AAR will be highly dependent on developing specific high integrity Flight Management System functionality. Handling Qualities, Flight Control Laws, Navigation and Hazard Analysis activities will be expanded beyond the civil parameters.

We shall need to account for treatment of fuel spillage and fire risks more involved than simply preventing fuel tank explosion. We may need to adopt Military standards for signalling and markings.

AAR is a demanding task in terms of crew workload and the associated human factors. Responsibility for control of the operation and making the AAR bracket must be with a dedicated tanker crew. What follows from this is that the tanker will connect from astern and below, leaving the receiver crew to simply deploy and recover the fuel transfer equipment. Tanker pilots will make the contacts, control the fuel offload, disconnect and take up the heading to the next rendezvous. From the receiver crew perspective the rendezvous point would be treated as a waypoint in the flight plan that included a refuelling phase. Contemporary AAR technologies in UK lead to use of drogue rather than boom refuelling. Boom refuelling, potentially, can be at faster speeds and currently requires a boom "pilot" to make contact and introduces a chance of human error. However automation will obviate such concerns

in due course. With the drogue approach in early days, the receiver (with regular airline crew) will trail a drogue for the tanker (piloted by specifically trained and type-rated crew).

The conversion of airliners to tanker and receiver roles has several examples: the classic VC-10, contemporary A330. Civil AAR modifications would be similar but with an element of role reversal for the proposed configuration. The receiver/airliner could be modified to incorporate a centre-line Hose Drum Unit (HDU), mounted at the rear of the aircraft and with a hose tunnel penetrating the aft pressure bulkhead. Received fuel would be first transferred into the centre wing tank and then out to engine feed tanks. On the tanker, an AAR probe would be added to the skull of the cockpit and connected to the centre wing tank for fuel dispense. The significant difference between this and today's military heavy aircraft configurations is that the tanker will pump "uphill" as it joins from astern and below. The necessary fuel system transfer gallery installation will inevitably involve running through pressurised areas. This is not an uncommon practice given the installation of Auxiliary Cargo Tanks (ACT) such as on the Airbus Corporate Jet ACJ-319. Design precautions ensure that all fuel pipes within the pressurised area are double-walled and a leak monitor is incorporated in the void between the pipes. The HDU installation would include ventilation around the unit. Fuel transfer lines within engine rotor burst areas would be protected by break-wires that if cut would stop all fuel transfers. This is common practice on today's airliners for fuel supplies to Auxiliary Power Units and transfer lines for tail plane trim tanks.

The ACJ-319 is a near-tanker conversion (except for a business flavour - fittings for 8 VIP). It can house 6 Auxiliary Cargo Tanks fitted increasing fuel capacity to 40,990 litres and range to 11,100km! We can imagine a full tanker conversion (no pax) to be near 60,000 litres, range about 3000 km.

AAR fuel system functionality should be supported by corresponding avionics. A State-of the-art Flight Management System (FMS) would include pre-programmed rendezvous and AAR bracket patterns. FMS functionality will also extend to predicting fuel used at the each flight plan waypoint taking into account any dispense or receipt phases. The cockpit Human Machine Interface would comprise of an AAR multi-functional display so that crews can see at a glance all valve states, tank quantities, fuel transfer/receipt targets, position of trailed hoses and any other relevant AAR system parameters. Soft keys on the display will allow crew control of the fuel transfer.

11 CONCLUDING REMARKS

Continuing Work in many facets of the AAR subject has led to consolidations, revisions and emergence of new ideas. These aspects have been summarized (**Figs. 39-43**)

- Replacing today´s Intercontinental air transport system (as it is) with AAR can reduce fuel burn and direct CO_2 emission by 15-30%.
- Number of LTO's and aircraft may increase; however, the total mass of the system in air will be lower.
- Operational constraints on the system with present traffic load will be manageable (scheduling, workload on feeder bases and impact from weather (mainly turbulence)
- Local environment – better or same (Noise, LAQ)

AAR can play an important role dealing with the sustainability challenge aviation faces. Short flight has to be mitigated to other transport modes as far as possible. AAR will give large benefits for long flights where no viable option exists

- The smaller more efficient AAR-cruisers inherently give opportunity to serve more point to point connections. Tankers the size of A320 can be very useful Civil tankers.
- It will be easier for the airline companies to make a business case for new connections compared to the larger baseline cruiser
- A variation of AAR cruiser size and AAR design ranges must be allowed for in order to optimize savings.
- Other, novel transfer configurations (tanker in front, or non-centreline) can improve aircraft efficiency, system performance and safety
- Civil AAR should not be viewed in isolation. Other concepts of air operations, like formation flying, and new technologies can be integrated with civil AAR.

Overall, the AAR (Cruiser- Tanker) concepts offer several benefits over the current air transport system. The improvements in fuel efficiency and reductions in weight offered are very large by any

current standards. We therefore need to work toward realization and adoption of the concepts.

ACKNOWLEDGEMENTS

The author has been engaged in the subject off and on for 15 years. Aviation projects always take a long time to fruition, especially when a new plateau needs to be reached. Aviation industry is conservative and necessarily so. Safety issues are paramount. Projects have to evolve.

Over the years, many scientists have been consulted, too many to mention by name here. Towards this paper, special thanks are for Dr Tomas Martensson of FOI, Sweden. We had the pleasure of working together in the EEC funded "RECREATE" programme. Mr T Nangia also helped in technical work.

Any opinions expressed are those of the author.

REFERENCES

1. IPCC (Intergovernmental Panel on Climate Change), "Mitigation of Climate Change - Chapter 8, Transport", IPCC Working Group III AR5 report, April 2014.
2. EEC FP7, RECREATE Programme (2011-15). Selected Dissemination papers, RAeS Applied Aerodynamics Conference, "Advanced Aero Concepts, Design & Operations", Bristol, UK, 22-24 July 2014.
3. WARWICK, G., "Fuel for Thought", Aviation Week, July 6-19, pp 38-43, 2015.
4. NANGIA, R.K., "Efficiency Parameters for Modern Commercial Aircraft", *RAeS Aeronautical Journal*, Volume 110, no 1110, pp 495-510, August 2006.
5. NANGIA, R.K., "Operations and Aircraft Design Towards "Greener" Civil aviation Using Air-to-Air Refuelling", *The RAeS Aeronautical Journal*, November 2006.
6. NANGIA, R.K., "Greener" Civil Aviation Using Air – to - Air Refuelling - Relating Aircraft Design Efficiency & Tanker Offload Efficiency", The RAeS Aeronautical Journal, September 2007.
7. NANGIA, R.K. & MARTENSSON, T., "Towards Design of Efficient Concepts for Civil Air to Air Refuelling (AAR)", RAeS Applied Aero. Conference, "Advanced Aero Concepts, Design & Operations", Bristol, UK, 22-24 July 2014.
8. NANGIA, R.K., Efficient Tankers & Logistics for Introducing Air to Air Refuelling (AAR) into Civil Aviation CATO / IMAPP Conference, Delft, NLD, 20-23 July 2015.
9. LI, M, "Conceptual Design of Joint-Wing Tanker for Civil Operations", RAeS Applied Aerodynamics Conference, Bristol, UK, 22-24 July 2014.
10. SPENCER, R.J., "Predicting the Certification Basis for Airliner Air-to-Air Refuelling", RAeS Applied Aerodynamics Conference, Bristol, UK, 22-24 July 2014.
11. BIRGELEN, T. & ZAJAC, S., "Air-to-Air Refuelling of Civil Air Transport Aircraft - A Certification Approach", RAeS Applied Aerodynamics Conference, Bristol, UK, 22-24 July 2014.
12. LEE D. et al, "Aviation and global climate change in the 21st century", Atmospheric Environment, 2009.

NOMENCLATURE

f	Number of refuelling operationion
L/D	Lift to Drag Ratio
LTO	Landing and Take Off
MTOW	Maximum Take Off Weight, lb
OEW	Operating Empty Weight
PRE	Payload Range Efficiency
R	Range (nm)
sfc	Specific Fuel Consumption
T/W	Thrust to Weight Ratio
VEM	Nangia Value Efficiency Parameter
VEOPX	non-dimensional "Nangia value Efficiency"
V	Airstream Velocity (kt)
W1	Weight when cruise starts
W2	Landing Weight (ignoring the landing phase properties)
WFB	Weight of Block Fuel
WFBR	Payload Weight Ratio WP/MTOW
WFBS	Weight of Fuel climbing to Cruise
WFC	Weight of Fuel on Cruise
WFR	Weight of mandatory Fuel Reserves
WOE	Aircraft Operating Weight
WP	Weight of Payload,
WPA	Weight payload at Point A
WPD	Weight payload at Point D
WPR	Weight of
X	Range Parameter
Z	= R/X , Dimensionless ratio between R and X

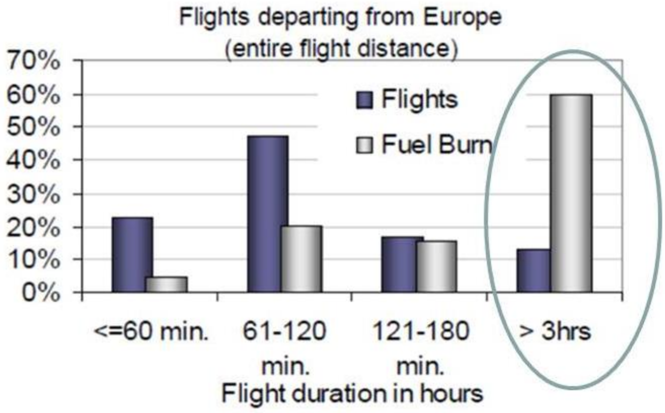


Figure 1. Concept of Operations (CONOPS), Inter-Continental Flights

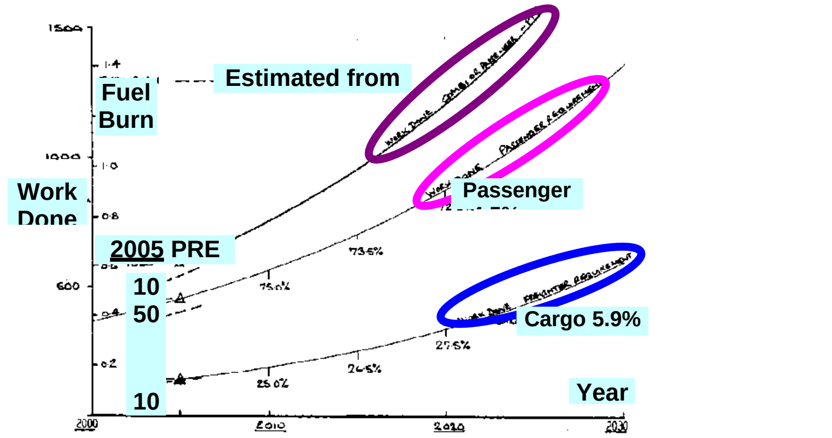


Figure 2. Estimated Air Transport "Work Done" [lb-nm] & Fuel Burn [lb] Growth: 2000 - 30 "Work Done" = Payload x Range (Passenger, Cargo

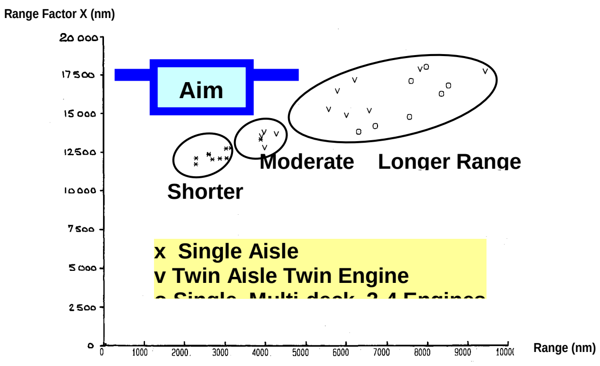


Figure 3. X-Factor, Design Point

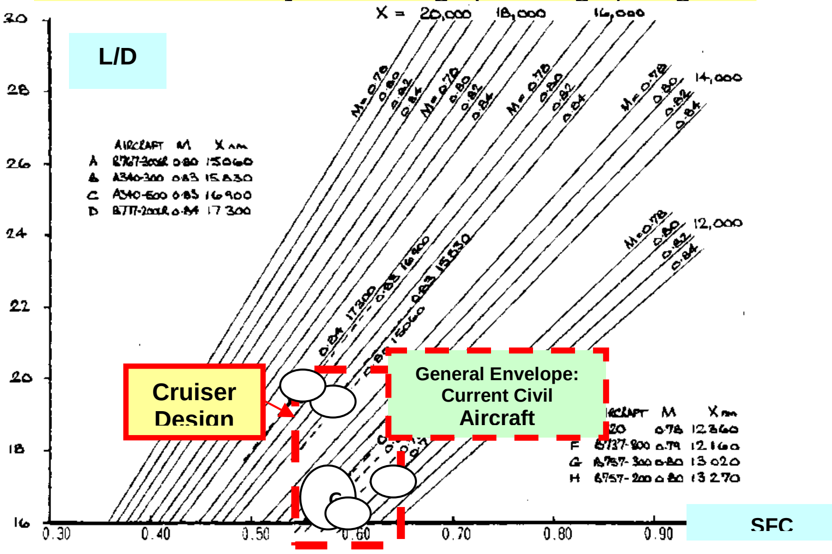


Figure 4. An Understanding of X for Commercial Aircraft,Variation of L/D with SFC for constant Mach & X generators. Typical Values for Current Civil Aircraft Types are included.

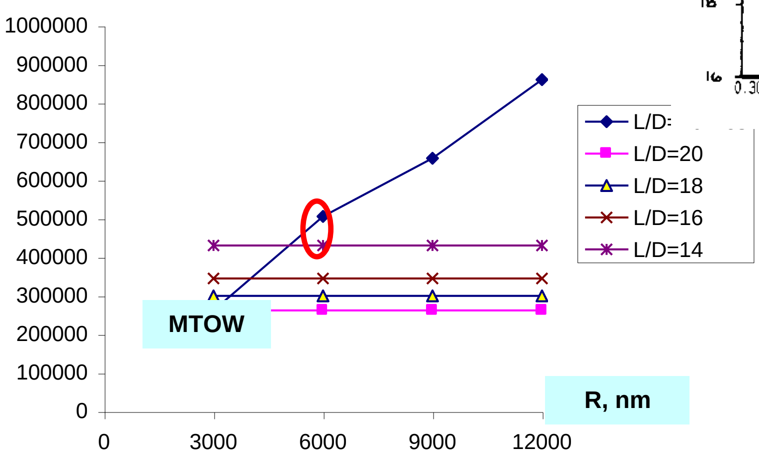


Figure 5. MTOW ~ Range, No AAR, L/D=20 compared with AAR Aircraft with L/D from 14 to 20

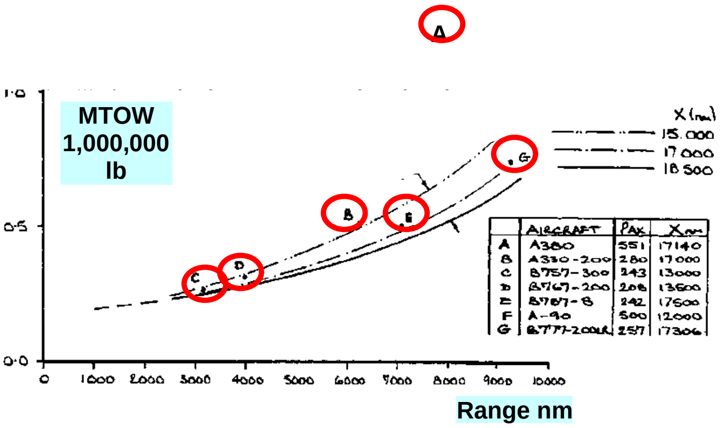


Figure 6. MTOW (1,000,000 lb) v Range (nm), Aircraft designed for 250 pax, X = 15,000, 17,000 & 18,500 nm, Ranges up to 9,000 nm

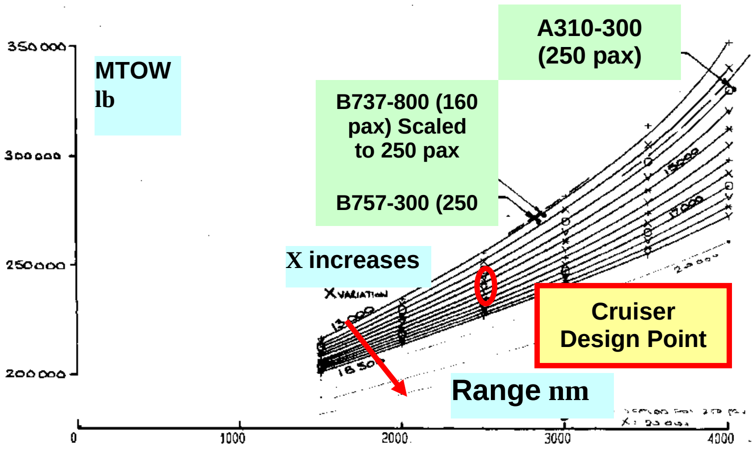


Figure 7. MTOW (lb) ~ Range (nm), Aircraft designed for 250 pax, X from 13,000 nm to 18,500 nm, Ranges 1,500 nm to 4,000 nm

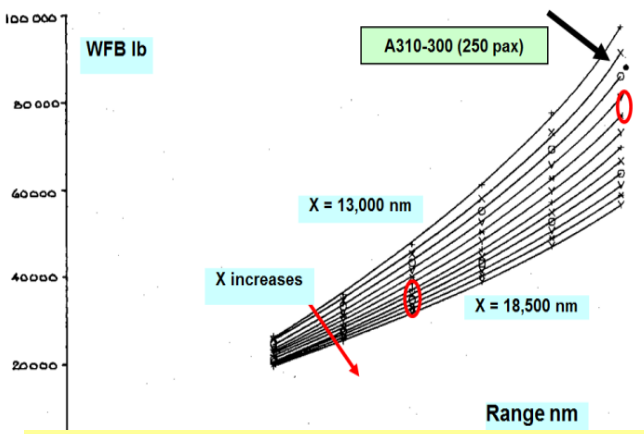


Figure 8. WFB (Block Fuel lb) ~ Range (nm), Aircraft designed for 250 pax, X from 13,000 to 18,500 nm, R 1500 nm to 4,000 nm

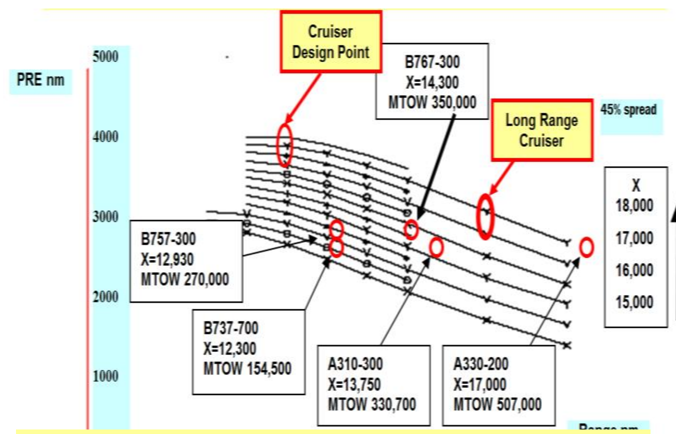


Figure 9. PRE (nm) ~ Design Range (nm), Aircraft designed for 250 pax, X from 13,000 to 18,500 nm, R 1,500 to 6,000 nm

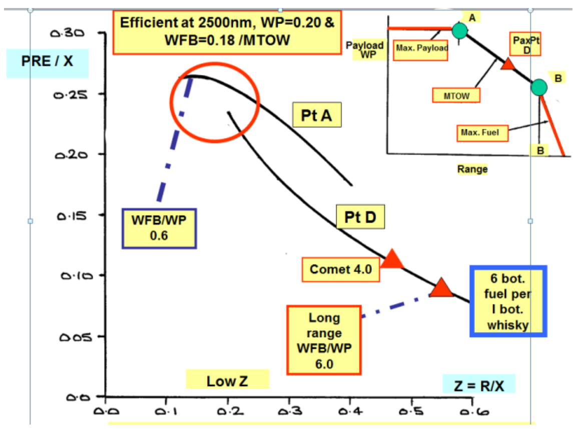


Figure 10. PRE/X vs Z = R/X, Pt A & Pt D

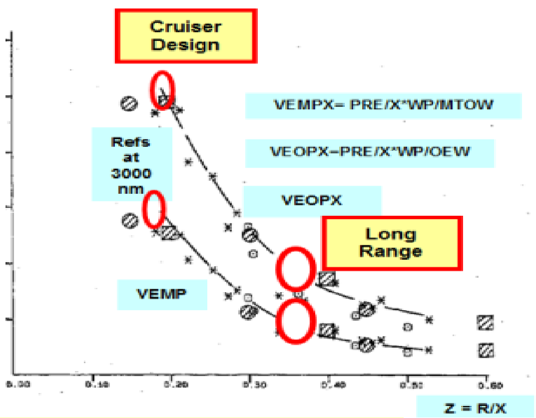
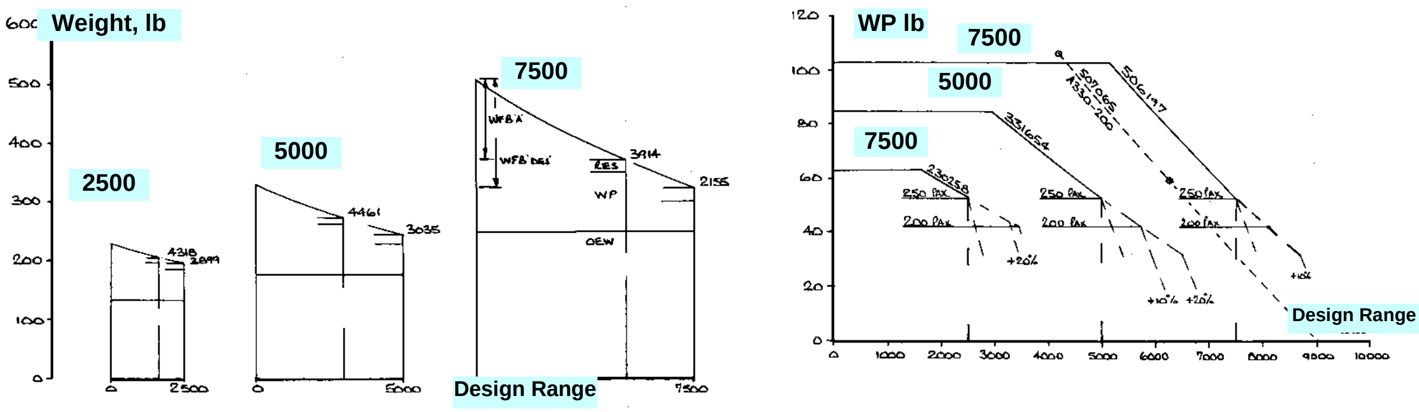


Figure 11. "Nangia" Non-D Value Efficiency Parameters VEMPX & VEOPX at Pt D (Based on [3]



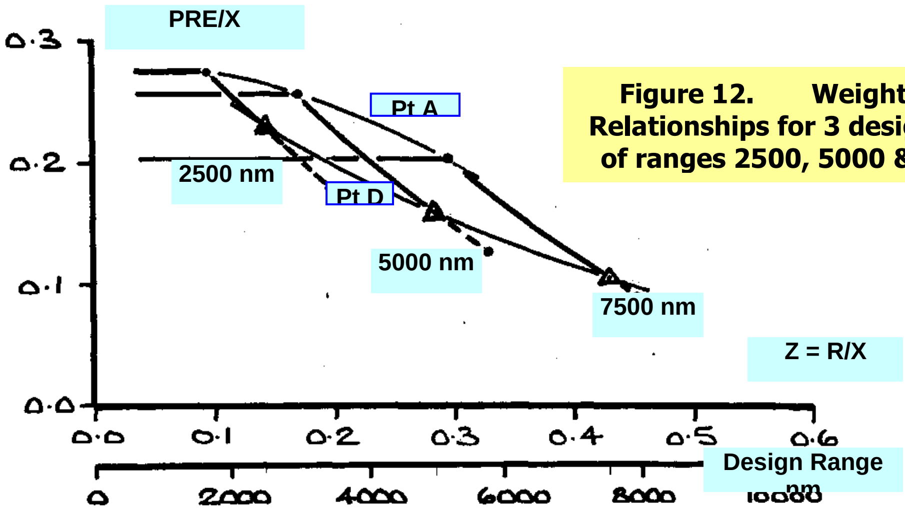


Figure 12. Weight & PRE/X Relationships for 3 designs capable of ranges 2500, 5000 & 7500 nm.

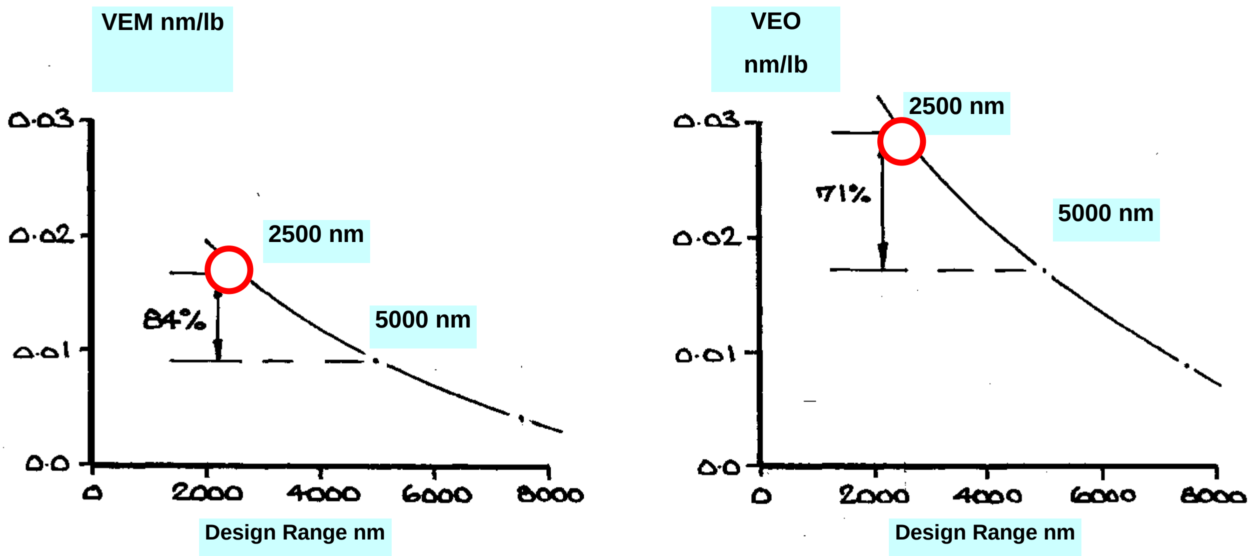


Figure 13. Value Efficiencies Relationships for 3 designs capable of ranges 2500, 5000 & 7500 nm.

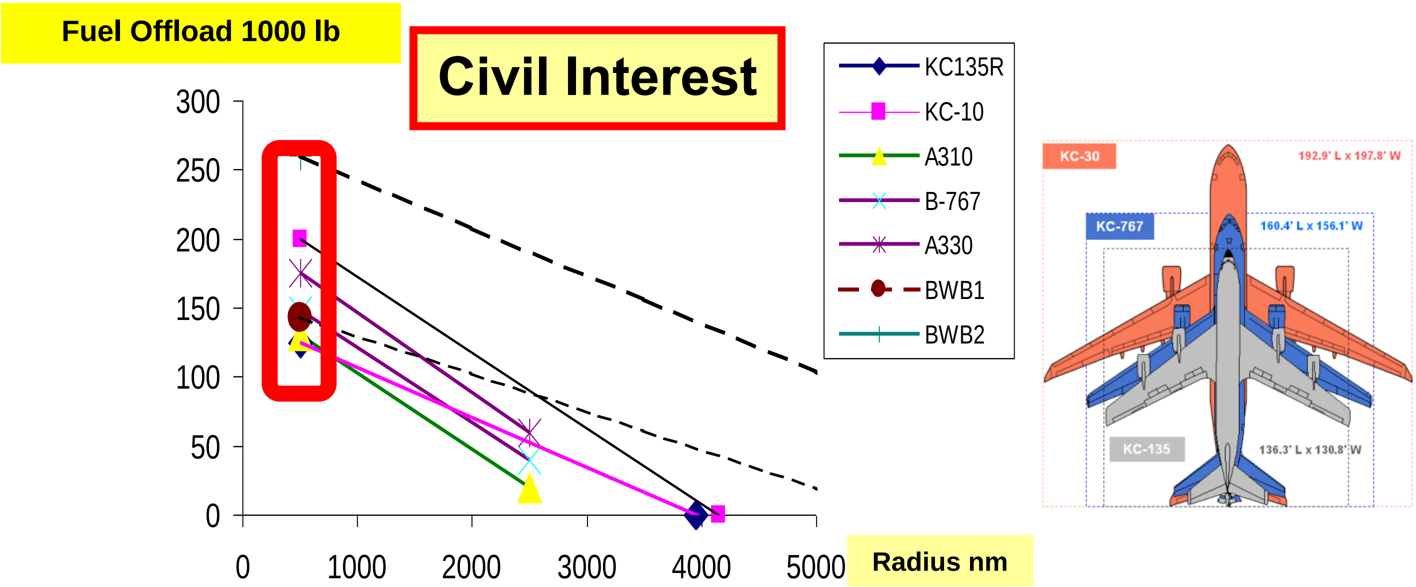


Figure 14. DIFFERENT TANKERS CAPABILITY

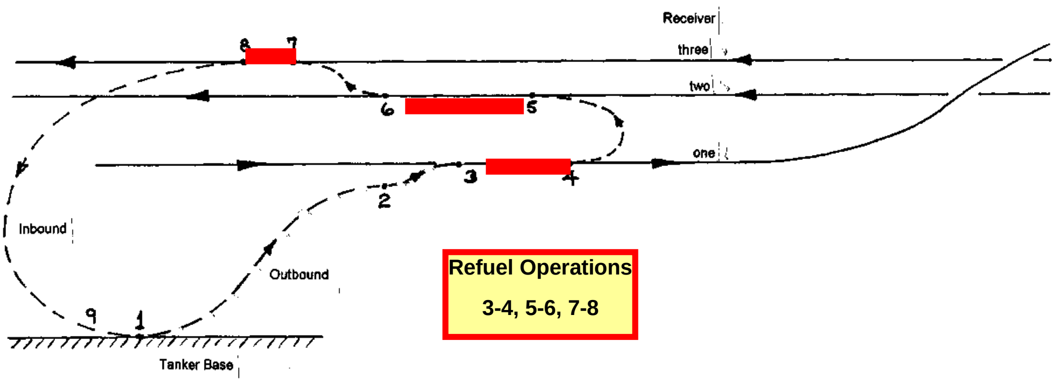


Figure 15. TYPICAL CIVIL AAR TANKER OPERATING SCENARIO INITIAL IDEAS

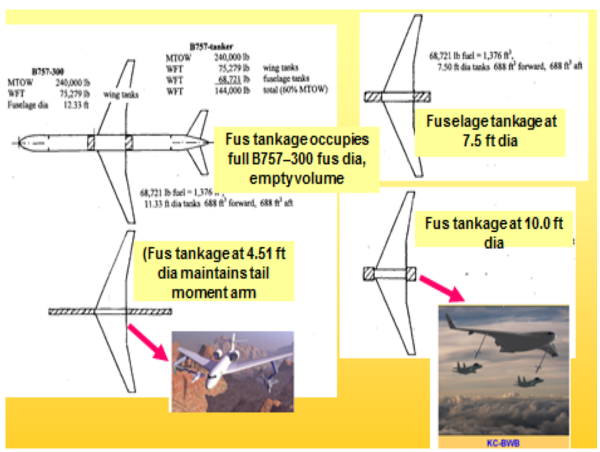


Figure 16. Conventional Wing-Fuselage-Tail Layout, Fuselage Sizing, Lead to Flying Wings

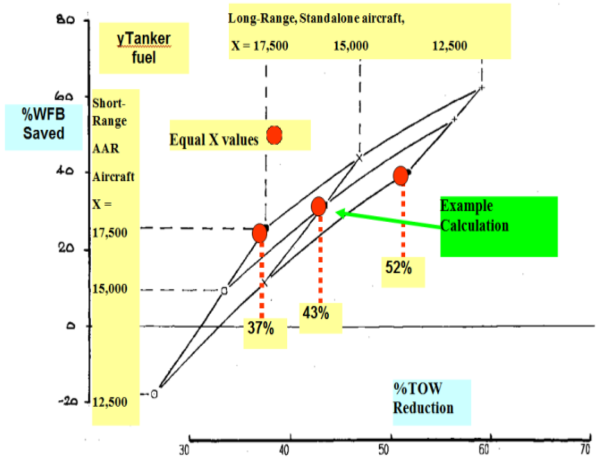


Figure 17. Fuel Burn and TOW Advantages Afforded by AAR, 250 Pax, 6000 nm Route, 3000 nm Design Refuels x 1 cf 6000 nm Design, X Varies

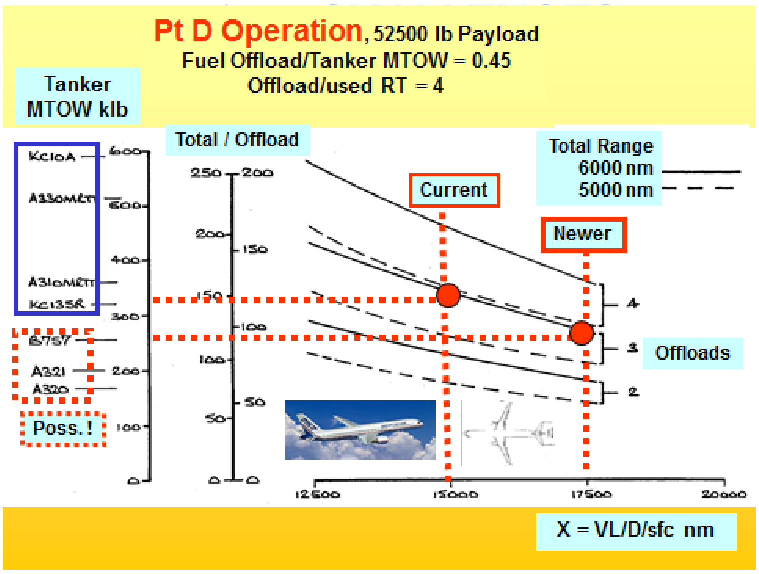


Figure 18. Tanker Weight & Offloads, X variation

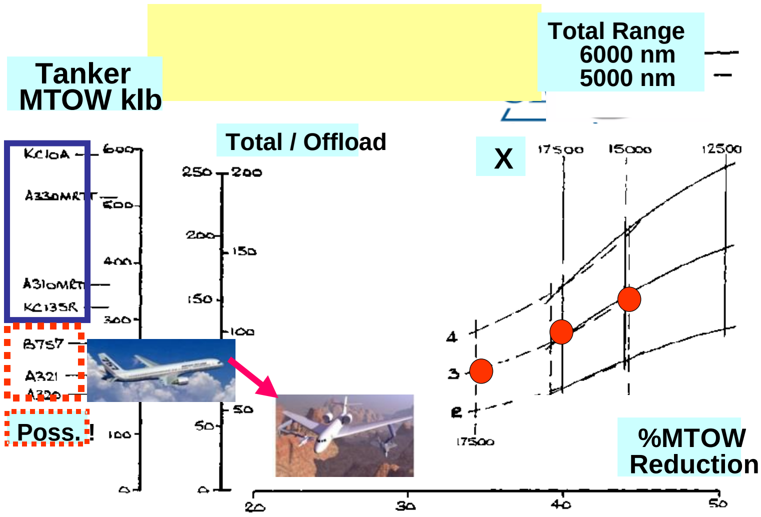


Figure 19.. Pt D Operation, 52500 lb Payload, Fuel Offload/Tanker MTOW=0.45, RT=4 Tanker Weight & Receiver Weight Reductions, AAR, Different X Values

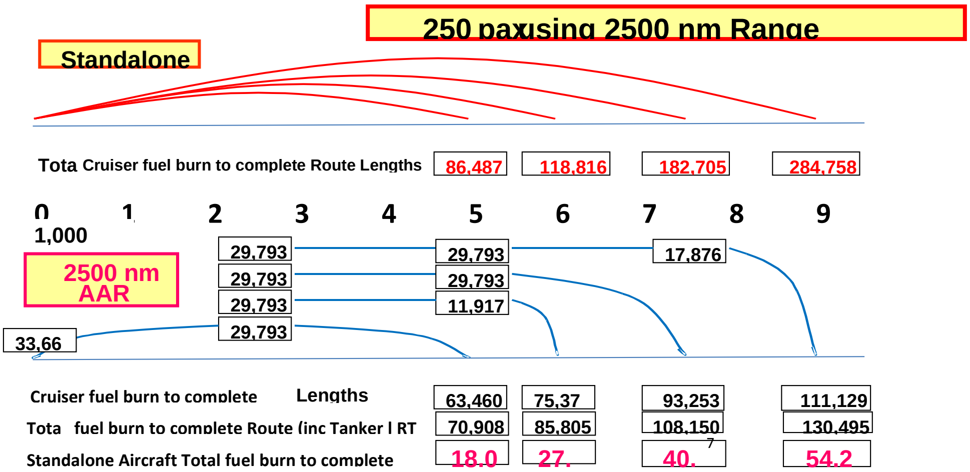


Figure 20. 250 pax, Comparing Non-Stop and Refuelled Flights over Different Ranges

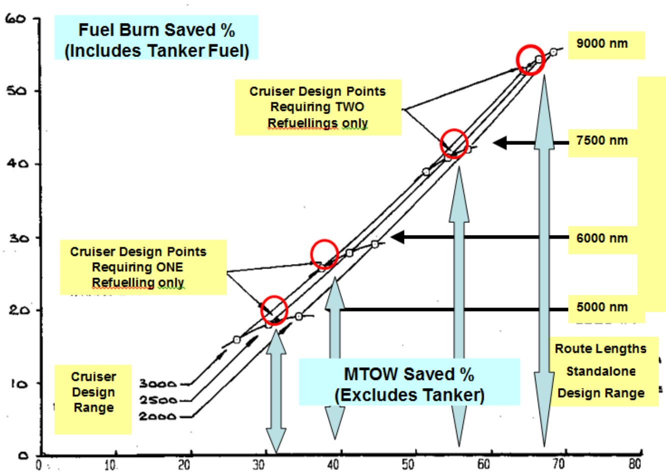


Figure 21. 3000 pax per day, Fuel Burn & MTOW Advantages afforded by AAR, Cruiser Design Ranges of 2000, 2500 and 3000 nm & 200, 250, 300 pax capacity. Stand-alone Cruiser Design Ranges to Match Service Route Lengths of 5000, 6000, 7500 & 9000 nm

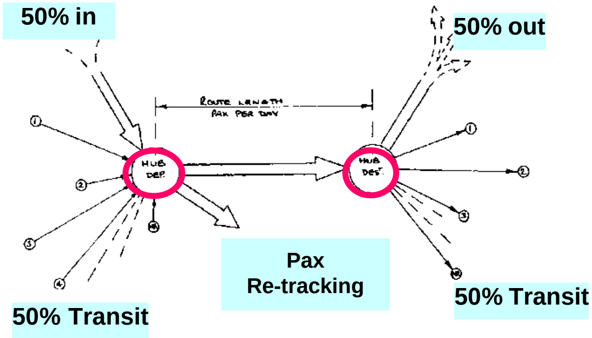


Figure 22. Hub & Feeder Network - 50% pax locally from Hub, Others in Transit via Feeders (4 say, Extra Fuel Burn)

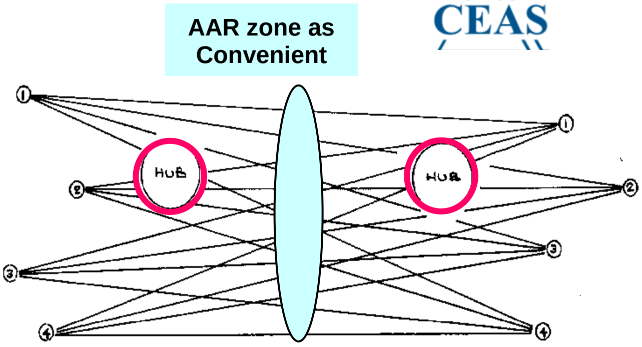
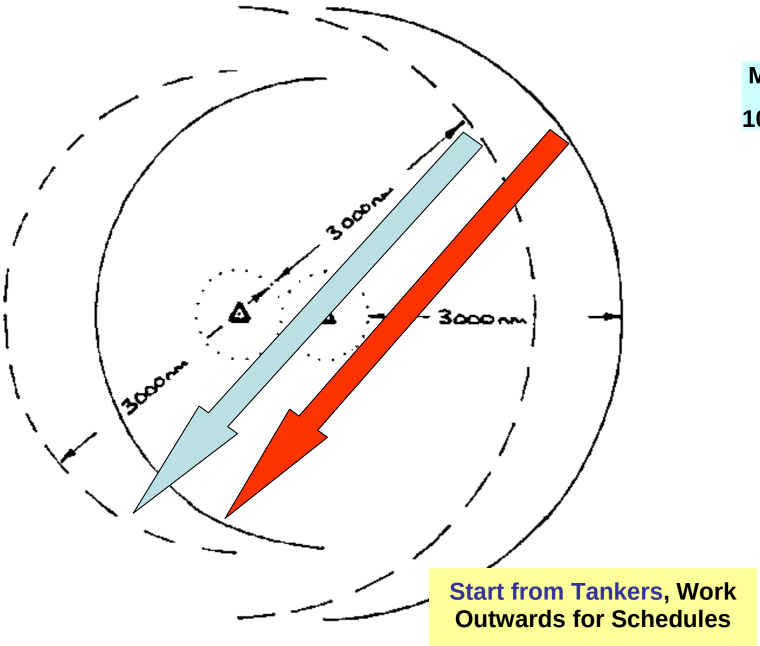


Figure 23. City Pair Network using AAR- Hubs Avoided for Transit Pax (Time and Fuel saved) - Pressure on Hubs RELEASED, Close Formation Flying encouraged



Showing Region Covered via Eastern Tanker Base
Formation Flying Feasible, more than 1 tanker

Figure 24. Twin Tanker Bases about 1000 nm

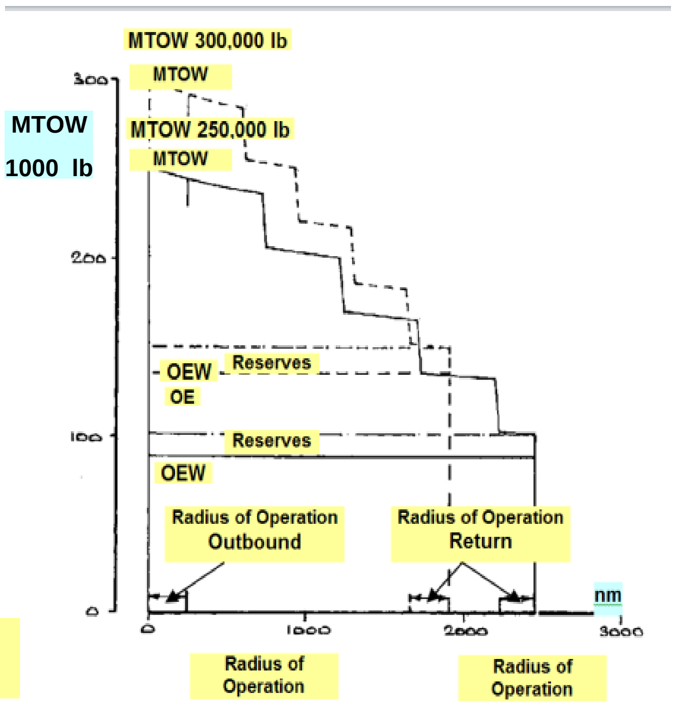


Figure 25. Feeder Weight Breakdown – Distance Flown, Four 30,000 lb Offloads, X 17,500 nm, MTOW 250,000 lb, OEWR 0.35, RT 4, Loiter 61 min, MTOW 300,000 lb, OEWR 0.45, RT 4, Loiter 42 min

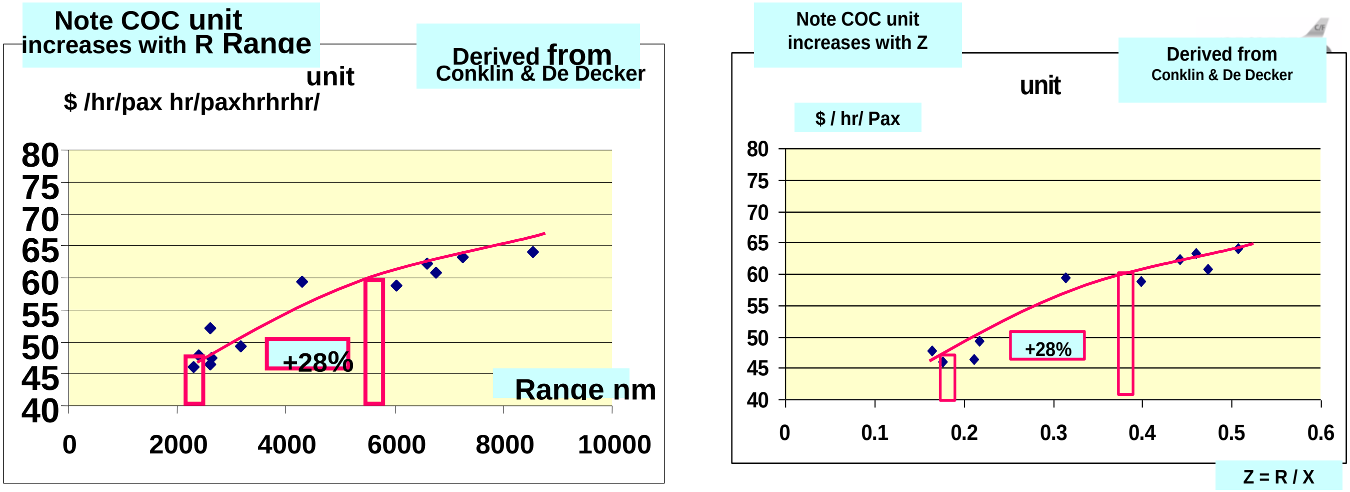


Figure 26. COC Relationships with Range and Z n

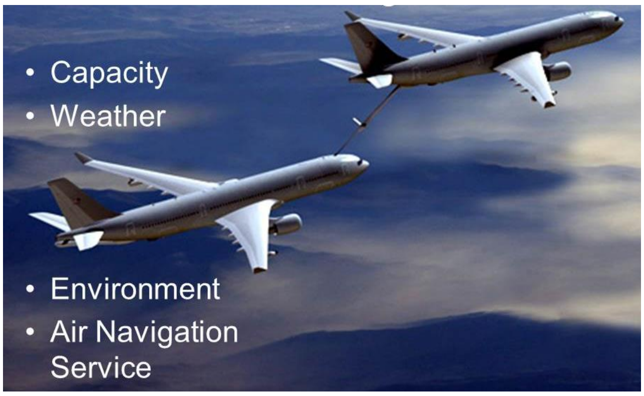


Figure 27. Operational Constraints. AAR

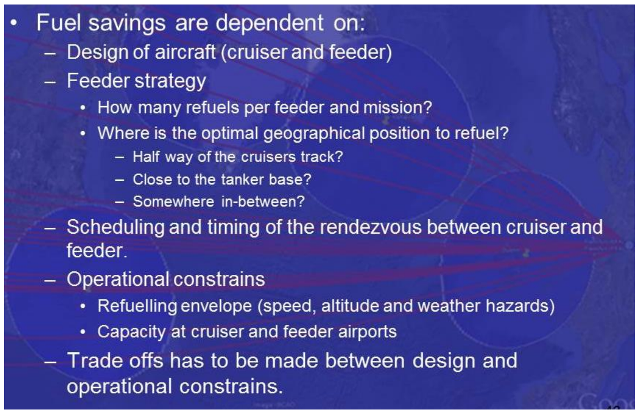


Figure 28. Fuel Savings Dependencies

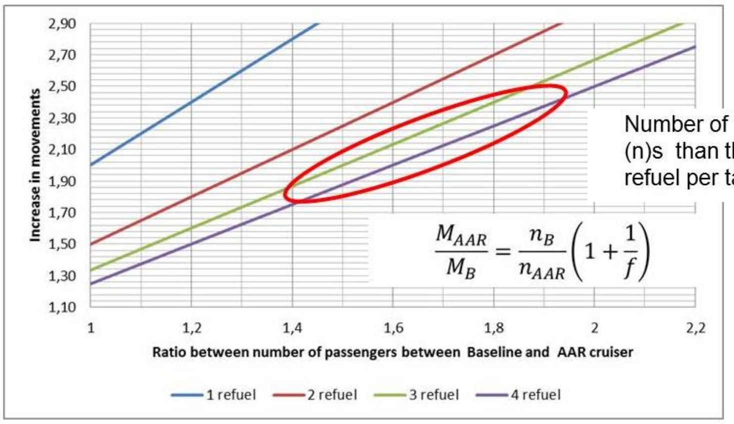


Figure 29. Capacity Aspects of Cruiser/Feeder Operations

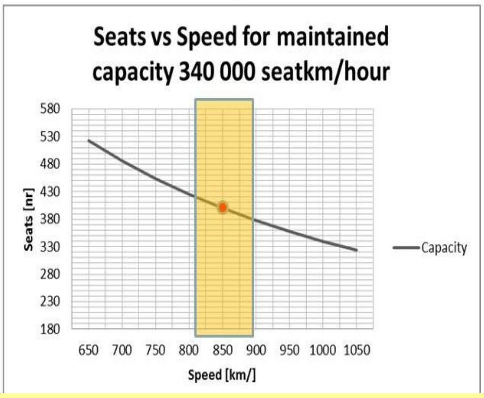


Figure 30. Capacity Aspects of Cruiser/Feeder Operations, Airline operates (24/7), Average speed 850 km/hr & 400 seats in Long-Haul Fleet

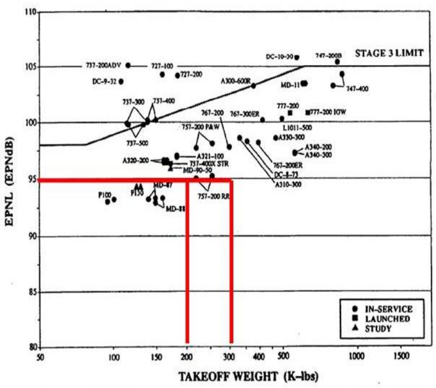
- To have a reasonable workload on the most used feeder airports the result is that, on average, three refuels per tanker is the best choice.
- For the lowest fuel burn in the system the re-fuelling usually takes place close to the tanker base (meaning that most cruisers make a detour for refuelling)
- Refuelling envelope Mach < 0,8 and < FL260
  - Needed for control authority on the boom.
  - Descending from cruise to < FL260 and back → loss 1 % fuel savings.
  - Refuelling < FL260 decrease risk of encountering turbulence
  - Vertical separation between cruise and refuelling aircraft (ATC)

Figure 31. Feeder Strategy Trade-offs

- Technical failures and/or dangerous events caused by weather during refuelling is the main concern.
- Weather impact
  - Poor Visibility — Clouds
  - Lightning — Cumulonimbus clouds
  - In-flight icing — Clouds with temperature below freezing
  - Turbulence — Clouds, Jetstream, mountain waves…

Figure 32. Significant Weather Hazards SIGWX

- Lower absolute noise levels (smaller cruisers), average noise levels about the



Impact of aircraft sizing on noise (ICAO Stage 3)

Figure 33. Noise Reduction

- Lighter AAR cruisers with smaller engines will (in general) emit less particles (Depends on emitted substance and phase of flight)

Figure 34. Better Local Air Quality

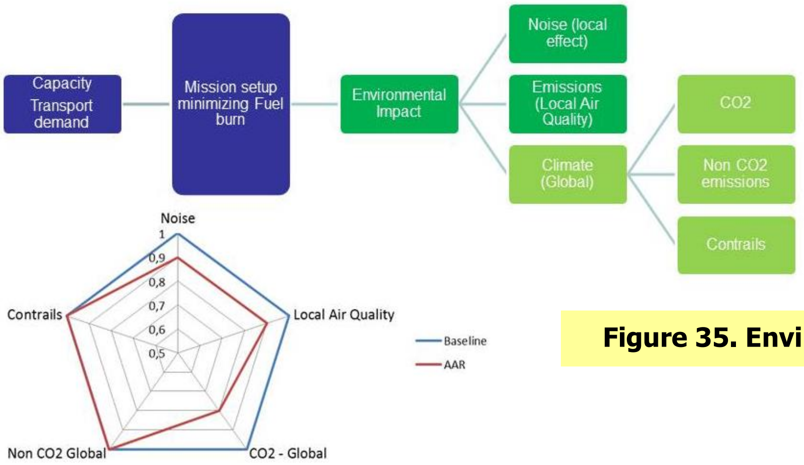


Figure 35. Environmental Impact of AAR

- Standard flight planning like today.
- New separation rules has to be developed (allowing for zero separation in the refuelling area
- ATM planning tools for optimising tanker scheduling depending on traffic load and weather has to be developed.

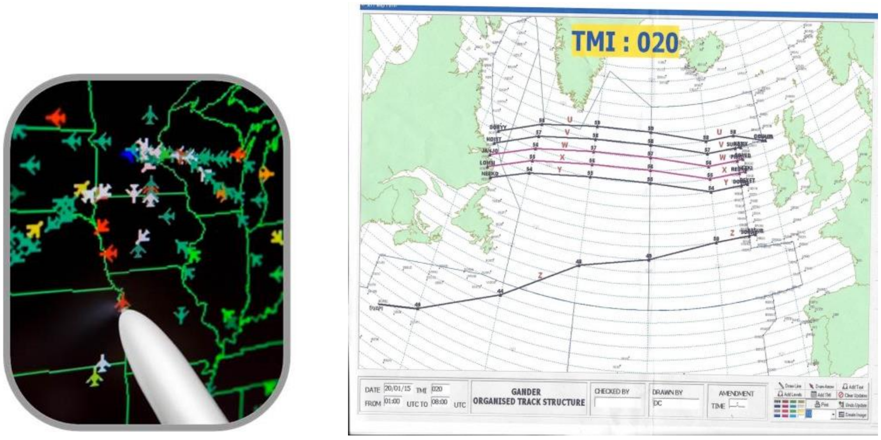
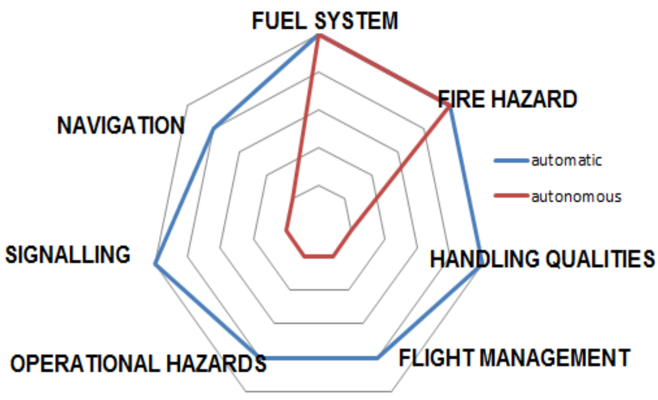


Figure 36. Air Traffic Control & a day plan at NATS, Prestwick (19 Jan 2015), Oceana Traffic in Tubes 60nm apart, Longitudinal Separation 10 mins to allow for different speeds and heights



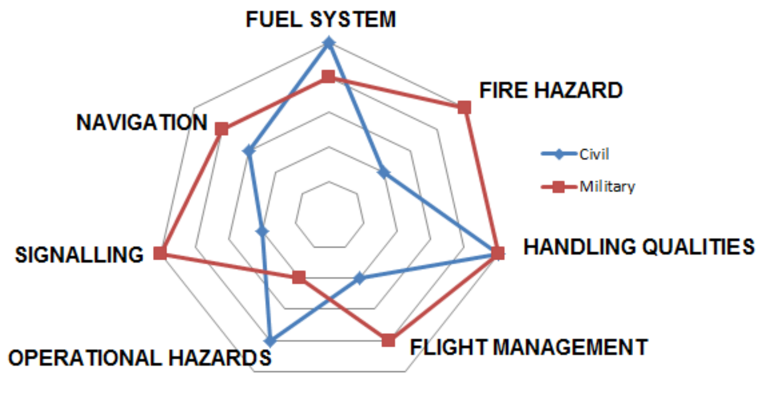


Figure 38. Civil vs Military Certification (A400M Experience)

Figure 37. Automatic or Autonomous !

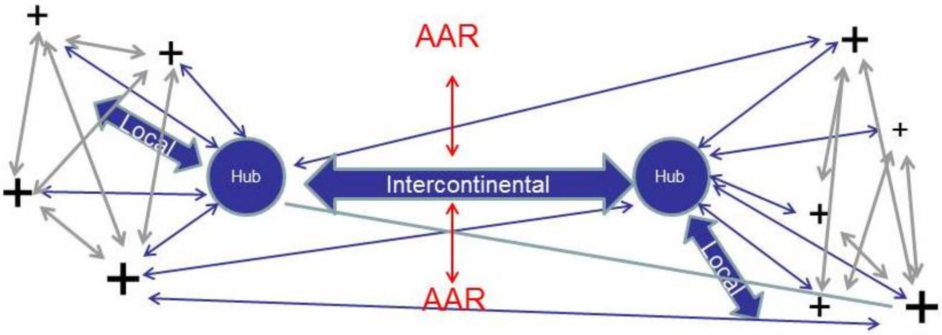


Figure 39. Our System Today and The Effect Of The Interaction Between Continental & Intercontinental Travel

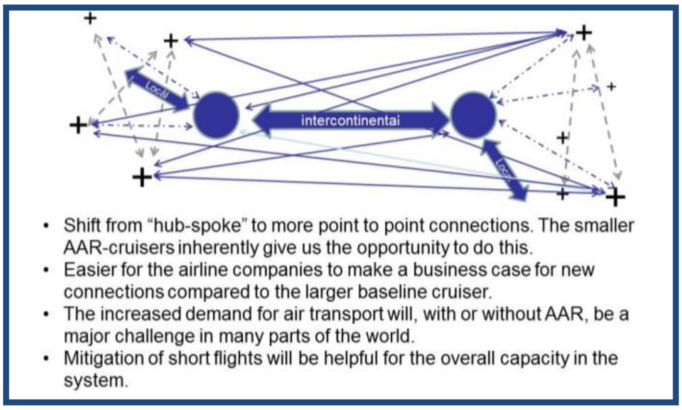


Figure 40. AAR Tomorrow

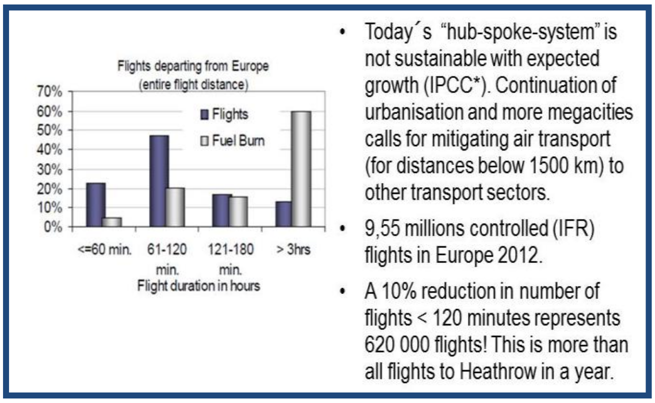


Figure 41. Mitigating Short Flights

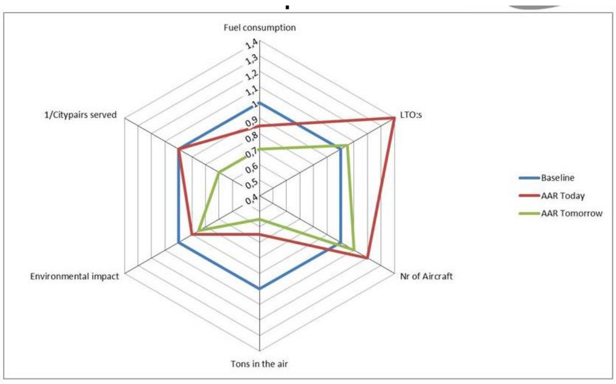


Figure 42. Expected Improvements From Cruiser/Feeder Operations, for the same Transport Capacity per unit time

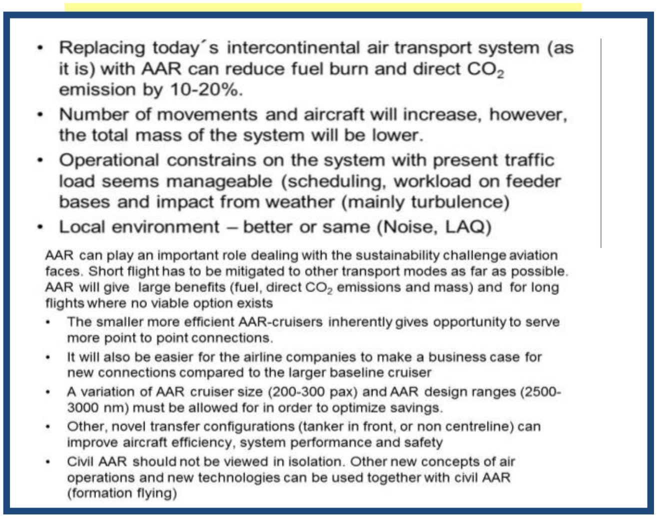


Figure 43. Main Benefits of AAR