COST-RANGE TRADE-OFF IN THE DESIGN AND OPERATION OF LONG RANGE TRANSPORT AIRPLANES

R. Martinez-Val, E. Perez, C. Cuerno and J.F. Palacin
Universidad Politecnica de Madrid, Spain

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Abstract

The objective of this study is to show the environmental and operating cost savings that could be achieved if long range transport aircraft were designed for shorter ranges; obviously at the drawback of longer trip duration, for the inevitable intermediate stop.
The maximum take-off weight and operating empty weight, main design variables of transport airplanes, would be greatly reduced. However, it would be impossible to take full advantage of this procedure for, on the one hand, it would be difficult to find a suitable airport at the exact midpoint and, moreover, there would be a certain increase in the total distance because of the deviation. The overall result will depend on the length of the route, the technology level (range factor and operating empty weight fraction with respect to maximum take-off weight), and other variables that will be discussed. Only for very long routes and/or very high fuel cost the shorter design range case represents a meaningful saving with respect to the non-stop flight.

1 Introduction

Commercial aviation has progressed at an astounding pace, both in terms of passenger.kilometres flown, as in terms of technological developments. And this stimulating situation is going to last over the next decades. Thus, all forecast predict that the passenger traffic will double in about 15 years [1-3] and there will certainly be new achievements in key areas such as aerodynamics, propulsion, structures, avionics, materials, air traffic management, etc [4].

Paradoxically, these relevant advancements have occurred without visible modifications of what is currently called the conventional configuration, first appeared in the late 1940s. Such configuration is characterized by a slender fuselage mated to a high aspect ratio wing, with horizontal and vertical tailplanes fitted to the fuselage tail cone, and pod-mounted engines under the wing [5]. The conservative approach with respect to the configuration is somehow counterbalanced by a permanent research effort, which has resulted in remarkable improvements in all performance and economics figures of merit [6].

A variant of the aforementioned layout, with the engines attached to the rear fuselage, was also developed during the 1950s and is still broadly used in business and regional jets. Modern turboprops share the same overall picture of the commercial jets, but with the engine nacelles mounted on unswept wings.

However, it seems that this conventional configuration is approaching an asymptote in its productivity and capacity characteristics around the size of A380 [7, 8]. And this is happening in a period of increasing environmental concern about pollution and noise [9-11].

The ever changing market and technology scenario leads the process of conceiving new airplanes, and the major questions are, as usual: What does the market need? Which design fits better in the long-term? How the evolving air traffic management will affect the overall efficiency of the air transportation system?

Two distinct approaches can be followed to answer those questions: pursuing the improvement of the current airplane layout and air traffic system; or adopting a more radical perspective to incorporate new configurations, such as blended-wing-bodies, wing boxes, etc, and the corresponding new air traffic rules [12-15].

The present paper relies on the idea that maintaining the conventional arrangement but incorporating new airplane operational schemes can still produce meaningful savings, both economically and environmentally, to add to the improvements naturally derived from the aforementioned continuous technological evolution.

Although passenger preferences are clearly in favour of non-stop flights, geopolitical reasons and performance limitations may lead to schedule some routes with intermediate stops. This is common in flights from Europe to Australia, with a stop at either Singapore or Bangkok. Also, in the past, when the USSR did not allowed flights over Siberia, European airlines found a track to the Far East via the North Pole (see Fig. 1), with a refuelling stop at Anchorage, shorter than alternative routes over India and Indochina.

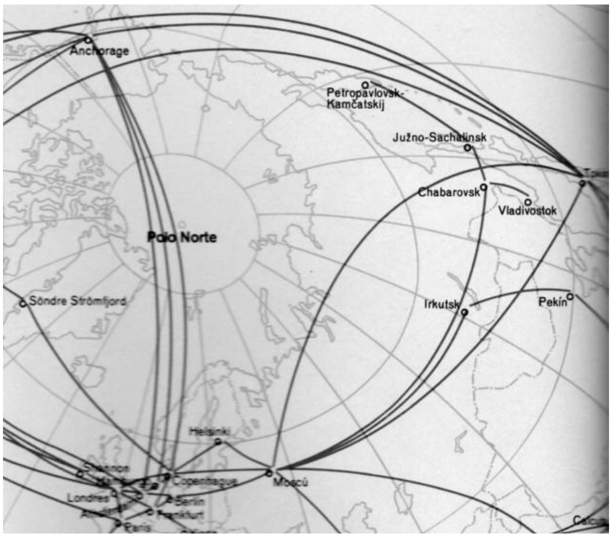

FIGURE 1. Polar routes from Europe to Japan via Anchorage, Alaska, USA, in the 1980s.

The present paper attempts at studying the potential advantages of designing long range airliners for medium range routes. The airliners would be lighter, i.e. would have lower maximum take-off weight (MTOW) and operating empty weight (OEW); but would obviously have the drawback of requiring a longer trip. The fuel burnt and the direct operating cost (DOC) would vary and could result in relevant savings, both in terms of DOC as well as in emissions.

2 Problem formulation

The aim of the present section is to describe, with methods proper of conceptual design level at which the study has been carried out, how all relevant airplane weights (MTOW, OEW and trip fuel) and DOC are computed, within some specified performance and route conditions.

By definition the maximum take-off weight is the maximum of all operational combinations of OEW, payload (PL) and fuel weight; this last appropriately split into trip (TF) and reserve fuel (RF) [16-18]:

$$MTOW \geq OEW + PL + TF + RF \tag{1}$$

The operating empty weight can be established as a fraction of MTOW, i.e.

$$OEW = f_E \, MTOW \tag{2}$$

The fraction parameter, f_E, mainly depends on the design range (the longer the range the lower its value) and on the technology level; for example, incorporating composites in the primary structure [19] or approaching an all-electric aircraft concept [20] reduce f_E .

According to the conceptual design level adopted for the present model, reserve fuel can be defined as a fraction (5%) of the landing weight, which translates into

$$RF = 0.055\left(OEW + PL\right) \tag{3}$$

Finally, the fuel burnt during the trip can be estimated as

$$TF = MTOW\left[0.04 + 0.975\left(1 - e^{-\frac{R-300}{K}}\right)\right] \tag{4}$$

Where the first right hand term represents the fuel required for take-off, climb, descent and landing; and the second term is the fuel used in the cruise phase, which starts at 0.975MTOW and is performed with an average range parameter, K. The actual range is diminished in 300 km to account for the distance flown during the non-cruise phases [16-18].

The former weight estimation method has been applied to two different airplanes, one with PL= 30000 kg and another PL= 50000 kg, representing 300 and 500 seat class aircraft at about 70 percent of the maximum payload [8, 21-23]; which is commonly close to the maximum productivity point [24]. Figures 2 and 3 show how MTOW and TF vary with range for the PL= 30000 kg case, with K= 29000 km and f_E varying between 0.51 at R= 9000 km and 0.45 for R= 15000 km.

The relationship between MTOW and range agrees very well with data of actual aircraft in this category. However, because of the high range parameter chosen, the results found are about 5 % below the MTOW-R pairs of A330, A340 and B777 for PL= 30000 kg; and around 15 percent below the values for IL-96, L-1011 and MD11. On the other hand, the ratio between trip fuel and MTOW only increase from 0.30 for R= 9000 km to 0.43 for R=15000 km, for the positive simultaneous effects of range and size.

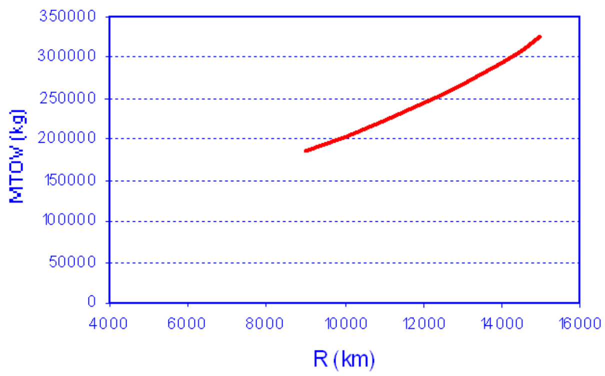

Figure 2. Maximum take-off weight as a function of range for PL=30000 kg.

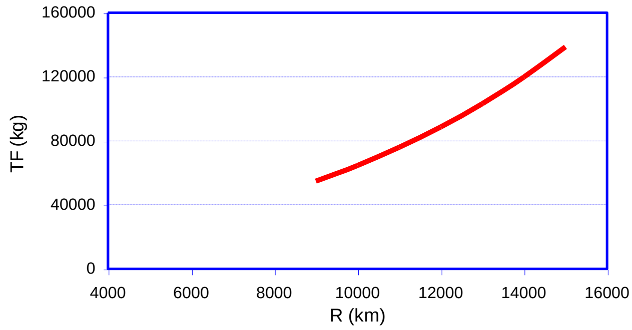

Figure 3. Trip fuel in terms of range for PL=30000 kg.

Analogously, Figs. 4 and 5 are the equivalent pictures for PL= 50000 kg, with the same range parameter and empty weight fractions. Again the results agree very well with the values of A380 and B747 for PL= 50000 kg, the actual aircraft data being about 5-10 percent above the solid line in Fig. 4.

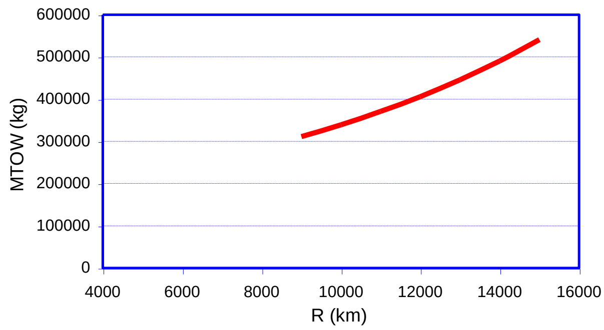

Figure 4. Maximum take-off weight as a function of on range for PL=50000 kg.

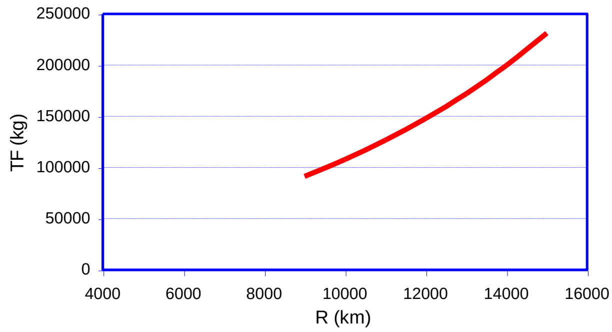

Figure 5. Trip fuel in terms of range for PL=50000 kg.

The results shown in these figures constitute the basis for later comparisons, when R, K or f_E vary.

Let us now define the short design range case. This means that instead of designing the airplane for a long range route, it is designed for a shorter one. It is easy to understand that all airplane weights will diminish. Equation 1 still holds, but the estimation of operating empty weight requires a new model:

$$OEW_{red} = 0.4 OEW + 0.6 f_E MTOW_{red} \qquad (5)$$

Where the subscript red stands for reduced range.

The splitting between a constant part and a reduced one comes from the fact that the fuselage and all its equipment and furniture are essentially independent of the range. It is the wing, tailplanes, engines and landing gear that are proportional to the reduced MTOW.

If the technology level is kept, the wing loading is kept too. Therefore the wing area will be smaller, which will imply a lower Reynolds number and, consequently, a slightly larger drag. This will decrease the range parameter by about 1 %. The results appear in Fig. 6.

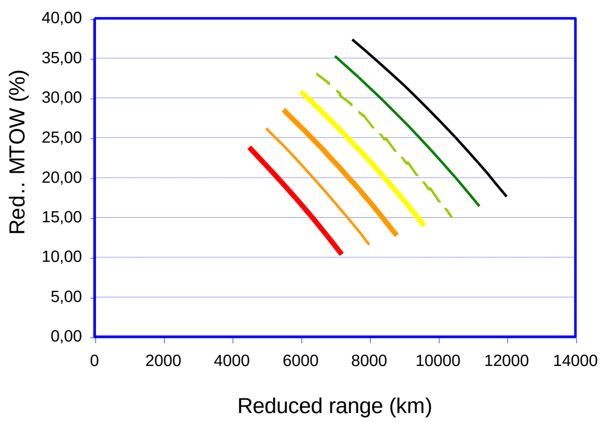

Figure 6. MTOW reduction for reduced ranges in terms of the original range (— R=9000 km, — R=15000 km) for PL=30000 kg.

As indicated formerly, the technology level also drives the design through the range parameter. In the present study its influence has been analyzed by stating that

$$K^* = f_K K \qquad (6)$$

Where K* is the new range parameter and K the original one. The impact of both a range reduction and the technology factor f_K is shown in Figures 7 and 8. It can be observed that, as expected, f_K has relatively more effect on TF than on MTOW, since in this last its influence is smoothed by the design range. The savings in MTOW are about 20-30 percent, but in trip fuel may be as high as 40-55 percent.

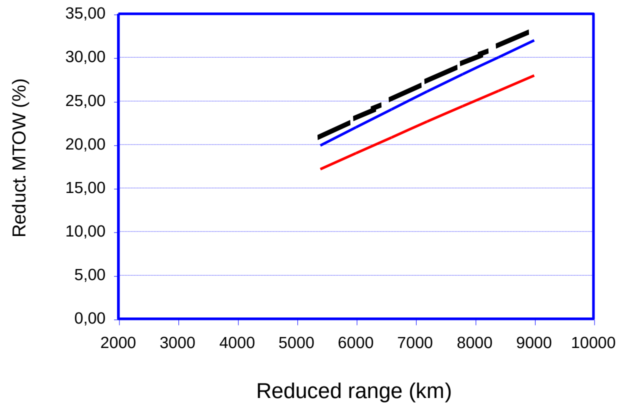

Figure 7. Reduction in MTOW for a range 60 percent the original distance. Range factor as indicated in Equation. 5: — f_K=0.9, — f_K=1, ▬ ▬ f_K=1.04.

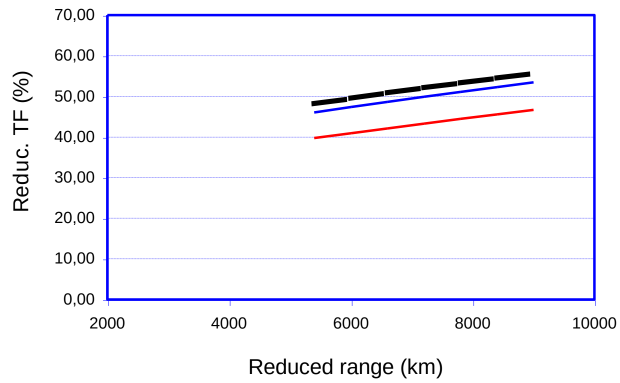

Figure 8. Reduction in TF for a range 60 percent the original distance. Symbols as in Fig. 7.

Obviously these are not fair comparisons with respect to the baseline airplane, designed for the original city pair route. The appropriate comparison requires the new aircraft to fly a second segment to cover the full route.

To this end an acceptable scenario must be defined. In the present case, the original route is split into two parts: a first one with 60 percent the original distance; and a second segment with 50 percent. This means that the intermediate stop is not exactly at the mid point and not exactly on the orthodromic, but close to both, which is representative of most commercially interesting city pairs.

Although the airplane is clearly lighter than the one designed for the non-stop flight (see Figs. 6 and 7), the global trip fuel is not necessarily lesser than that of the baseline case. Within the hypotheses and constraints of the aforementioned scenario, there are only some fuel savings when the original route is longer than about 9300 km (5000 nautical miles) as shown in Fig. 9 for PL=30000 kg. For shorter distances than that one, the extra fuel burnt in the doubled non-cruise phases, plus the extra cruise distance counterbalance the potential savings.

All these results and comments apply for PL= 50000 kg too.

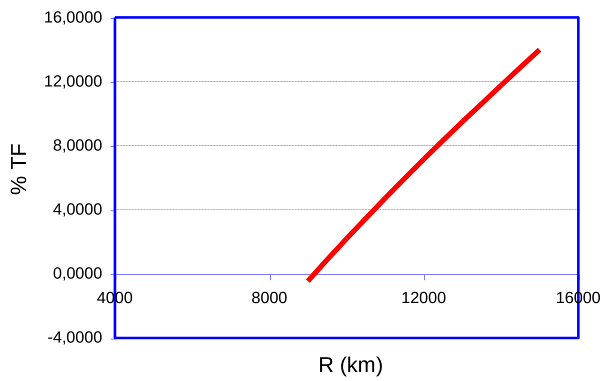

Figure 9, Fuel savings in the two segments flight, as a function of city pair distance.

Fuel consumption is directly related to CO_2 emissions, since each kilogram of jet fuel generates 3.57 kg of carbon dioxide [25, 26]. Although the results are not positive for ranges below 9300 km, splitting the original route into two segments (60 and 50 percent) implies a relevant decrease in environmental impact for very long routes.

3 Cost analysis

The former scenario, of the airplane being designed for 60 percent of the original distance and covering a second slightly shorter stage to reach the destination airport, has been analyzed also in terms of direct operating cost (DOC). In the present case, DOC is not estimated in absolute terms but in relative ones, since the real DOC involves numerous unknown parameters.

As usual, DOC includes contributions related to the aircraft price, crew, fuel, airport and navigation taxes, and maintenance [24, 27, 28]. Explicitly this means

$$DOC = C_{price} + C_{crew} + C_{fuel} + C_{tax} + C_{maint} \quad (7)$$

Since DOC is computed in relative terms, the former sum adds up to 100 for the baseline data set.

The contributions are assumed to vary according to Eqs. 8-12. The main independent variables are MTOW, OEW, flying block time (cruise time plus half an hour for take-off, climb, descent, landing and taxiing), and crew block time (flying block time plus an extra half hour, to have the airplane ready before flying and to leave it after the flight) [29]. When the route is split into two segments (subscript s in the equations), both the flying block time and crew time are longer (1.5 hours) for the intermediate stop. This extra time is not only due to the stop itself, but to the fact that airports suitable for wide bodies are commonly very busy.

On another side, the distance is 10 percent longer than the city pair route (the first and second segments being 60 and 50 percent the original distance, respectively). This is the meaning of 1.1 R in Eqs. 8, 9 and 12. The airplane is assumed to cruise at 850 km/h (around M=0.80), but there is no relevant difference when it does at M=0.83. The specific contributions are computed as

$$C_{price} = c_p \left(\frac{MTOW_s}{MTOW} \right)^{0.8} \frac{\left(\frac{1.1R}{850} + 2 \right)}{\left(\frac{R}{850} + 0.5 \right)} \quad (8)$$

$$C_{crew} = c_c \frac{\left(\frac{1.1R}{850} + 2.5 \right)}{\left(\frac{R}{850} + 1 \right)} \quad (9)$$

$$C_{fuel} = c_f \frac{TF_s}{TF} \quad (10)$$

$$C_{tax} = c_{t1} \left(\frac{MTOW_s}{MTOW} \right)^{0.7} + c_{t2} \quad (11)$$

$$C_{maint} = \left[c_{m1} \left(\frac{OEW_s}{OEW} \right)^{0.7} + c_{m2} \left(\frac{MTOW_s}{MTOW} \right) \right] \times \times \left(\frac{1.1R}{850} + 2 \right) \Big/ \left(\frac{R}{850} + 0.5 \right) \quad (12)$$

For the PL= 30000 kg airplane, a typical sharing for medium size wide body is c_p=25, c_c=15, c_f=30, c_{t1}=7, c_{t2}=8, c_{m1}=8 and c_{m2}=7 [24, 27-29]. The results, for R ranging between 9000 and 15000 km, are depicted in Fig. 12. The disadvantages already indicated for the splitting and lengthening of the route are also found here, and the lighter airplane is not competitive unless the distance between origin and destination is longer than around 11000 km. Again similar results are found with PL= 50000 kg, with a breakeven point at 10500 km and, a different cost sharing; namely:. c_p=22, c_c=13, c_f=35, c_{t1}=8, c_{t2}=7, c_{m1}=8 and c_{m2}=7.

Needless to say, the results are very dependent on fuel cost, since C_{fuel} is the largest contributor to DOC. Therefore, if the fuel price rises or if a pollution tax is levied on aviation, the situation could differ. This is also explained in Fig. 10, that shows the impact of fuel price increasing by 50% and of adding an environment protection tax which, together with higher fuel price, doubles the original cost. Interestingly, neither of both effects are relevant in terms of cost cut down.

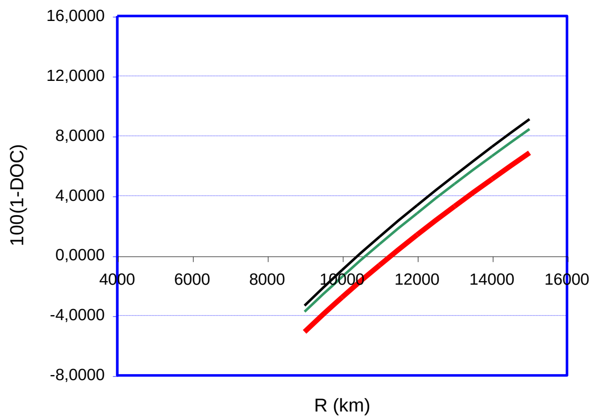

Figure 10. Relative DOC variations when the route is split into two segments of 60 and 50 percent the original distance, for PL=30000 kg. — current cost sharing; — 50% increased fuel prices; — increased fuel prices plus eco-tax.

4 Conclusions

The effect of splitting long range routes into two segments has been analyzed for two payloads: 30000 and 50000 kg. The splitting respects geographic and commercial constraints. The main findings are as follows:

The airplane designed for a reduced range is considerably lighter (around 20-30 percent), both in MTOW and OEW.

However, the potential fuel savings are counterbalanced by the duplication of the non-cruise phases and the extra distance considered in the model as a realistic scenario. Only for routes longer than about 9300 km (5000 NM) the overall result is positive.

Technology level effects have also been studied, through the OEW/MTOW ratio and the range parameter, but they appear to be of secondary relevance, since their effects are smoothed out by the key variable: the route range.

In terms of direct operating cost the results are, even, less positive; for the extra flying time and extra crew time required. Only for very long routes, above 11000 km (6000 NM), the DOC is lesser than the baseline non-stop flight. In the best case, for R=15000 km, the economic saving is about 7 percent. Higher fuel prices and/or new taxes on fuel hardly improve the savings up to 8-9 percent.

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Corresponding author

rodrigo.martinezval@upm.es