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HIGHLY EFFICIENT CIVIL AVIATION, NOW VIA OPERATIONS - AAR & CHALLENGES

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Global civil aviation growth at 5+% yearly poses extreme environmental challenges. Advances have appeared gradually through improved aerodynamic shapes, using carbon fibres, and enhanced engines; however, as these technologies mature, direct efficiency advances require increasing effort. Often Passenger convenience is forgotten e.g. the long-range air traffic has developed on hub-spoke basis implying extra feeder flights, transit passenger inconveniences, capacity issues.

Efficiency metrics emphasize "Why, How & What", with an understanding of the range sensitivities, operational concepts and performance goals via the important "X-factor". For given range, current aircraft are "greener" than previous generations. Medium range aircraft are always greener than those for short or long ranges. However, currently, the major trend is for the latter: twin-aisle A350, A380, B787, B777X (10+% payload, 40+% fuel to MTOW). Shorter range single-aisle aircraft are "feeders" or newer derivatives: A320, B737 class (20+% payload, 20+% fuel to MTOW).

New technologies could feature in future e.g. Natural Laminar flow, riblets, enhanced loads alleviation, composite tailoring, morphing structures, distributed propulsion, bio-fuels etc. These may make significant improvements and lead to unconventional layouts e.g. blended wing bodies, high aspect ratio wings, oblique wings, and joined wings. Additionally, significant environmental gains can be made via operations e,g AAR and Formation flying.

Air-to-air refuelling (AAR) has been practised and perfected by the Military for 80+ years. Tankers are sky "gas-stations". The Military objective is for mission success rather than fuel economy. Tankers accompany and refuel short-range aircraft over longer missions. AAR can be a strong enabler for the civil aviation. Small dedicated tankers (A320 size) can operate over short radii, refuelling longer range cruisers. AAR will always retain top hierarchy over any technological advances, offering step change towards highly efficient aviation. We discuss the pros and cons of operational issues, routing and constraints, turbulence, air navigation and environmental impact.

Replacing today´s inter-continental system with AAR gives fuel and CO_2 reductions of 15-30% depending on range. Additionally, 30-40% weight savings lead manufacturers focus on smaller aircraft. Major COC and DOC reductions of a similar order occur. Noise, emissions, wake effects are favourable, meeting ACARE / NASA goals. A by-product is that laminar-flow aircraft introduction can be eased.

Increasing AAR benefits occur as Point A to B system replaces the hub--spoke system. The smaller AAR-cruisers imply ground-based opportunities: smaller airports and new connections, easing the transit passenger handling and reducing travel time. For sustainable aviation growth and future urbanisation, short flights are replaced by other means. The capacity relief becomes available for long flights (only aviation is suitable). Maintaining transport capacity, less AAR enabled cruisers are needed; these operate at 20+% payload to MTOW. More likely is that the total airborne mass is lower.

Certification and Operational rules will need revision. New tankers or other types modified from civil aircraft respect most CS-25 regulations. We aim for automatic refuelling (as demonstrated by A330 tanker recently and as in US-UCAV programme). We allude to newer versatile twin-aisle cruisers with differing capacities operating world-wide ranges with AAR, blending with formation flying. All this should "spur/re-vitalise" Aviation. We propose practical demonstrations. A game changer in sight!

Keywords: Aircraft Efficiency & Environment, Innovative Concepts, Breakthrough Technologies, AAR, Global Air transport, Passenger Convenience.

1. Introduction

Civil aviation world-wide, passengers and cargo, is growing at 5%+ yearly **[1]**, **Fig.1**, doubling in 15 years. The aviation fuel usage is about 2.7% of total word-wide fuel usage (IPCC). This poses a number of environmental challenges to the industry. Consequently, there are several EU, Clean Sky and NASA initiatives focused on achieving significantly improved designs in terms of efficiency and environmental considerations (noise and emissions). Many advances have been made through the development of improved aerodynamic shapes, use of carbon fibres, and enhanced engines. However, as these technologies mature, direct efficiency advances require increasing developmental effort.

Fig.2 shows the concept of operations. Although longer flights are a smaller proportion of total flights, they burn more fuel. **Fig.3** illustrates the historic volatility of oil price. In 2017-18, the oil price has been around \$50-\$90 per barrel. The trend remains uncertain. In short term, airlines benefit. Longer term: Global GDP will receive an uplift!

Even if the continued efforts on improving aircraft and engine efficiency are accounted for, increasing demand and lower oil prices will lead to higher emissions. Following IPCC, **[2]**, high speed rail can substitute for short-distance air travel up to 800 km range and in limit to 1500 km (e.g. Beijing – Shanghai) - 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 limits the availability of slots at the big hubs. There is an additional trend; moving away from high capacity airliners - flexibility. With continued urbanisation - more megacities over Earth, air transport could be reserved for long distance inter-continental travel, where no other viable options exist. Reduction of short flights will allow increased availability of slots for longer flights.

2. Operations & Passenger Friendly Perspective, Hubs and/or Point A to B

In general, the traffic system for longer ranges has evolved on Feeder - Hub – Hub - Feeder basis. Large aircraft operate between major International hubs. Passengers arrive and depart from the hubs, via surface or air. The hubs serve a considerable proportion of in-transit pax in relation to total pax. At London Heathrow airport in 2017, 30% of total pax were in transit i.e. flying in to fly out. The most popular destinations e.g. New York, Dubai, Dublin, Hongkong and Amsterdam are all hubs. Further, pax transferring to a "sister" airport for continuing their onward journeys are not listed as transfer pax from LHR's 4 "sisters": Gatwick, Stansted, Luton & City - Statistics games!

Amsterdam Schiphol airport figures for transit pax are higher at 55%+ and it may include London Heathrow 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.4**, may have 50% of pax arriving via connecting flights and similarly at the destination hub. Some pax are "re-tracking", over regions close to the travel origin or final destination. All this implies extra 1000 nm, 5-7 hrs time and inconvenience for a very large pax.

It is fair to say that as long-range aircraft become available and air traffic continues to grow, more point A to B operations take place (generally from long runways), although less fuel-efficient (**Sections 3-4**). Qantas are introducing non-stop services between Australian hubs and LHR.

Within the EU-FP7 "RECREATE" programme (2011-15), **[3-4]**, 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 show 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 he methodology chosen feeders intercepting the cruisers. Operational constraints like air traffic management, weather / environmental impact were assessed at all times. Consideration was given to details of operations and the success of certifying aircraft, fuel transfer systems, methods and procedures for reaching the civil market. So far, no real showstoppers have been identified for civil AAR certification.

With renewed confidence, we can take a pro-active stance towards AAR civil exploitation. Potentially AAR bestows a step change towards higher efficiency. Apart from major fuel and weight savings, AAR will reduce pressure on the large hubs - a relief in the systems immediately; direct routing is encouraged straight away.

***An Example*:** consider 3000 pax travelling via 6 large 500-seaters from a hub over longer ranges. At departure, 1500 pax would arrive via connecting flights (intrinsically difficult to assess exactly how many). In "dribs and drabs", many flights would be included over a transit period. At a minimum, for a 500-seater, 250 transit pax mean 3 feeders. For 3000 pax, 15 to 20 connecting flights may be implicit and 6 hub pairs are served. At arrival, 1500 pax will connect for their final destinations via 15-20 feeder flights.

Today the hubs are large cities (or megacities) with populations of 5 million+. Inherently, the megacities are the popular destinations and with increasing Earth urbanisation, airports will reach full capacity. London Heathrow is at 99% capacity. The operating slots are at premium. Most take-offs involve a wait of 15-20 minutes. on the tarmac. Arriving flights stack up, loitering, wasting fuel for 20-30 minutes.

It is recognised (**Section 3**), that long-range and short-range flights are not fuel-efficient. Moderate range flights, about 3000 nm attain high efficiency. The hub-spoke system lacks in this respect also.

Airlines pioneered the hub-spoke system as the intercontinental infrastructure focussed on a few locations. However, from an environmental perspective it makes little sense. For future, it must be eroded away. Eurocontrol figures suggest that from 10 million controlled (IFR) flights, 70% were shorter than 2 hours. If only 10% of the short flights were mitigated to other transport means, it would represent 700,000 flights c.f. 500,000 flights handled at London Heathrow yearly.

So, from pax viewpoint, an obvious choice will be to introduce Intercontinental "point-to-point connections" between "mid-sized cities", efficiently. Most connections will be with mid-range aircraft. Long ranges are still inefficient, but there are some answers as follows!

Promising ideas requiring relatively small changes to mid-range aircraft and offering significant fuel benefits are operational: staging flights (hopping) and AAR. Formation flying couples easily with AAR. Intimately connected with AAR is the need for efficient tankers and their design and operational logistics.

AAR origins are from military circles over last 80+ years. AAR on demand is taken for granted. The tankers operate like "gas stations" in sky. The missions need to succeed rather than be concerned with fuel economy. Often tankers accompany, refuelling shorter range aircraft over longer missions. However, the civil operations aim at saving fuel and the tankers operate over shorter radii. Time is saved and connecting flights are minimised (more later).

3. Efficiency Metrics & Design Sensitivities

Efficiency metrics and design sensitivities arise from the Breguet range equation **[4-9]**. The metrics have a strong bearing on consideration and evaluation of current and future aircraft and operations.

We define WFBS as the fuel used during climb to cruise altitude, approximately 2.2% MTOW over about 100nm distance. The range parameter X = V L/D/sfc, where V is the velocity, L/D the Lift to Drag Ratio and sfc refers to the fuel consumption metric. 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 fuel usage) and W1 is the weight when cruise starts. For convenience, we can also use a non-dimensional form of X as MX= X/speed of sound. Using the weight of the fuel burnt during cruise (WFC), the weight of the entire block fuel (WFB) is:

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

The peak value of PRE/X w r t Z (=R/X), depends intimately on WFBS. This PRE/X character can be explained **[5]**. We use the weight of the payload (WP), fuel reserves (WFR)

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 currently. It depends on sfc and it may reduce to 3.5% MTOW for new 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 and its peak 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 ranges. We ensure that short range aircraft lies near the peak of the PRE/X ~ Z curve.

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. 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 follows: VEO=PRE/WOE.

VEOPX also serves a measure of approach and landing noise. Higher value is better for lower structure weight, costs (acquisition / 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. Aircraft size is strongly dictated by take-off field length, operating altitude, Mach number and range.

4. Metrics & Efficient Cruisers

The importance of X-factor cannot be over-stated. The current aircraft demonstrate a very wide range of values (**Fig.5**) - Short range aircraft between 11 –13,000 nm, Moderate range aircraft between 12,500 - 14,000 nm, Long range aircraft touch 17,500 nm. A 30% spread is seen. More recently, the Airbus NEO and Boeing MAX series of single aisle aircraft claim X-factors improvements of 10-15%, largely due to better propulsion efficiency. A reason for smaller X for shorter range aircraft is that they operate generally from shorter runways, so Thrust to Weight ratio is relatively higher cf longer range aircraft **[5]**.

We emphasise that in any analyses for AAR, 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 arisen.

Fig.6 summarises ratios of OEW, fuel and payload with respect to MTOW.

Fig.7 shows the payload range diagram for B-737-800 and the payload- range combination frequencies of flights from FAA data, overall several years. From similar diagrams for several aircraft, we have deduced **Fig.8**. This emphasises, that 60% of flights do not exploit the full potential or capability of aircraft. Further details on such issues are to be presented in a future paper.

Figs. 9-10 illustrate the variation of PRE on payload ~ range diagrams of two long range aircraft. These confirm that PRE levels drop as the range increases.

It is significant that at their design points, the current civil aircraft have similar PRE (2000 to 2300 nm). This implies that a B737-700 could be refuelled once at 3000 nm and achieve the same PRE as an B777. The B737-700 has relatively low efficiency (X = 12,300 nm) and MTOW of 154,500 lb. The B777 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 3,500 nm, an improving over the A330-200 by over 50%. This can be directly related to fuel burn saving, allowing for tanker fuel.

Following the relationships of **Section 3**, **Fig.11** 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.

It is implied that 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 reflected in selection of the Design Point for the Cruiser aircraft at the estimated achievable efficiency

Fig.12 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.

Good measures for comparisons are in terms of X-factor or ML/D, sfc and PRE. These are not always published, but these can be deduced.

5. Concepts, Some Promising - How do they fare!

We need to focus at aircraft in short to moderate 2000 - 4000 nm range. We can assume AAR for longer ranges. However, reference from long ranges is also needed. Jupp **[10]** considers the design of future civil aircraft, indicating the environmental and fuel price challenges.

Several theoretical studies have been aimed at improving ML/D via unconventional features e.g. **[11-18]**. Nangia **[19]** has reviewed some of these. **Fig. 13** summarises the historical trend to 1990 of ML/D. Note the level of ML/D touched 15. **Fig. 14** shows ML/D vs range for some future concepts. Note the disparities in efficiencies between the various types. Some BWB's and LFC types show very high, somewhat overly optimistic ML/D values. We need confidence to be generated in new aircraft types with considerable technical and financial resources. At present, we can surmise that ML/D about 19 is realistically achievable.

6. Operational Concepts Selection, Cruisers & Tankers Design

The longer flights constitute a smaller fraction of all flights, but they burn a large proportion of fuel in air transport. Hence, the potential for fuel saving is high in Inter-continentals as no other real travel alternative exists.

Based on efficiency and AAR considerations in **[5-9]**, the non-dimensional metric w r t to Z=R/X allows realistic near-future technology levels in the design space. The Cruiser and Tanker AAR concepts are:

Cruisers: 250 passenger capacity, Design Range 2500-3000 nm, MTOW 240,000 lb, sfc 0.525, **Fig.15.**
For comparisons, a long-range cruiser needs to have a double the range.

Tanker: Offload capability – 35,000 lb per each refuel of a Cruiser, 3 operations

- Flight profile – 2 -3 hours total flying time. Least the better
- AAR procedure - 20 minutes including a wet contact for 5 minutes
- Examine different formations. Tanker at rear preferred

Inferences Towards AAR

We appreciate the fuel and weight efficiencies from airline perspective. **Fig.16** shows the interpretations of the weight, payload and derived PRE/X for 3 designs for different ranges (2500, 5000 & 7500 nm). Note the high gains in Value efficiency for using the 2500nm cruiser over longer ranges. **Fig.16** enables 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 **[7]**.

7. Military & Civil AAR Tankers - Differences

The military tankers are often multi-role with long operation radii, **Fig.17**. The offloads decrease as the range increases. Often several support tankers are needed. The dedicated military tankers (e.g. KC-135) are capable of carrying a fuel load - 65% of MTOW. For the civil scenario we need smaller ranges (about 1000 nm) and a fuel capability of 65% MTOW can be assumed. Each tanker mission can refuel 2 to 4 cruisers, **Fig.18**. Military refuel operations are at 20,000ft, avoiding the civil flights. In civil context, if the tanker has sufficient thrust, the limits need not apply. Such considerations differentiate between civil and military tankers. Recently, automatic AAR has been demonstrated by an A330 tanker refuelling a F-16 (May 2018).

Fig.19 shows an example of how a tanker, the size of B757 in weight could be envisaged as a flying wing or one with a "pencil" fuselage. This would imply lightness and efficiency (high L/D).

Fig.20 shows an example of fuel burn and MTOW advantages via AAR over 6000nm 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 obtain MTOW advantage but fuel burn advantage reduces.

Even an A321 could be modified into a very effective tanker, capable of 3 refuel operations. We can imagine newer efficient tanker types, with very much slimmer fuselages and low drag. Li **[20]** has studied a small Joined-wing Tanker. Probably, the most efficient tanker would just be an "all-wing".

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

For 250 pax over 2500 nm, **Fig.21** compares non-stop long-range flights and refuelled flights. Note the fuel burn figures. Similar numbers from other ranges lead to **Fig.22**, assuming a block of 3000 passengers travelling in a day over different route lengths. Note the substantial fuel burn and TOW advantages with AAR using cruisers capable of 2000 to 3000 nm length. 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 served. The analysis has given the confidence and allows consideration of a realistic world-wide scenario.

8. Operational Traffic Network With AAR, Tanker Bases

Re-visiting the example of **Section 2** for 3000 pax, with AAR, infer that 12 aircraft carrying 250 pax each, connect 12 city pairs. Several more realistic scenarios arise as many thousands of pax fly daily between many city pairs.

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 10-11%. This really constitutes a step change and a departure from current state. There remains a need for modelling such aspects in greater detail.

Fig.23 shows that city pair network can be established with different sized aircraft (thin or thick routes). AAR zones are conveniently located. Fuel and time savings are implicit. 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 at convenient bases and work outwards to include flights from many city pairs. This is in contrast to other ideas that begin with existing air network and then site intermediate tanker bases on popular routes. The existing route network will naturally alter as AAR establishes.

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

This allows a greater coverage of airports within 2500 - 3000 radius of each tanker base. Further the tankers fly mostly on straight tracks between the bases. However, tankers could be at one base depending on the demand. This system then enlarges the refuelling domain to be in the region of 1500 to 2000 nm. As the traffic builds up on dense routes, extension could be to 3 bases (nearly equi-spaced). This will add further to safety and despatch reliability.

Fig.25 shows how the tanker range extends during the flight of refuel operations. Additionally, high T/W is available for second 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
- Lower take off weights improve field performance. Reduction in Wake hazard effects implicit
- 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%

9. Costing Implications

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

With 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 basic information relating finance and flight parameters underpins the detailed AAR studies in due course.

10. Operational Constraints for AAR

Tanker Operation

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 stems from work with conventional (centre-line) tanking formation - tanker ahead and downstream downwash effects on the Cruiser. A reason for military AAR at altitudes near 20,000 ft is to avoid civils.

Unconventional tanker layouts can be proposed, enabling amelioration of downwash effects (by moving away from centre-line restrictions). New unconventional configurations are "envisaged work" for moderate ranges (allowing small fuel capacity), blending in well with future aircraft design. Further work is needed with tanker aspects, behind the Cruiser. Tanker with higher T/W capability could have a higher altitude ceiling - the boom will be in lower dynamic pressures.

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 landing and take-off operations (LTO) depends on the payload capacity ratio (n) between the baseline Cruiser (suffix B) and the intended AAR Cruiser (suffix A). The number of refuels each tanker performs per mission (f) also affects the LTO's in 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 be actually 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 A to B connections. The use of smaller AAR cruisers is a "win-win" solution.

Fig.31 summary serves as a reminder for AAR Tanker strategy trade-offs studies needed.

11. Inferences about Environment

Weather Considerations

Weather 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 **[5].**

The AAR operation implies contact in mid-air. Hazards en-route during flight can make safe fuel transfer impossible. 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 automatic AAR on UCAV's).

A civil AAR system will use a similar forecasting system as the military's (daily basis) for safe AAR areas. Recently, Airbus has demonstrated automatic refuelling using the A330 tanker.

Climate Impact

The impact of Aviation on climate remains a controversial topic **[21]**. Assuming continued use of traditional carbon-based fuels in combination with the predicted growth of the sector poses sustainability question. However, the AAR concept is an option in the right direction.

Contrails produced are of concern. A system with AAR can be similar to today´s baseline. The tankers with the proposed refuelling envelope generate very little contrails. In general, for contrail formation, the temperatures are below -40°C and these are rare below 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 of the order of 0.05 W/m^2 **[2]**. 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.

Noise Considerations

The "Nangia value efficiency" provides a reasonable first order estimate of the noise impact. The envisaged AAR Cruisers with high payload range efficiencies will have a positive favourable impact on noise near airports, **Fig.33**.

Using typical current-day aircraft types, transitioning towards an AAR-system, will give a reduction of the noise-exposed area for high-intensity noise. For low-intensity noise levels, it is not clear that AAR will improve the situation if there are more 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.

If the cruiser takes off at reduced weight and refuels at altitude, the improved take-off climb rate and possibly de-rated power will dramatically reduce flyover and side-line noise.

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 ones - AAR would be beneficial, **Fig.34**. However, there is no simple proportionality between the emitted substances.

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. Note the benefits in noise, CO2 and LAQ issues. Again, low weight take-offs and de-rated power will reduce fuel burn and CO2 emissions until refuelling altitude is reached. NOX emissions can be reduced by operating the powerplants at lower temperature and power.

Air Traffic Control & Navigation Service

Apart from developing Air Traffic Control regulations allowing AAR, no fundamental new issues for Air Navigation Service are envisaged, **Fig.36**. The airspace is already congested in Europe, US and Asia. Note a day-plan at NATS, Prestwick (19 Jan. 2015). The Oceana Traffic is arranged to fly in ”Tube-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 with or without AAR, is a major challenge.

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 is a non-trivial issue.

Shortening the time between LTO’s is a way to increase capacity. This remains under research and some improvements can be expected. The wake vortices produced at the runway determine the flight safety hazard and set time separation limits and hence the attainable capacity.

Certification Issues, Tanker Conversions

Following **[22-23]** and **Figs.37-38** AAR operation is to be automatic and maintain civil safety standards i.e. 1 in 10^9 rather than being autonomous. Autonomous AAR is beyond the scope of current civil certification. With recent experience on A400M certification, 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.

The treatment of fuel spillage and fire risks is more involved than simply preventing fuel tank explosion. May need adoption of Military standards for signalling and markings.

Another risk is the build-up of precipitation static electricity on the tanker and/or the cruiser. An in-flight hook up could cause an electrical discharge along the refuelling boom and sparking near the refuelling receptacle. Some AAR tankers pause the fuel transfer until the electrical discharge is complete.

AAR is a demanding task in crew workload and the associated human factors. Responsibility for control of the operation and the AAR process is with a dedicated tanker crew. 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 contact, control the fuel offload, disconnect and go 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 employ drogue rather than boom. Boom refuelling, potentially, allows faster speeds and currently requires a boom “pilot” to make contact, introducing a chance of human error. However, automation will obviate such concerns. In the early days, the receiver (with regular airline crew) will trail a drogue for the tanker (piloted by specifically trained and type-rated crew).

Several examples exist of conversions of airliners to tanker and receiver roles: the classic VC-10, contemporary A330 & B767. Civil AAR modifications would be similar but with an element of role reversal! 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 roof of the cockpit and connected to the centre wing tank for fuel dispensing. The significant difference between this and today’s military heavy aircraft 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 e.g. the installation of Auxiliary Cargo Tanks (ACT) 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 APU’s 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 ACT 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 is supported by corresponding avionics. A state-of-the-art Flight Management System (FMS) would include pre-programmed rendezvous and AAR phase patterns. FMS functionality will extend to predicting fuel usage at the each flight plan “waypoint” taking into account any dispense or receipt phases. The cockpit Human Machine Interface would comprise an AAR multi-functional display so that crews review all valve states, tank quantities, fuel transfer/receipt targets, position of trailed hoses and other relevant parameters. Soft keys on the display will allow crew control of the fuel transfer.

12. Concluding Remarks

The metrics of civil aviation show that the current trend longer range aircraft are not fuel-efficient. There is potential in continuing work on innovative layouts. A few promising ones have been mentioned, but practical data is not yet available. We make a case for moderate range aircraft designs. These can be used with AAR for longer ranges.

Continuing work in many facets of the AAR subject has led to consolidations, revisions and emergence of new ideas (summarized in **Figs. 39-42**)

- Replacing today´s Intercontinental air transport system with AAR can reduce fuel burn and direct CO_2 emission by 15-30%. Similarly, NOX reductions will occur.

- Number of LTO's and aircraft are lower (less small range feeders). The total mass of the system in air is 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, local air quality).
- AAR can play an important role, dealing with the sustainability challenges. Short flights can be mitigated to other transport modes. 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 using smaller airports (easier for the airlines)
- Simplify Global air transport routing system, improving passenger perspective and transit time).
- Tankers the size of A320 can be very useful for Civil AAR and could be readied for demonstrations.
- A variation of AAR cruiser size and AAR design ranges can be allowed for optimising savings.
- Other, novel transfer configurations (tanker in front, or non-centreline) can improve aircraft efficiency, system performance and safety.
- Civil AAR is not in isolation. Other operation concepts e.g. formation flying, and new technologies can be integrated with civil AAR. Air Traffic Management for AAR is facilitated with GPS & ATM
- Ground operations & airport logistics simplified, Less need for Airport expansion. Maintenance of smaller aircraft, larger payload fractions

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 – a game changer in sight. We need to be generous and pro-active in work toward realization and adoption of the concepts. It should enable growth of popular mass air travel. Several technological evolutionary developments will arise, rejuvenating the aviation scene. We visualise efficient Twin-Aisle configurations e.g. Joined Wings, Distributed Propulsion layouts. In the "Clean Sky" era, we should aim for practical demonstration: hopefully EU or NASA!

Acknowledgements

For this lecture, the author feels greatly honoured for SAE's recognition, perpetuating the memory of William Littlewood to over 4 decades now. William was president of both SAE (1954) and AIAA (1959). He was renowned for his contributions to the design of, and operational requirements for civil transport aircraft.

The author has been engaged in the quest for efficient air transportation for 2 decades. Aviation projects invariably take a long time to fruition, especially when a new plateau needs to be reached. The industry is conservative and necessarily so. Safety is paramount. Several scientists have been consulted. Body of work has built up to support the inferences in this paper. Special thanks are for members of RECREATE project. Mr Tim Nangia also helped in technical work. Any opinions expressed are from the author.

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Nomenclature

AAR	Air-to-Air Refuelling	VEMPX	Nangia Value Efficiency Parameter
BLI	Boundary Layer Ingestion	VEOPX	non-D “Nangia value Efficiency”
BWB	Blended-wing-body	V	Airstream Velocity (kt)
COC	Cash operating cost	W1	Weight when cruise starts
DOC	Direct operating cost	W2	Landing Weight
f	Number of refuelling operations	WFB	Weight of Block Fuel
HWB	Hybrid-wing-body	WFBR	= WFB/MTOW
LFC	Lifting fuselage concept	WFBS	Weight of Fuel to Cruise
L/D	Lift to Drag Ratio	WFC	Weight of Fuel during Cruise
LTO	Landing and Take Off		
MTOW	Maximum Take Off Weight, lb	WFR	Weight of Fuel Reserves
MX	X/Vsound	WOE	Weight Operating Empty
OEW	Operating Empty Weight	WP	Weight of Payload,
Pax	Passengers	WPA	Weight payload at Point A
PRE	Payload Range Efficiency	WPD	Weight payload at Point D
R	Range (nm)	WPR	WP/MTOW
RT	Tanker fuel/Fuel off-loaded	w r t	with respect to
sfc	Specific Fuel Consumption	X	Range Parameter
TW	Tube-Wing Aircraft	Z	= R/X , Dimensionless ratio
T/W			

See also:
2018 Aviation Technology, Integration, and Operations Conference
June 25-29, 2018, Atlanta, Georgia, USA
AIAA 2018-3591
Session: SAE/AIAA William Littlewood Memorial Lecture
https://doi.org/10.2514/6.2018-3591

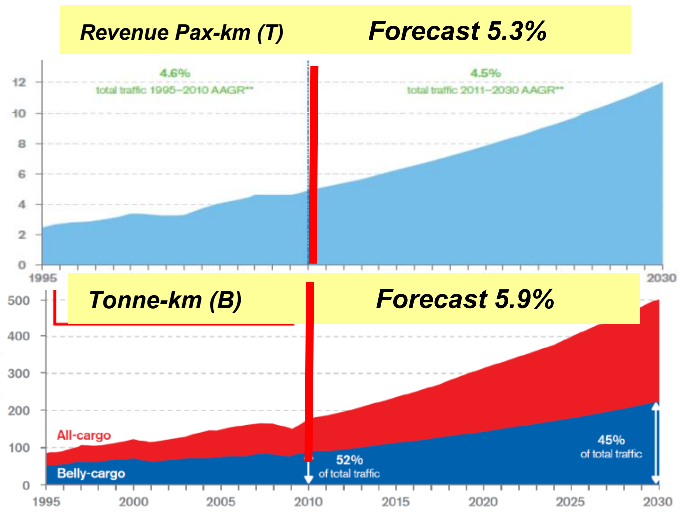


Figure 1. World Scheduled Passenger & Cargo Traffic

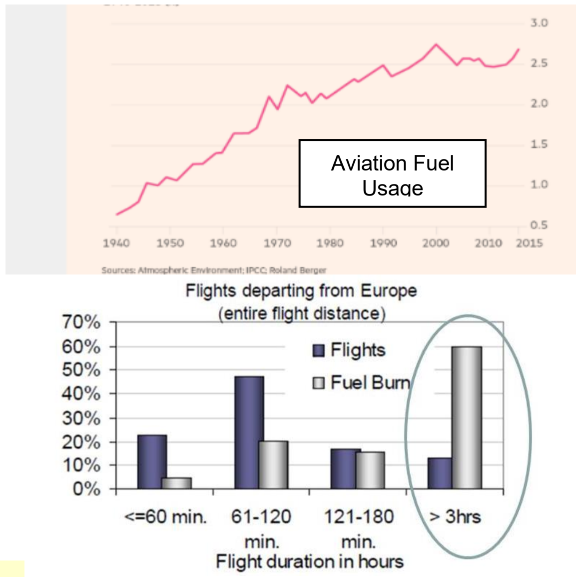


Figure 2. Fuel Usage & Concept of Operations (CONOPS), Inter-Continental

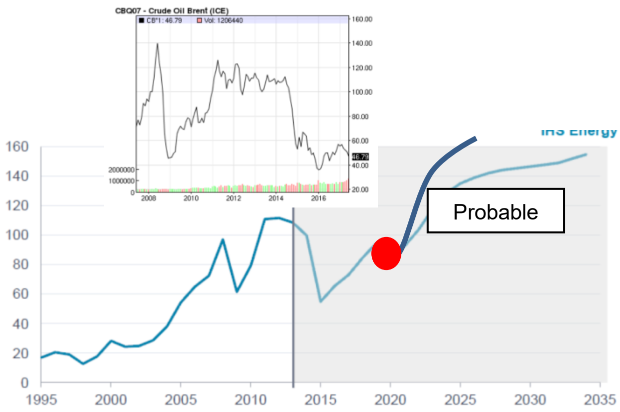


Figure 3. Volatile Oil Price ($/USG), uncertain future

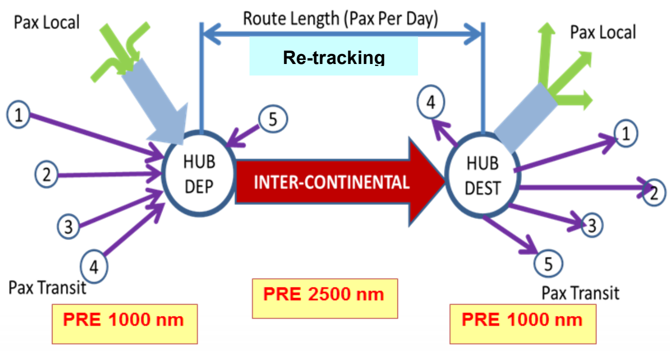


Figure 4. Hub & Feeder Network - 50% pax locally from Hub, Others in Transit via Feeders (5 say, Extra Fuel Burn)

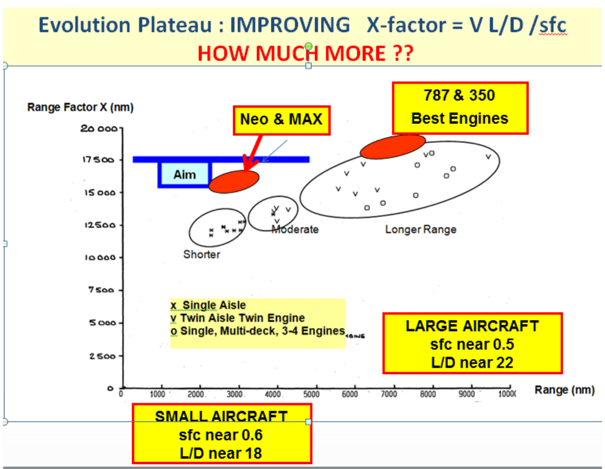


Figure 5. X-Factor, Design Point

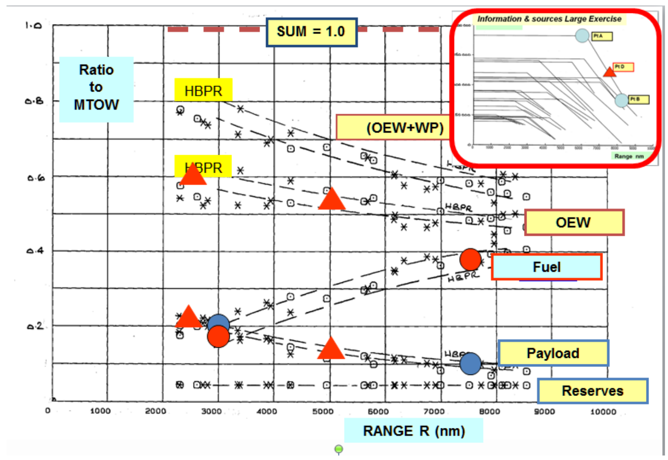


Figure 6. Pt D, OEW, Fuel & Payload Ratios vs Range

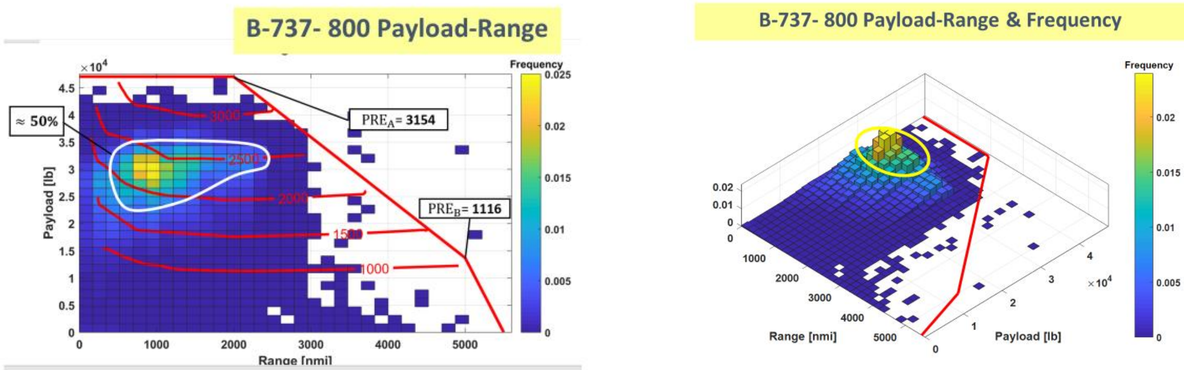


Figure 7. Payload Ratios vs Range, Frequencies

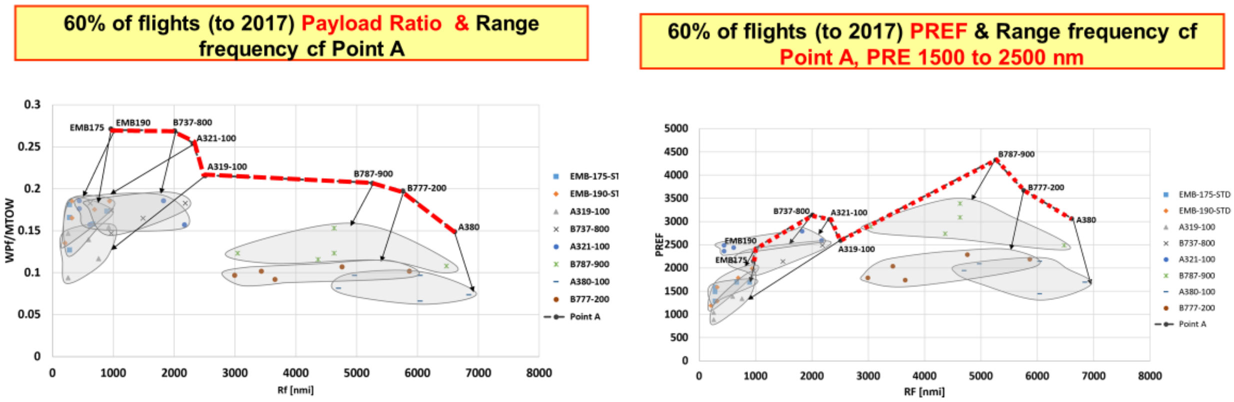


Figure 8. Payload Ratios vs Range Frequency

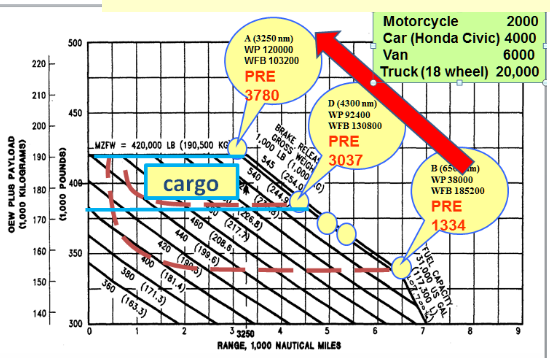


Figure 9. B-777 baseline, Payload ~Range & Derived PRE Levels, M0.84 cruise

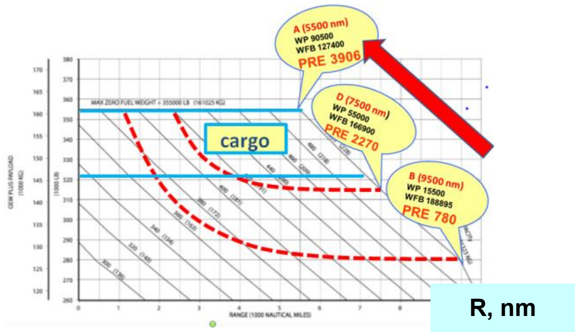


Figure 10. Long range B787 Payload ~ Range & Derived PRE Levels

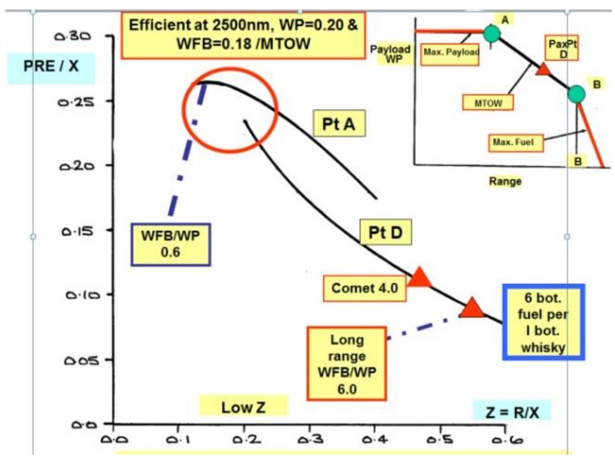


Figure 11. PRE/X vs Z = R/X, Pt A & Pt D

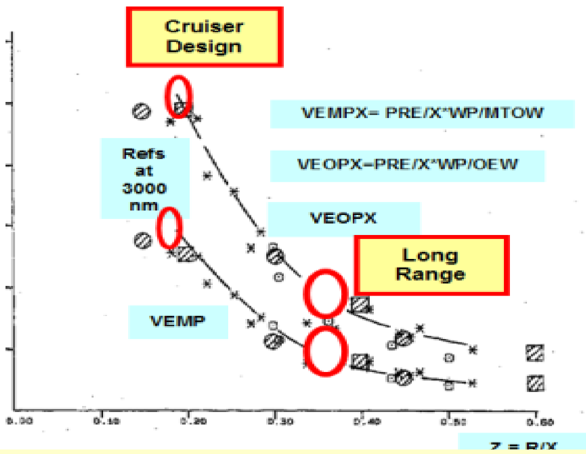


Figure 12. "Nangia" Non-D Value Efficiency Parameters VEMPX & VEOPX at Pt D (Based on [5]

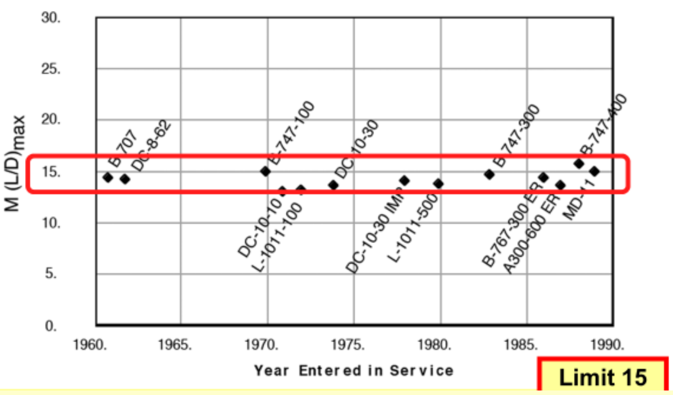


Figure 13. ML/D, Aircraft Ranges above 4500nm, to 1990

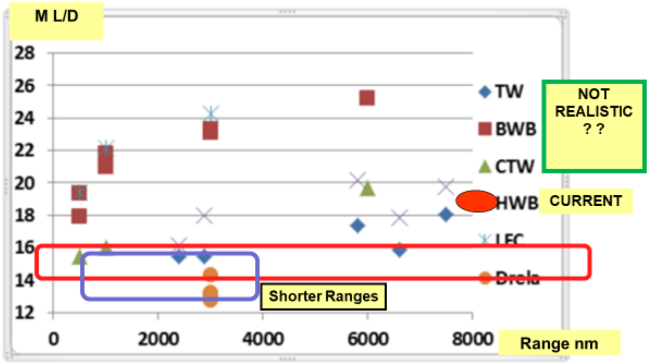


Figure 14. Summarising ML/D Predictions, All Ranges, Not all REALISTIC !

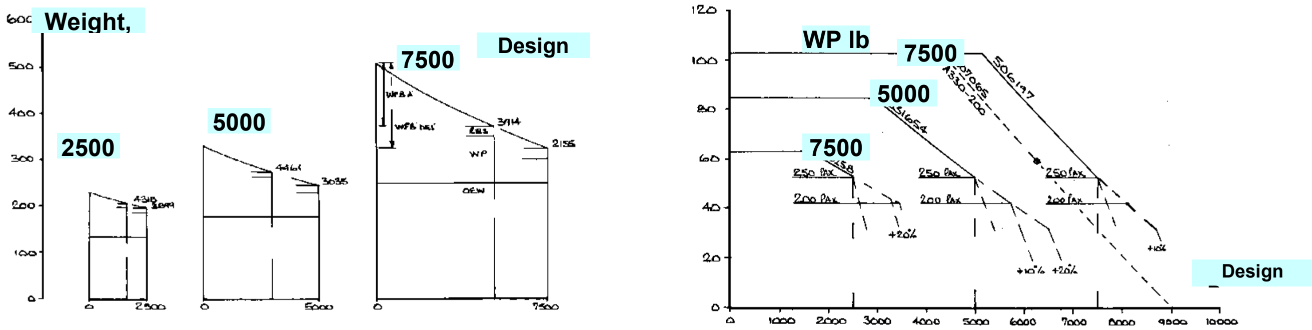
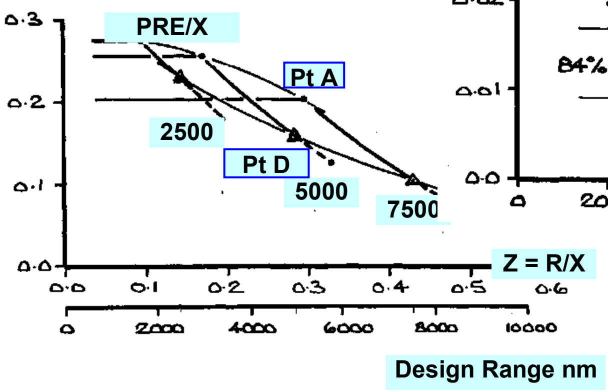


Figure 15. Payload & Weight Relationships for 3 designs capable of ranges 2500, 5000 & 7500 nm.



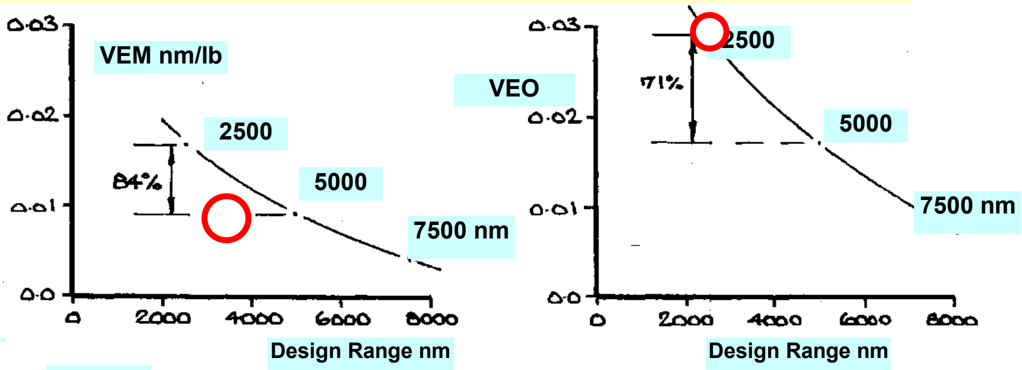
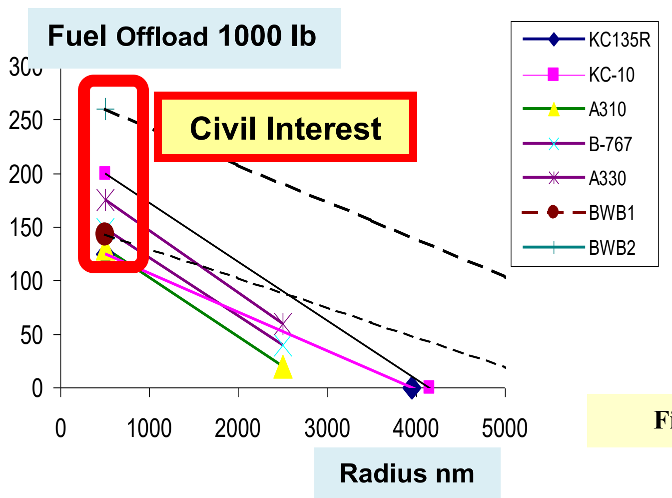


Figure 16. PRE/X & Value Efficiencies for 3 designs capable of ranges 2500, 5000 & 7500 nm.



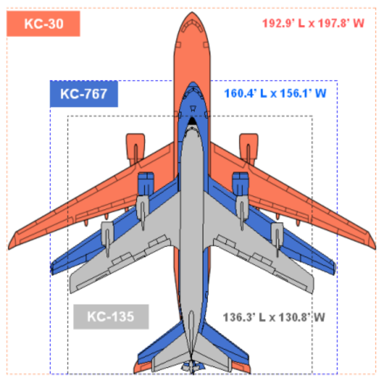


Figure 17. Different Tankers Capability & Civil Interest

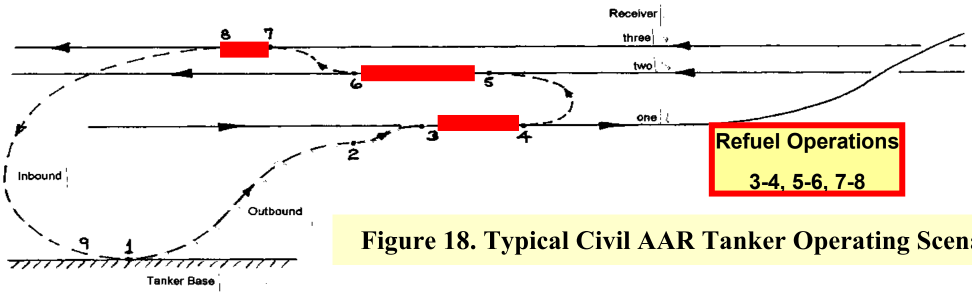


Figure 18. Typical Civil AAR Tanker Operating Scenario,

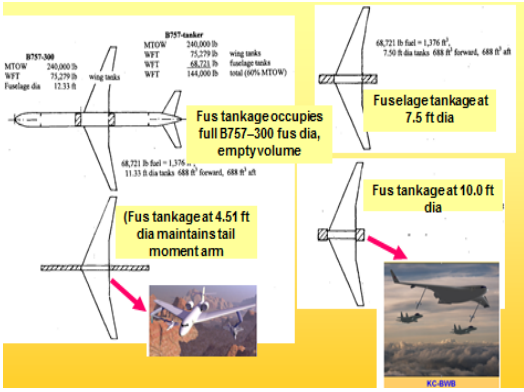


Figure 19. Conventional Wing-Fuselage-Tail Layout, Fuselage Sizing leads to Flying Wings

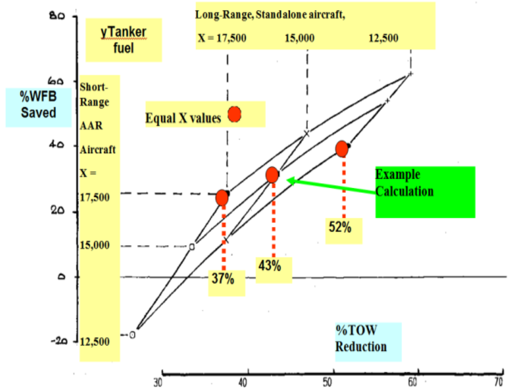


Figure 20. Fuel Burn & TOW Advantages via AAR, 250 Pax, 6000 nm Route, 3000 nm Design Refuels x 1 cf 6000 nm Design, X Varies

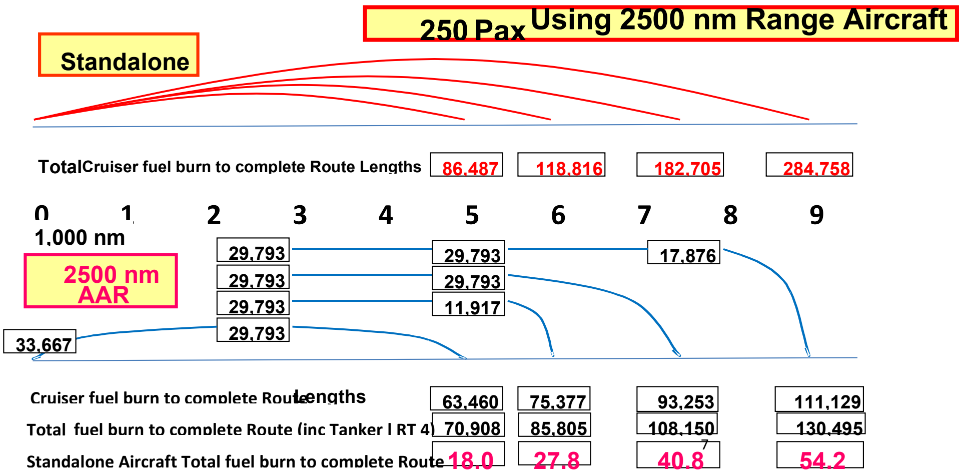


Figure 21. 250 pax, Comparing Non-Stop & Refuelled Flights over Different Ranges

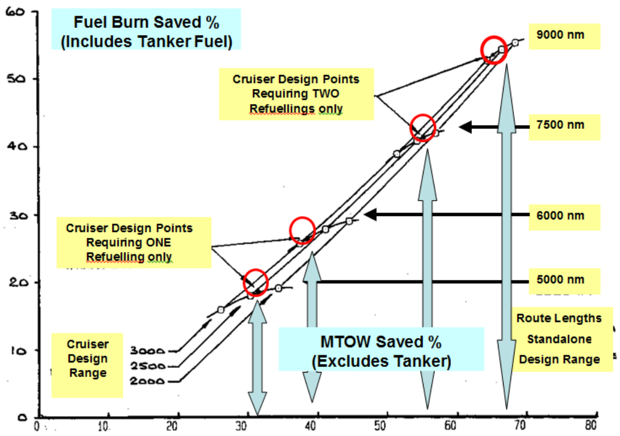


Figure 22. 3000 pax per day, Fuel Burn & MTOW Advantages via AAR, Cruiser Design Ranges of 2000, 2500 and 3000 nm & 200, 250, 300 pax capacity. Stand-alone Cruiser Design Ranges to Match Service Route 5000, 6000, 7500 & 9000 nm

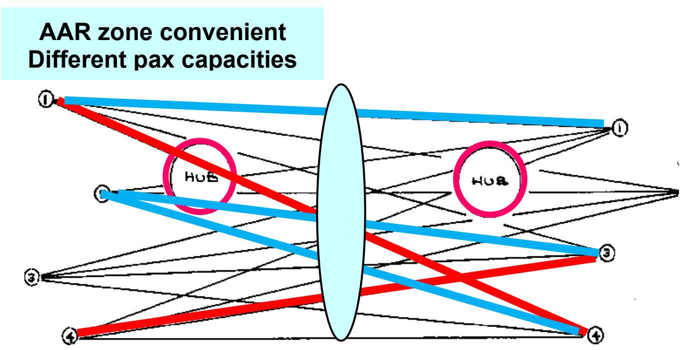


Figure 23. City Pair Network using AAR- Hubs Avoided for Transit Pax (Time and Fuel saved) - Pressure on Hubs RELEASED, Close Formation Flying encouraged

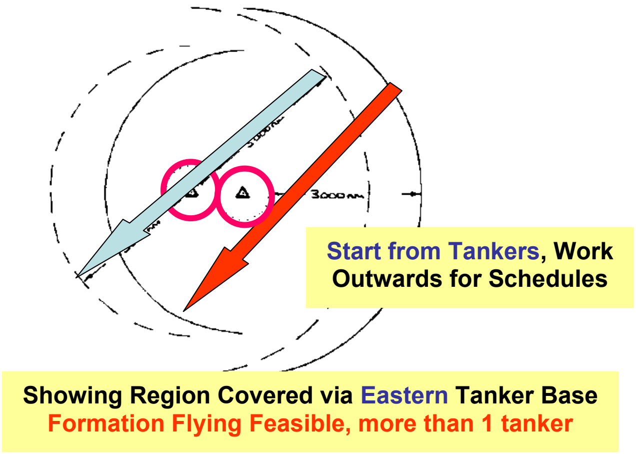


Figure 24. Twin Tanker Bases about 1000 nm apart

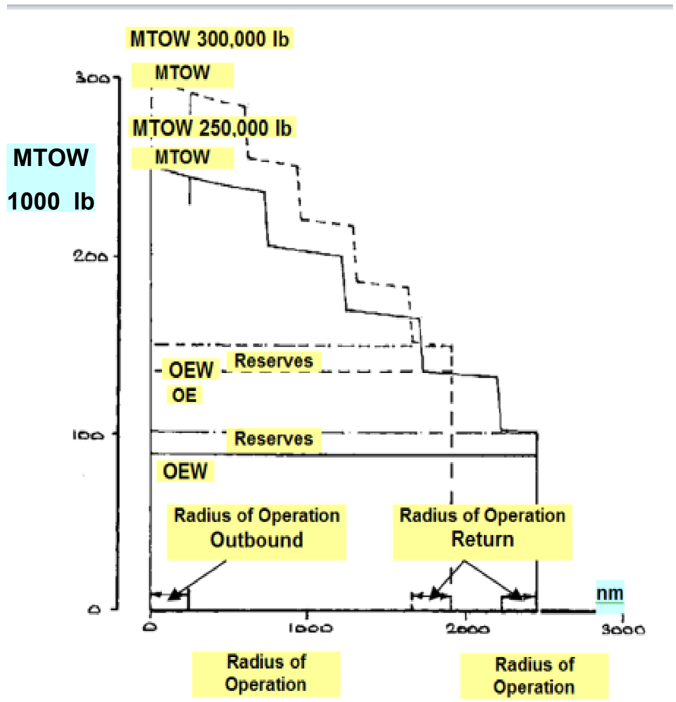


Figure 25. Feeder Weight Breakdown – Distance Flown, Four 30,000 lb Offloads, X 17,500 nm, MTOW 250,000 lb, OEWR 0.35, RT 4, Loiter 61 min, MTOW 300,000 lb, OEWR 0.45, RT 4, Loiter 42 min

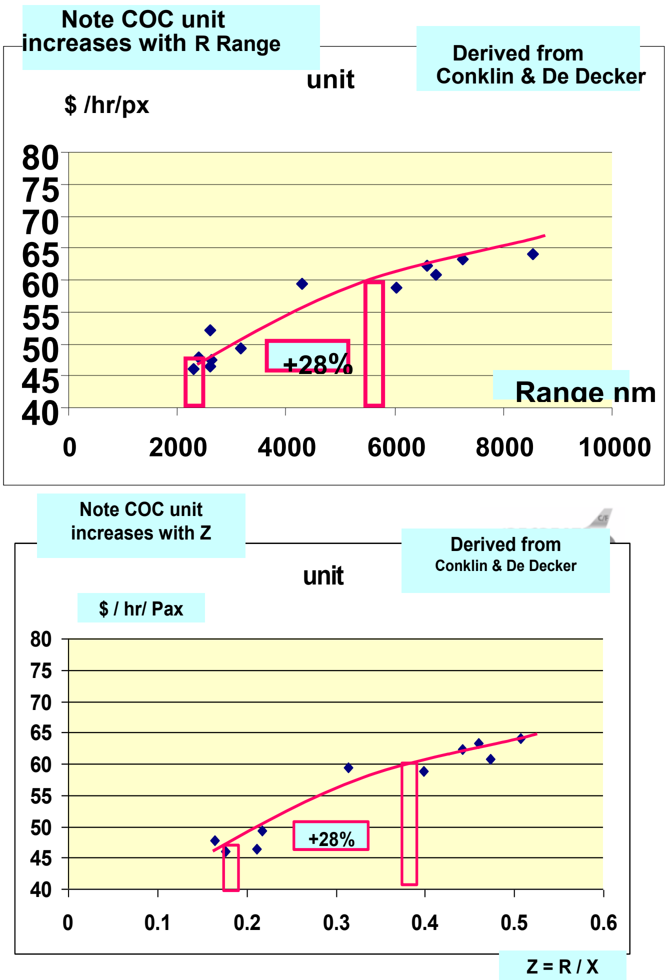
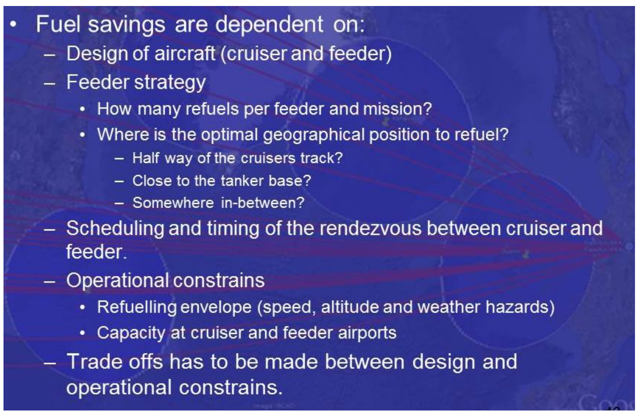
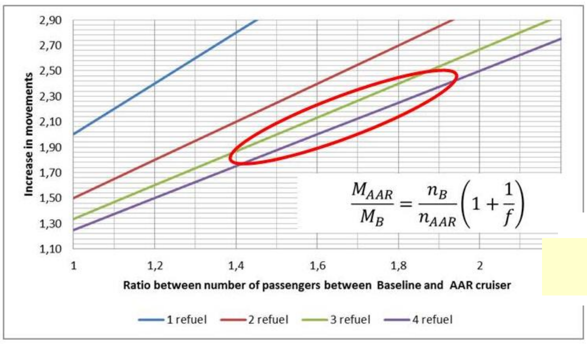


Figure 26. COC Relationships with Range and Z



28 Figure 39. Fuel Savings Dependencies



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

Number of flights (M) increase with AAR since the cruisers has le

Figure 29. Capacity Aspects of Cruiser/Feeder Operations

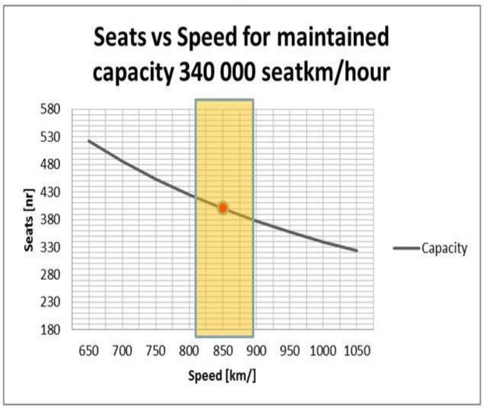


Figure 30. Capacity Aspects of Cruiser/Feeder Operations, Airline operates (24/7), Average speed 850 km/hr & 400 seats in Long-Haul Fleet

- 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)

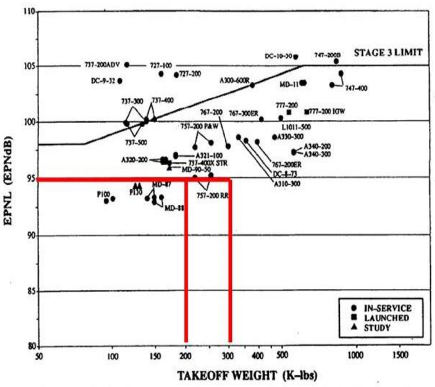
Figure 31. Feeder Strategy Trade-off Studies

n

- 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…

32 Figure 43. Significant Weather Hazards SIGWX

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

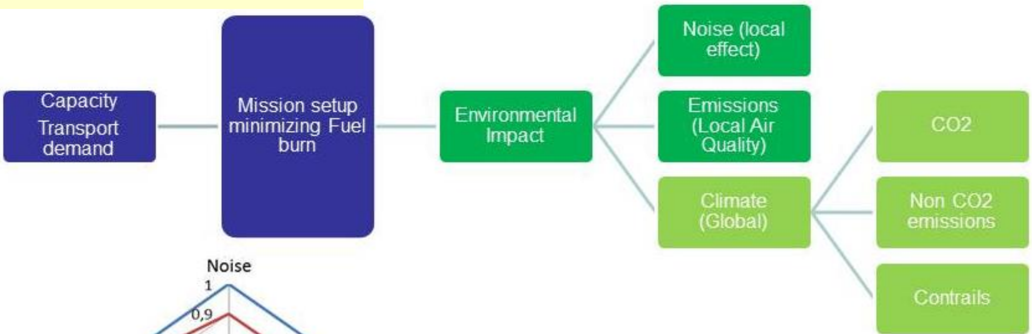


Impact of aircraft sizing on noise (ICAO Stage 3)

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



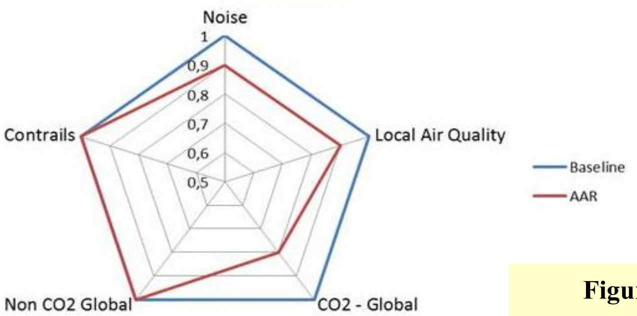


Figure 35. Environmental Impact of AAR

- 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.

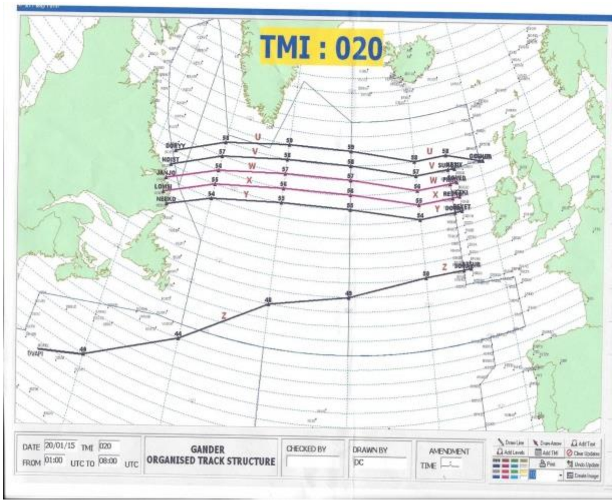


Figure 36. Air Traffic Control & a day plan at NATS, Prestwick (19 Jan 2015), Oceana Traffic in Tubes 60nm apart, Longitudinal Separation 10 mins to allow for different speeds and heights

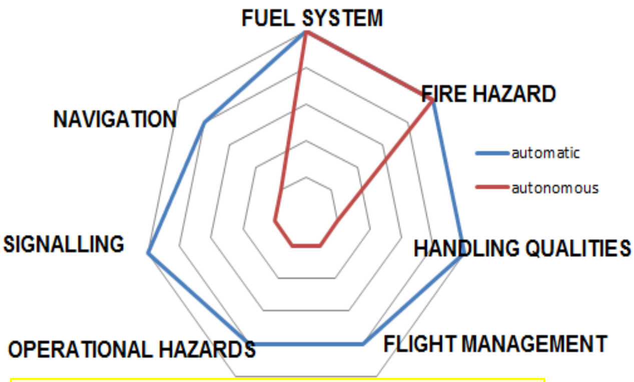


Figure 37. Automatic or Autonomous !

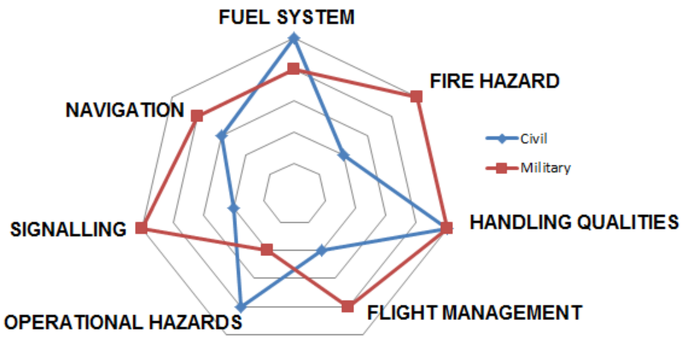
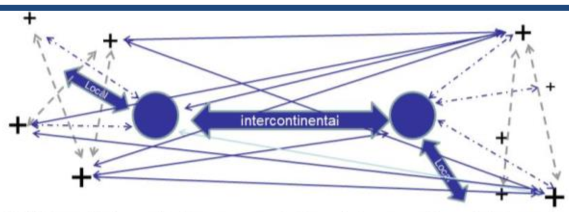
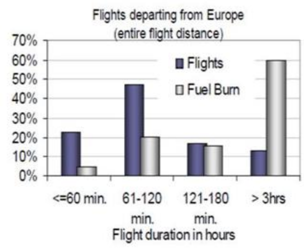


Figure 38. Civil vs Military Certification (A400M Experience)



- Shift from "hub-spoke" to more point to point connections. The smaller AAR-cruisers inherently give us the opportunity to do this.
- Easier for the airline companies to make a business case for new connections compared to the larger baseline cruiser.
- The increased demand for air transport will, with or without AAR, be a major challenge in many parts of the world.
- Mitigation of short flights will be helpful for the overall capacity in the system.

Figure 39. AAR Tomorrow



- Today´s "hub-spoke-system" is not sustainable with expected growth (IPCC*). Continuation of urbanisation and more megacities calls for mitigating air transport (for distances below 1500 km) to other transport sectors.
- 9,55 millions controlled (IFR) flights in Europe 2012.
- A 10% reduction in number of flights < 120 minutes represents 620 000 flights! This is more than all flights to Heathrow in a year.

Figure 40. Mitigating Short Flights

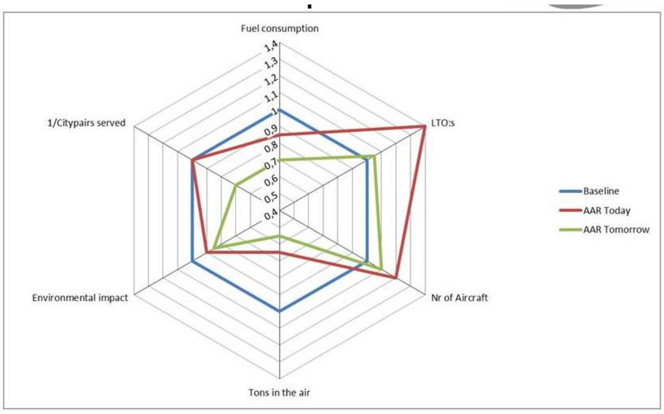


Figure 41. Expected Improvements From Cruiser/Feeder Operations, for the same Transport Capacity per unit time

- Replacing today´s intercontinental air transport system (as it is) with AAR can reduce fuel burn and direct CO_2 emission by 10-20%.
- Number of movements and aircraft will increase, however, the total mass of the system will be lower.
- Operational constrains on the system with present traffic load seems 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 (fuel, direct CO_2 emissions and mass) and for long flights where no viable option exists

- The smaller more efficient AAR-cruisers inherently gives opportunity to serve more point to point connections.
- It will also 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 (200-300 pax) and AAR design ranges (2500-3000 nm) 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 new concepts of air operations and new technologies can be used together with civil AAR (formation flying)

Figure 42. Main Benefits of AAR