Efficiency parameters for modern commercial aircraft

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ABSTRACT

Currently, there is great emphasis, worldwide, on environmental issues. This will have an impact on civil aircraft design, manufacture and operation.

Since the advent of the jet engine and swept wing aircraft, the trends have naturally tended towards greater productivity through increasing speed and payload. The cruise speed of conventional civil aircraft is unlikely to increase beyond current levels. Further increases in productivity are achieved by increasing payloads. This has led towards larger aircraft with the capability for increased ranges. It is shown that designing aircraft for longer ranges increases fuel burn significantly.

A series of aircraft operational parameters have been analysed. Selected data and established trends for current and future aircraft are presented. The data has been interpreted into efficiency terms, relating payload, range, fuel consumed and a measure of unit costs. It is shown that 'value' (cost) and noise effective efficiencies decrease dramatically with increasing range.

Environmental and economic considerations, in the future, may well demand greater efficiency in preference to productivity. One solution for long-range services is to use short-range hops. Another is via air-to-air refuelling. This will be addressed, in more detail, in a future paper.

NOMENCLATURE

*c*1, *c*2	technology constants (see Section 4)
CFRP	carbon fibre reinforced plastic
DOC	direct operating costs
EXP	exponential
HBPR	high by-pass ratio
L/*D*	aircraft lift/drag ratio
M	Mach number
OEW	operating empty weight
PRE	= *WP* **R*/*WFB*, payload range efficiency
R	range (nm or km)
SFC	specific fuel consumption
TOW	take-off weight (*MTOW*, maximum)
V	aircraft velocity
VEM	= *PRE*/*MTOW*, value efficiency per *MTOW* unit
VEO	= *PRE*/*OEW*, value efficiency per *OEW* unit
VEMPX	= *VEM***WP*/*X*, non-dimensional value efficiency, Section 6
VEOPX	= *VEO***WP*/*X*, non-dimensional value efficiency, Section 6
WFB	block fuel load
WFB/*WP*	fuel payload fraction
WFRes	or *WFR*, reserve fuel load
WFT	total fuel load
WP	payload

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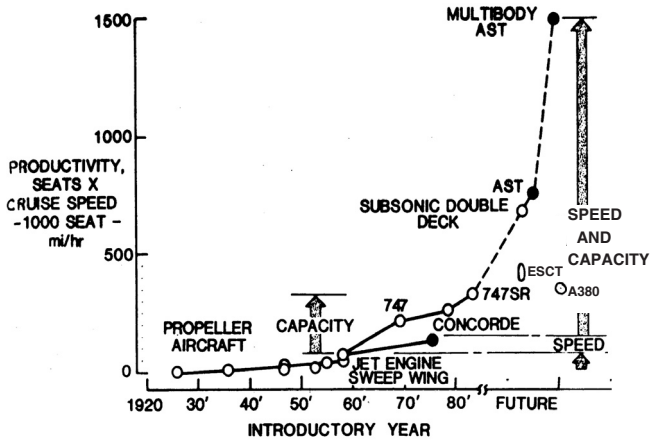


Figure 1. Improvements in productivity of long range transport aircraft (Dollyhigh *et al*[1]).

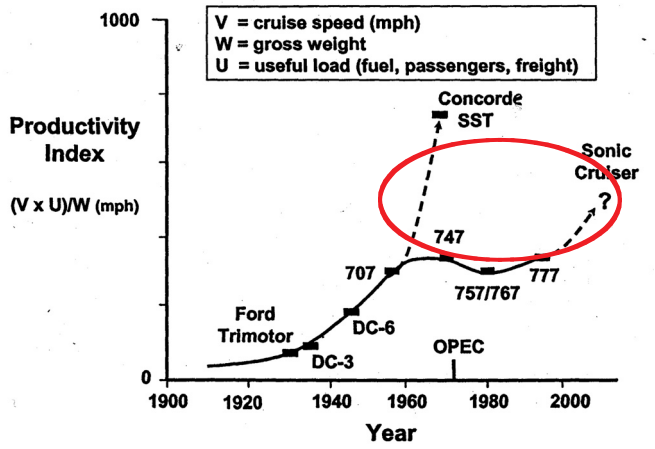


Figure 2. Evolution in the productivity of commercial aircraft. (McMasters[2]).

WP/*WFB*	payload efficiency
X	= *V* * (*L*/*D*) / SFC
Z	= *R*/*X*
ZFW	zero fuel weight (*MZFW*, maximum)

1.0 INTRODUCTION

With the current emphasis on environmental issues worldwide, questions arise concerning the real efficiency parameters of air travel used by manufacturers, consumers and legislators. As the demands on civil aviation expand, the aircraft design and operation scenario is continually and evermore 'ruthlessly' subjected to environmental and efficiency issues. Conventional aerospace technology improvements, which are intended to improve efficiency, are beginning to level out.

In this paper we look at productivity and efficiency trends (Refs 1-2) and develop the efficiency theme to include fuel usage in a consistent way. From an economic and environmental viewpoint, the conclusions lead to the adoption of alternative aircraft designs and operating procedures. These might involve intermediate short-range hops or air-to-air refuelling of smaller aircraft to complete current high capacity long-range flights. These aspects will be addressed in another paper.

This paper is 'multi-faceted' in that it endeavours to improve upon some of the results published by the Greener By Design Group (Refs 3-4), develops the analysis methods along more practical lines and describes feasible ways of improving efficiency in economic and environmental terms.

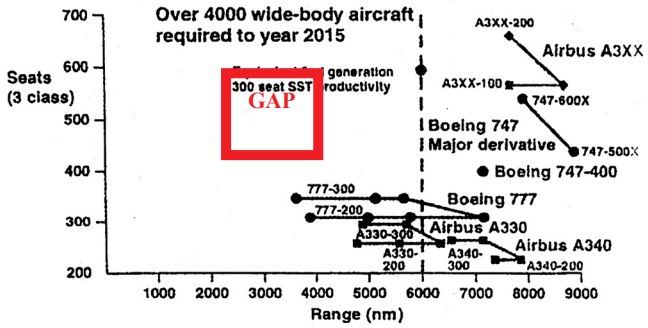


Figure 3. Aircraft seats *v* range for next generation aircraft (Green).

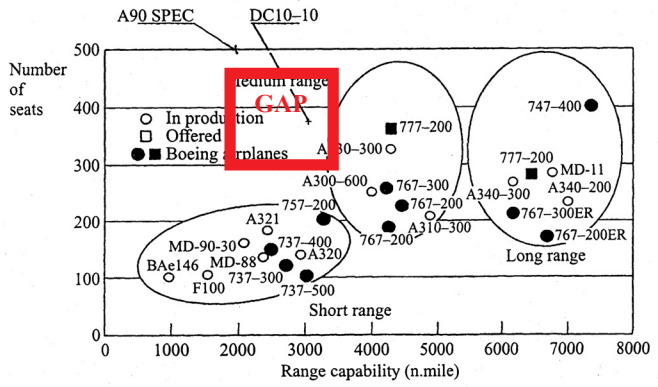


Figure 4. Airliner seat/range capabilities, 1996 (Fielding).

2.0 PRODUCTIVITY AND/OR EFFICIENCY

In general, the commercial aviation trend has been towards increased speed, range and payload capacity. Newer products have continued to emphasise increased productivity. This is often presented for example in Ref. 1, as the product of seating capacity and speed (seat-miles-per-hour), Fig. 1. The introduction of the jet engine and swept-wing technologies, saw a dramatic increase in speed, and therefore productivity, during the 1960s. The introduction of supersonic Concorde in the mid 1970s resulted in a three-fold increase in speed. However, productivity was effectively halved since the technology available at the time limited Concorde's size to 100 passengers. Values in Ref. 1 for the then-proposed subsonic double-decker, advanced supersonic transport (AST) and multi-body AST designs are plotted at initially conceived introductory dates. The European supersonic civil transport (ESCT) and A380 values have been added at approximate design dates to provide comparative levels of productivity.

Alternatively, the productivity index, Fig. 2[2], has been defined as the product of the useful load (payload plus fuel) and speed per unit gross weight. The resulting units are miles-per-hour. The trends for the period 1900 to 2000 are shown. Productivity for conventional, subsonic, aircraft has remained fairly constant since the introduction of the Boeing 707. In the 1970s, Concorde provided a quantum leap in productivity index by virtue of its dramatic increase in speed and in spite of its relatively small size. The fact that it could carry only a limited payload over 3,000nm is obscured in this type of presentation. The future, over the next quarter century at least, will be with subsonic aircraft (Mach 0·8-0·85 cruise). We may assume, therefore, that the trends in Fig. 2 are levelling out.

Range and payload are highly inter-related (Refs 5-9). The general trend for increasing seating capacity with increasing range is shown in Figs 3[3] and 4[7]. There are significant gaps in technology for high capacity and medium ranges. The question arises as to whether we

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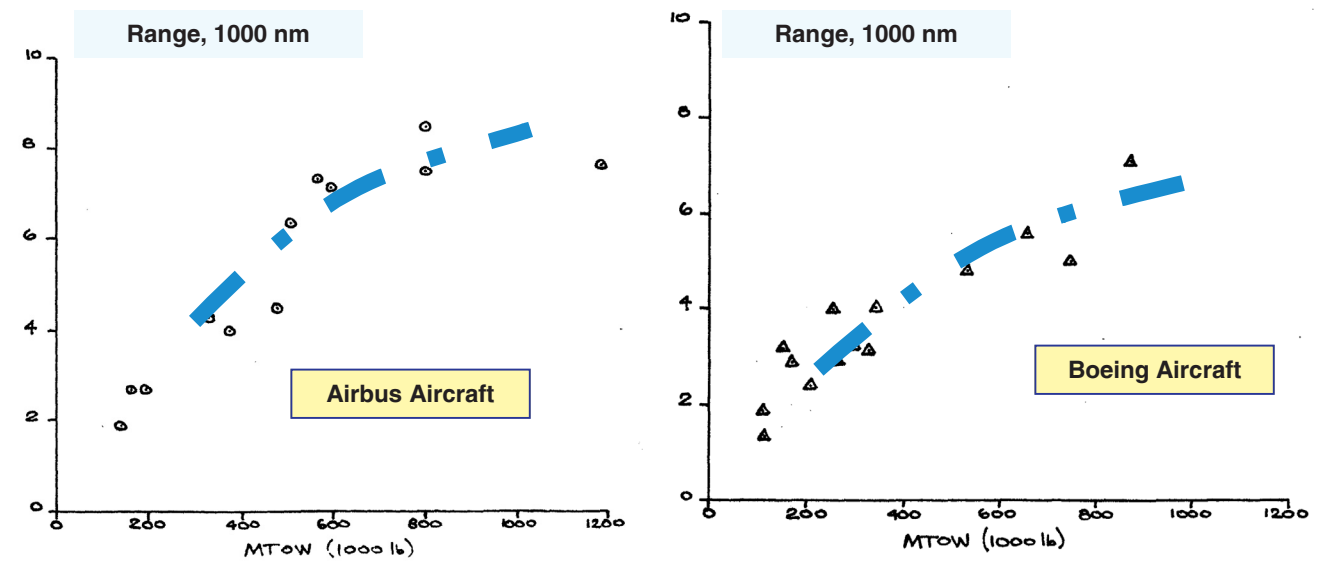


Figure 5. Aircraft range *v MTOW*. Broad brush trends.

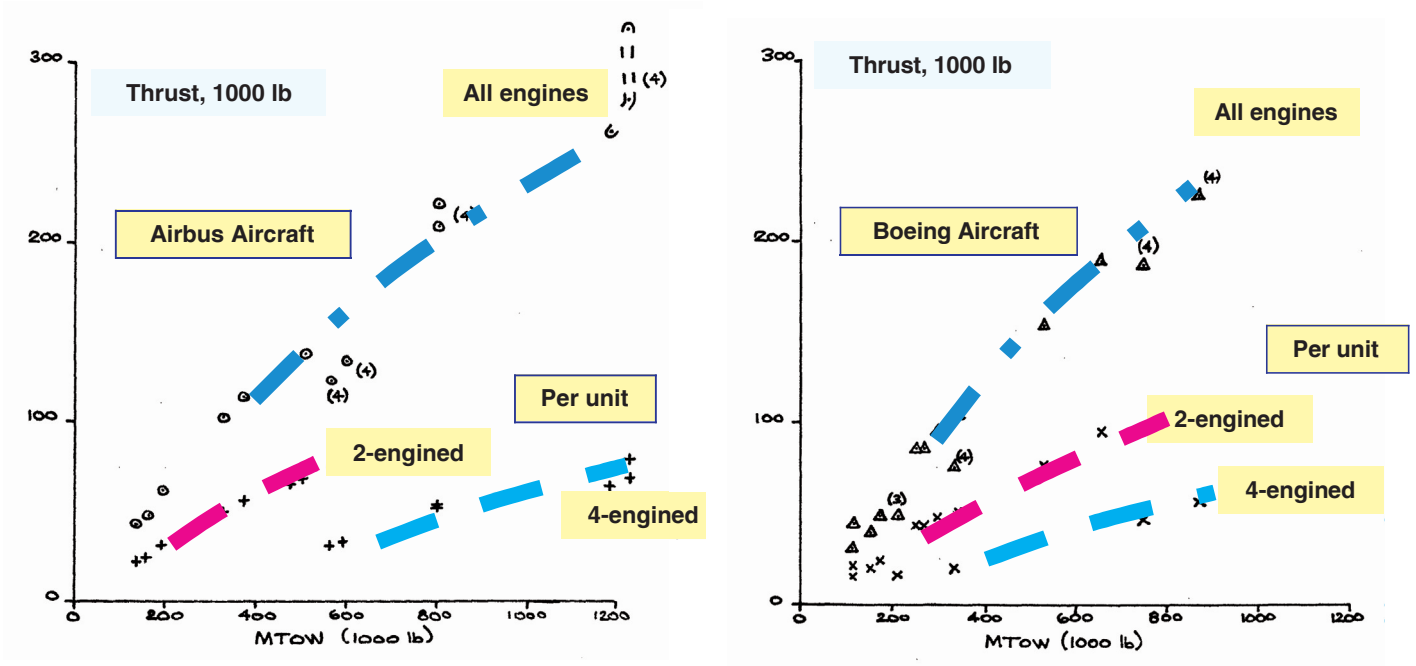


Figure 6. Installed thrust *v MTOW*. Broad brush trends.

should continue with ever-larger aircraft and consequently ever-larger propulsion systems. *MTOW* of 1·2m lb is exceeded by the A380. The Airbus argument is that congestion, economy and environmental concerns lead to larger, more efficient aircraft. However, Airbus is hedging its bets by including smaller aircraft as part of the family. The Boeing argument has been that smaller, long-range aircraft give more convenient high frequency point-to-point services. Lately, under competitive pressures, Boeing has launched the developed 747-8. It would appear that there is currently room for both philosophies. As technology has improved, greater diversity is possible as shown by the B767-200ER. However, we have not noted any flying variants with large passenger payloads (e.g. 350+ passeners) designed for short or medium ranges. Fielding[5] mentions a parametric study of A-90 aircraft, a 500-seater for 2,000nm range. Although not optimised for short range, a variant of the Boeing 747 with high density seating (568 passengers) is operated by Japan Air Lines (JAL) (See Section 5).

The graphs of Figs 1 and 2 do not focus on the whole story, as far as overall efficiency is concerned, in that neither the fuel consumed nor the range is taken into account. Indeed, fuel cannot be considered as 'useful' payload. The data presented in Figs 1 and 2 are merely indicative of the flying capability of the aircraft.

Longer-range aircraft are heavier (Fig. 5) and therefore require higher thrust (Fig. 6). The thrust/*MTOW* ratio is of the order 0·3 and it decreases slightly with range (bearing in mind the scatter of data, Airbus data in circles and Boeing data in crosses), Fig. 7. Also shown are the ranges of thrust required for twin-engined, 250-

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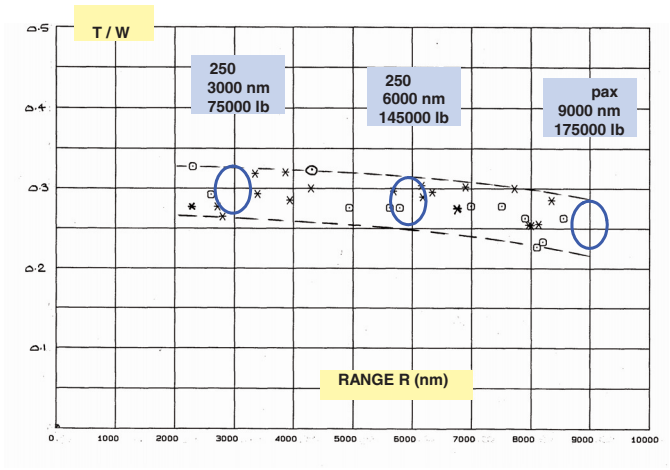


Figure 7. Installed thrust/*MTOW vs* range.

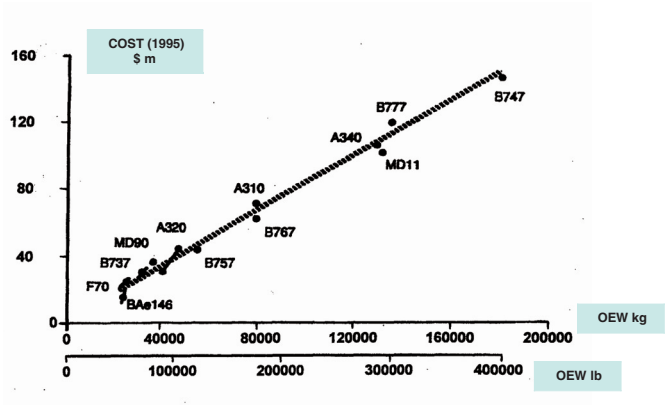


Figure 8. Aircraft purchase price – *OEW*, 1995 (Avmark).

seat aircraft designed for 3,000, 6,000 and 9,000nm. The 3,000nm aircraft will require two engines of about 40,000lb thrust each compared with 80,000lb each for the 9,000nm aircraft. The noise issues come increasingly into prominence as *MTOW* increases. Large aircraft can only operate out of hub airports and noise abatement considerations may limit operations to certain hours. As a result, slot availability for heavy, long-range, aircraft is at a premium. The airlines can meet the increasing demand for long-range services by increasing the number of passengers moved per slot. Hence this has led to 'super-jumbos'.

The efficiency of transport systems needs to be judged in terms of speed, range and economics. For air transport, the latter should include the costs of airframe manufacture, maintenance, operations and fuel. From an environmental viewpoint, the quantity of fossil fuel used needs to be considered or the impact on the environment of alternative fuels. Fossil fuel is threatened by availability, cost and environmental impact. First thoughts are that we can imagine kerosene being reserved for air travel as surface transport (road, rail and sea) more easily converts to other 'greener' technologies. Obviously there will be accompanying political and governmental pressures to consider in all this!

It would be beneficial, therefore, to focus on more realistic efficiency parameters (Refs 3-4), for example, the product of payload and range per unit of fuel consumed, referred to here as payload range efficiency (*PRE*).

Two new factors: 'Nangia value (cost) and emissions efficiency parameters' have been introduced and these will be explained in Section 6.

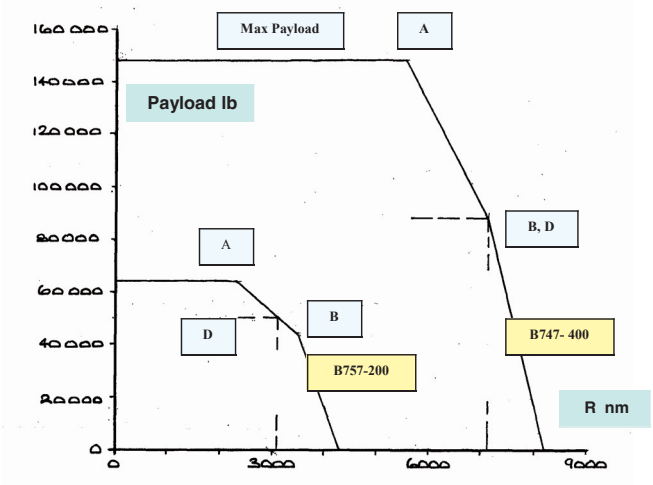


Figure 9. Typical payload-range diagrams, B757-200 and B747-400.
Note: Data not fully consistent in all sources!

Figure 8 shows that costs of ownership increase as the *OEW* of the aircraft increases. The values relate to 1995 data (Jenkinson) based on conventional materials. One way of saving *OEW* is to use lighter, more expensive materials such as carbon fibre composites. Also aircraft price is determined by market demand and extra capability (e.g. improved speed or range may give a premium). The values may need to be factored upwards for current technology costs and market prices.

2.1 Payload range considerations

Figure 9 compares payload-range diagrams of a small and a large aircraft. Point A (Pt A) denotes the maximum range for maximum payload. Maximum payload is achieved typically by all-cargo and combi (part passenger, part cargo) variants, and is sometimes approached (say to 80% or so) by stretched variants carrying increased passenger numbers in a one-class single-aisle economy layout. See Section 5 with regard to Japan Air Lines (JAL) experience.

Pt D is the more usual prime design point, typically for full passenger load plus bags in a two or three class cabin configuration. The range at Pt D is always more than that at the maximum load design point Pt A and is usually at a payload just above or equal to the intersection of the *MTOW* and maximum fuel capacity lines, Pt B.

3.0 ASSIMILATION AND ANALYSIS OF AVAILABLE DATA

Using available data on current generation commercial aircraft (Airbus and Boeing), we have established trends, against design range and aircraft weight, for many of the contributory weights and weight fractions (e.g. *WP*, *WFT*, etc.). The effects of advances in technology and manufacturing techniques were borne in mind. We have focussed on the range of turbojet aircraft with nominal cruise at Mach about 0·78 to 0·85 (460 - 490kt). The statistical data have been obtained from a variety of sources including manufacturers (websites and publicity), textbooks and current papers (Refs 5-9). It should be stressed that in collecting the data from various sources, a level of 'scatter' (noise) is unavoidable.

The main variables used in the analysis are listed in the Nomenclature with definitions as follows:

MTOW is the maximum permissible weight of the aircraft at take-off. It is limited by the airframe structure, undercarriage parameters, engine capacity and flight design conditions. Aircraft are often operating at *MTOW* when carrying the design *WP* over the design range.

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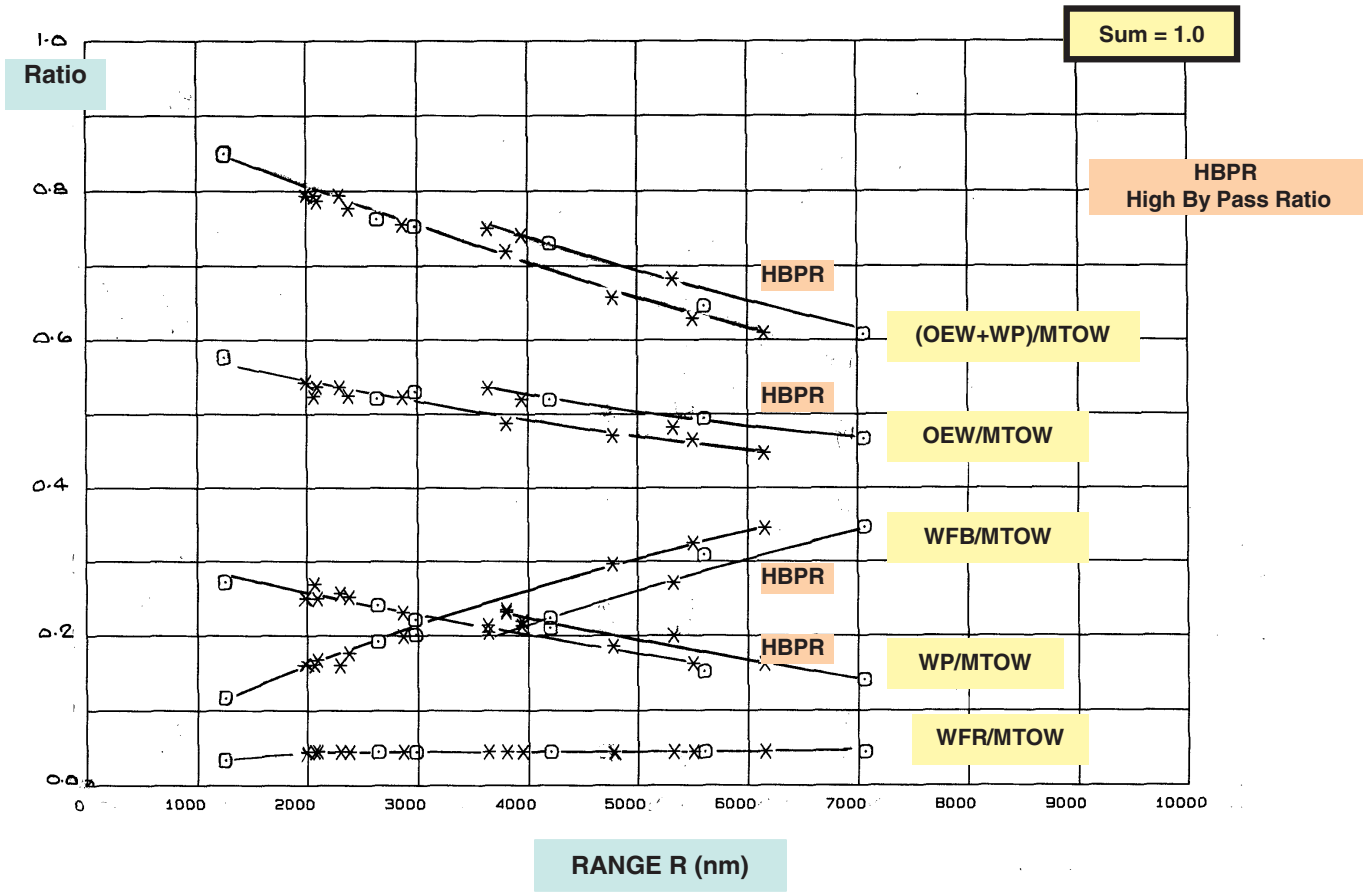


Figure 10. Pt A, commercial aircraft, derived *OEW*, fuel and payload ratio trends.

OEW comprises airframe and engine structure weight (including residual fuel, engine oil, water, etc.), fixed equipment (communication equipment, seats, etc.) and the flight and cabin crew.

WP includes the weight of passengers, their baggage and any additional cargo.

WFT is the sum of the block fuel (*WFB*) required for that aircraft weight and range and the necessary reserves (*WFRes* or *WFR*). This does not include residual fuel that is not accessible by the pumping system. The residual fuel is, more correctly, a part of *OEW*.

OEW + *WP* is *ZFW*, i.e. the aircraft weight plus payload but without any useable fuel onboard.
TOW = *OEW* + *WP* + *WFB* + *WFRes* (*MTOW* at design point).

The trends account, where appropriate, for early, current and advanced technology or short, medium and long-range aircraft.

The data has been analysed in several ways. A whole host of cross-plots provided the background and help in understanding and establishing credibility. Here only the summary figures are presented.

The ratios, with respect to *MTOW*, of the main weight variables (*OEW*, *WFB* and *WP*) are plotted against range in Figs 10 and 11. Figure 10 is for Pt A and Fig. 11 is for Pt D. Note that for a given aircraft, Pt A range will be shorter than that for Pt D.

It is worth noting that the installation of modern high by-pass ratio (HBPR) engines makes a difference by increasing the *OEW* and reducing fuel burn. Estimated curves, differentiating between earlier aircraft and modern generation aircraft with HBPR engines, are shown.

From the results in Fig. 11, for a 3,000nm range aircraft *WP* is 20%, *OEW* is 54-60% and *WFB* is 18-23% of *MTOW* (*WFRes* is 4·5%). In contrast, for a 6,000nm range aircraft *WP* falls to about 11%, *OEW* is 49-53% and *WFB* increases to 30-36% of *MTOW*. It is interesting to include Airbus and Boeing data together even though standards vary and each manufacturer may use different assumptions. The close correlation is encouraging and interesting in view of the large number of independent variables, e.g. *WP*, *WFB*, *L*/*D*, *SFC*, weight and technology standards, optimisation and compromises. Even the long-range, dedicated derivatives such as the B767-200ER (6,805nm) lie very close to the trends.

It is however, recognised that unusual aircraft using more of the exotic materials (e.g. to reduce *OEW*) may well depart from the trends. Further work could be done here to improve correlation for future trends.

Note that reserve fuel amounts to 40-50% of payload at longer ranges (7,000 - 9,000nm).

The performance of aircraft is evaluated using the well known Breguet range equation. The range *R* follows from aircraft weights: at start (*W*1) and at end (*W*2) of the flight

$$R = X \ln (W1/W2)$$

X is the range parameter, related to the flight speed and technology levels: lift-drag ratio (*L*/*D*) and specific fuel consumption (*SFC*). It is defined as:

$$X = V\, L/D \,/\, SFC.$$

X has unit of length and a convenient non-dimensional form then follows by writing *Z* as non-dimensional range:
$Z = R/X = \ln (W1/W2)$.

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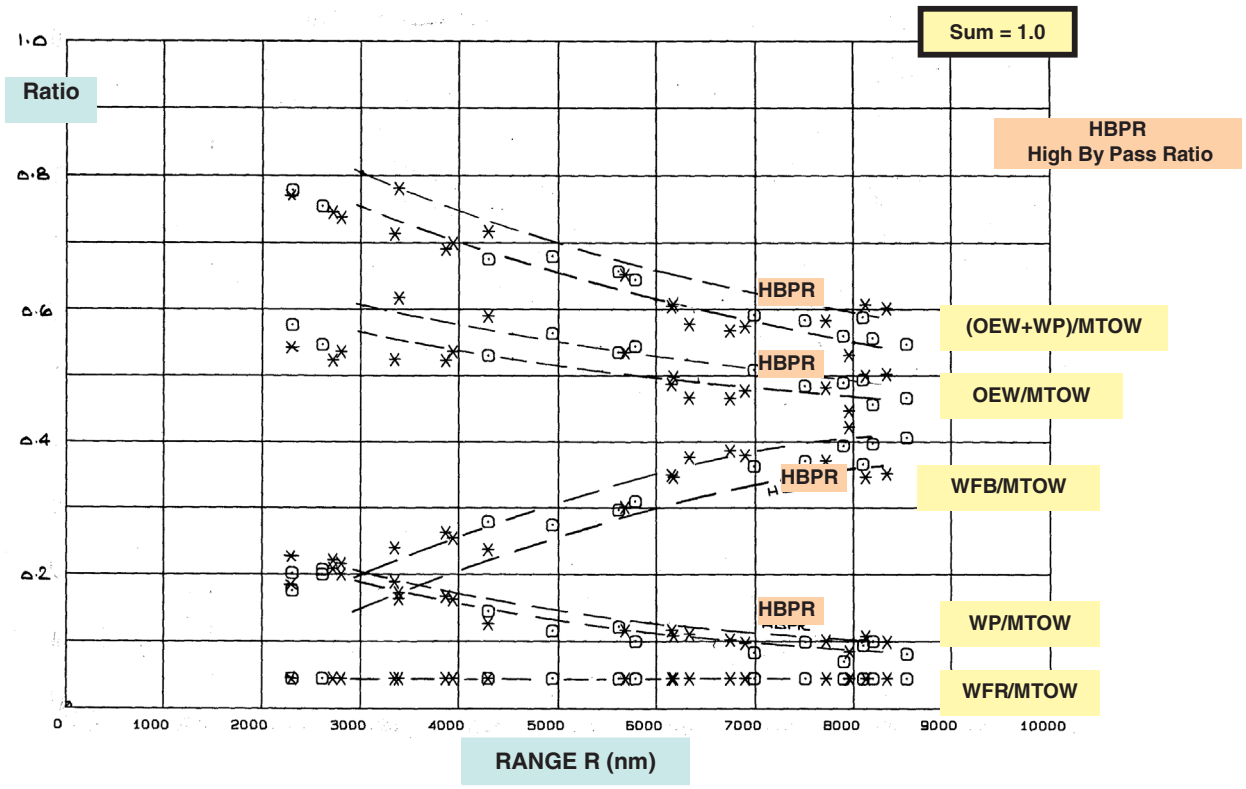


Figure 11. Pt D, commercial aircraft, derived *OEW*, fuel and payload ratio trends.

From the database available on the performance of various aircraft, e.g. payload-range diagrams and various weights e.g. Fig. 9, we know that they cruise at different speeds with different L/D and the SFC varies a good deal. The range parameter X determined from matching the payload-range diagrams varies appropriately and very significantly, Fig. 12.

The more modern aircraft operate at substantially higher X values compared with the 'older' medium range aircraft.

It is reasonable to consider the available data, allowing for the range parameter X variations and work in non-dimensional terms as far as possible. This will then allow us to compare/predict and extrapolate (if necessary) more readily on an equivalent technology basis.

Figure 13 shows the variation of the ratio of design payload (Pt D) to max payload (Pt A) (*WPDesign*/*WPmax*) with design range. There is some 'scatter' depending on the airframe having two or four-engines. For the two-engined aircraft, it is reasonable to use values for this ratio as 0·8 for 3,000nm range, 0·55 for 6,000nm and 0·5 for 9,000nm.

The variation of WPDesign/WPmax with range is due to consideration that long-range aircraft carry a large proportion of fuel. In turn, the weight of this fuel dictates the structure weight. The total aircraft weight and sometimes the fuel capacity defines the wing area (size). At the design Pt D, usually the fuel tanks are either nearly or totally full. Some of the fuel weight can be exchanged for payload, at the expense of range, without affecting the structure. On the other hand, the shorter-range aircraft carry a lesser fuel proportion and the wing size driver may be the high-lift capability. For all ranges, Pt D payload will be lower than Pt A payload.

It is worthwhile remarking on 'stretched' versions. One way to increase payload capability (fuselage plugs) is at the expense of range. On the other hand, longer-range versions exist with fuselage length shortened to improve matching of smaller payload capability with range. It will always be desirable from a payload/fuel efficiency point of view, to bring Pt D closer to Pt A. However, other issues and limits do come into play.

4.0 DERIVING PRE & WFB/WP AT Pt A, UPDATING GREEN'S WORK (of Ref. 3)

As mentioned earlier, a convenient measure of aircraft efficiency is payload range efficiency (*PRE*). This is interpreted as 'useful work done' for unit fuel used i.e.

PRE = payload × range / fuel burnt, i.e. = $WP \times R$ / WFB (in nm or km units).

The relevant non-dimensional parameters, relative to achieved technology standards, are obtained using the range parameter X:

PRE/X and $Z = R/X$.

4.1 Green's reports, Pt A results

In Ref. 3, assuming current technology (X = 30,850km, 16,512nm), the results of a parametric design study into the effects of range on fuel economy, are shown in Fig. 14. Relating the analysis to Pt A, this figure shows general curves of *PRE* for aircraft designed for 5,000, 7,500 and 15,000km ranges. We note that both the 7,500km and

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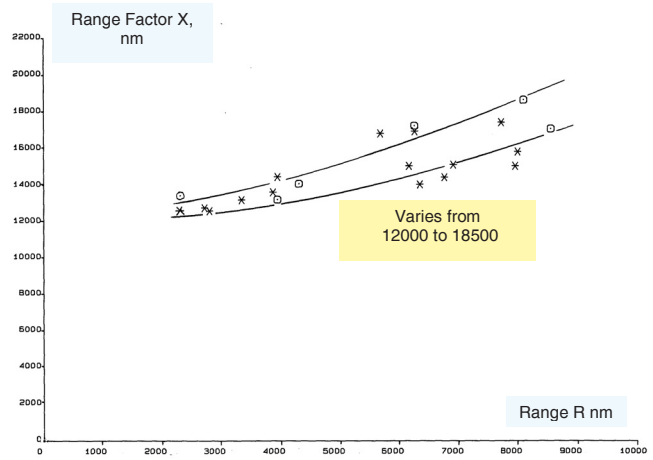


Figure 12. Commercial aircraft, derived *X* at design point.

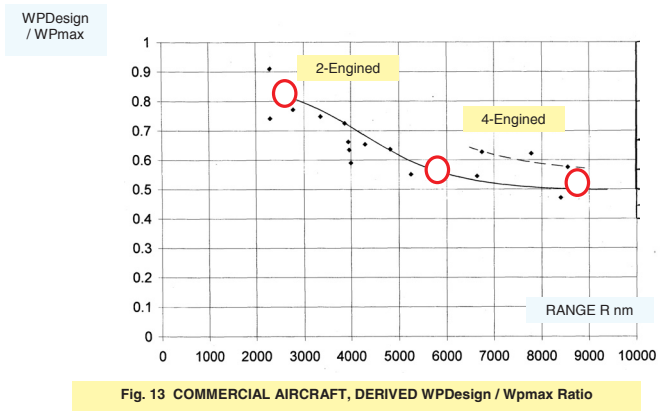


Fig. 13 COMMERCIAL AIRCRAFT, DERIVED WPDesign / Wpmax Ratio

Figure 13. Commercial aircraft, derived *WPDesign*/*Wpmax* ratio.

15,000km designs have their best fuel efficiency at 6,000km (Ref. 3, Appendix A2) while the 5,000km design has its best fuel efficiency at its design point. The outer envelope in Fig. 14 encompasses the fuel efficiencies for all design ranges. This reaches a maximum at about 4,000km design range. As discovered/established later, this graph, although providing a motivation for much work, was erroneous as reserve fuel was not included.

4.2 Pt A analysis, current data

Figure 15 shows the *PRE*/*X* – *Z* at point A. Inevitably there is some scatter in the original data but the non-dimensional trends appear to be reasonable and understandable. The correlation to a first approximation is independent of the size of aircraft. Note also that curves extend to about $Z = 0{\cdot}42$. This corresponds with the usual maximum values for combi aircraft. The *Z* range also corresponds approximately to that for freighter aircraft. For given values of *R* and *X*, we can easily obtain *PRE*. Auxiliary scales for $X = 14{,}000$, 16,000, 18,000 and 20,000 (nm) should help.

Figure 15 also incorporates Green's results from Fig. 14. Note that Green's curve is increasingly 'optimistic' as the range increases. It is close to being 25% over-optimistic at *Z* near 0·4. It is slightly pessimistic near *Z* of 0·13. The cause for this needed a fair deal of detailed work and it has now been acknowledged as being due to the omission of fuel reserves. Recently these limitations of an otherwise elegant approach in GBD reports have been updated (Ref 10). The trends are helpful.

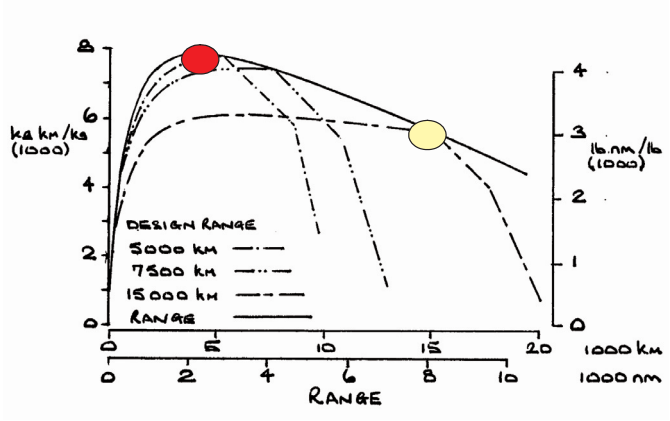


Figure 14. Variation of *PRE* (km) with range (km) and design range (Pt A), 470 seater, (Green) Conversion factor: I nm = 1·852 km.

Following Green[3], the *OEWR* is defined in terms of structural constants *c*1 and *c*2:

$$c1 \text{ (inc fuel reserves)} = OEWR - (c2 - 1) \times Wpmax/MTOW$$

At Pt A, *c*2 is set at 2·0 and *c*1 then follows. This in turn, using the Breguet equation, leads to:

$$PRE/X = 1/c2/((1 - 0{\cdot}978 \times EXP(-Z))/(Z^*(0{\cdot}978 \times EXP(-Z) - c1))).$$

In Fig. 16, we show curves for *PRE*/*X* variations with *Z* for *c*1 values between 0·30 and 0·44. At Point A, *c*2 is set at 2·0. The curve from Green's work corresponds to $c1 = 0{\cdot}3$ (and $c2 = 2{\cdot}0$). The practical data trends of Fig. 15 are displayed and we note that over the range of results, to *Z* about 0·4, *c*1 varies between 0·28 and 0·36.

Using Green's results and the practical data, Fig. 17 shows a comparison of the weight breakdown of 470-seater (44·8t payload) aircraft designed for 5,000, 10,000 and 15,000km ranges. *OEW*, *WP*, *WFB* and *MTOW* are shown. This is supported by Fig. 18 graphs showing the various ratios with respect to *MTOW*. A small degree of extrapolation is implied for deriving results from practical data. In general for combi aircraft, Pt A is usually at range < 15,000km.

From Green's results (Fig. 17(a)), we note that for constant WP, increasing the range three-fold, increases *OEW* by 41% and an extra 321% *WFB* is required. Consequently *TOW* increases by 76%. The *OEW* omits fuel reserves. More simply, flying 470 passengers 15,000km in three 5,000km hops takes 85·8 tonnes fuel ($3 \times 28{\cdot}6$t) whereas completing that journey in an aircraft designed for that range takes 120·4 tonnes of fuel, an extra 40%.

From the practical data (Fig. 17(b)), we note that for constant *WP*, increasing the range three-fold increases *OEW* by 126% and an extra 506% *WFB* is required. Consequently *TOW* increases by 125%. The *OEW* accounts for reserve fuel. More simply, flying 470 passengers 15,000 km in three 5,000km hops takes 84 tonnes fuel ($3 \times 28{\cdot}0$t)whereas completing that journey in an aircraft designed for that range takes 170.4 tonnes of fuel, an extra 103%. These numbers and others including weights and ratios (Fig. 18) represent a very sizeable 'correction' in absolute and relative terms, of the work in the GBD reports.

All the above tells a story about maximum payload point, Pt A trends. We need now to extend the analysis to the prime design point *D* for passenger loads, bearing in mind the Pt A trends.

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5.0 DERIVING PRE/X, WFB/WP AT Pt D & RELATING Pt A

From the payload-range diagrams of several aircraft, Fig. 19 shows the *PRE*/*X* – *Z* at point D. Inevitably there is some scatter. As in Fig. 15, the correlation to a first approximation is independent of the size of aircraft. The non-dimensional trends appear to be reasonable and understandable. As in Fig. 15, for given values of *R* and *X*, we can easily obtain *PRE*. Auxiliary scales should help. Selected points are for 3,000, 6,000 and 9,000nm at *X* = 15,000 and 20,000nm. Note the large % *PRE* reductions (penalties) with respect to 3,000nm as a reference.

Figures 20 and 21 show the *WFB*/*WP* – *Z* relationships at points A and D respectively. The correlation to a first approximation is independent of the size of aircraft. However more work on this size aspect could be done. The trends on a non-dimensional basis are encouragingly 'smooth'. Selected points are for 3,000, 6,000 and 9,000nm at *X* = 15,000 and 20,000.

From Figs 19 and 21, using practical data at differing values of *X*, we have derived *PRE* and *WFB*/*WP* variations with range *R* with respect to a reference range of 3,000nm. It is interesting to note the implications in terms of percentages.

For *PRE*, we use % decrease in *PRE* as:

$$100^* [1 - PRE/PRE(3{,}000)].$$

The % improvement required in *PRE* then follows from:

$$100^*[PRE(3{,}000) - PRE]/PRE.$$

For *WFB*/*WP*, the % increase in *WFB*/*WP* is:

$$100^* \{1 - (WFB/WP) / [(WFB/WP) \text{ at } (3{,}000)]\}.$$

In the following, the parameter *X* varies from 20,000 to 15,000 (higher % occur at lower *X*).

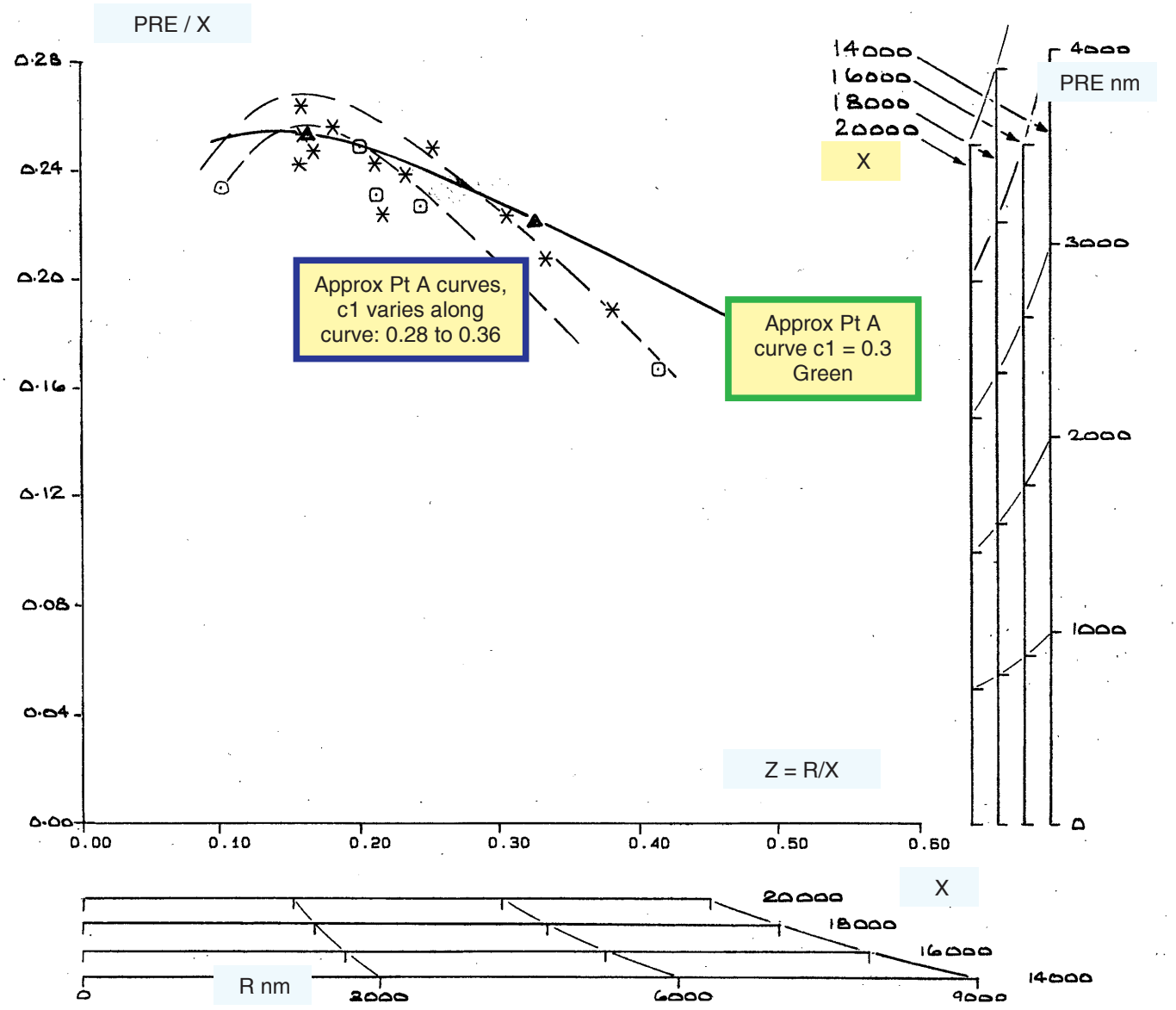


Figure 15. Commercial aircraft, *PRE*/*X* and *Z* = *R*/*X* relationships, Pt A.
Note: Parallel scales of *R* and *PRE* implied for differerent *X* values.

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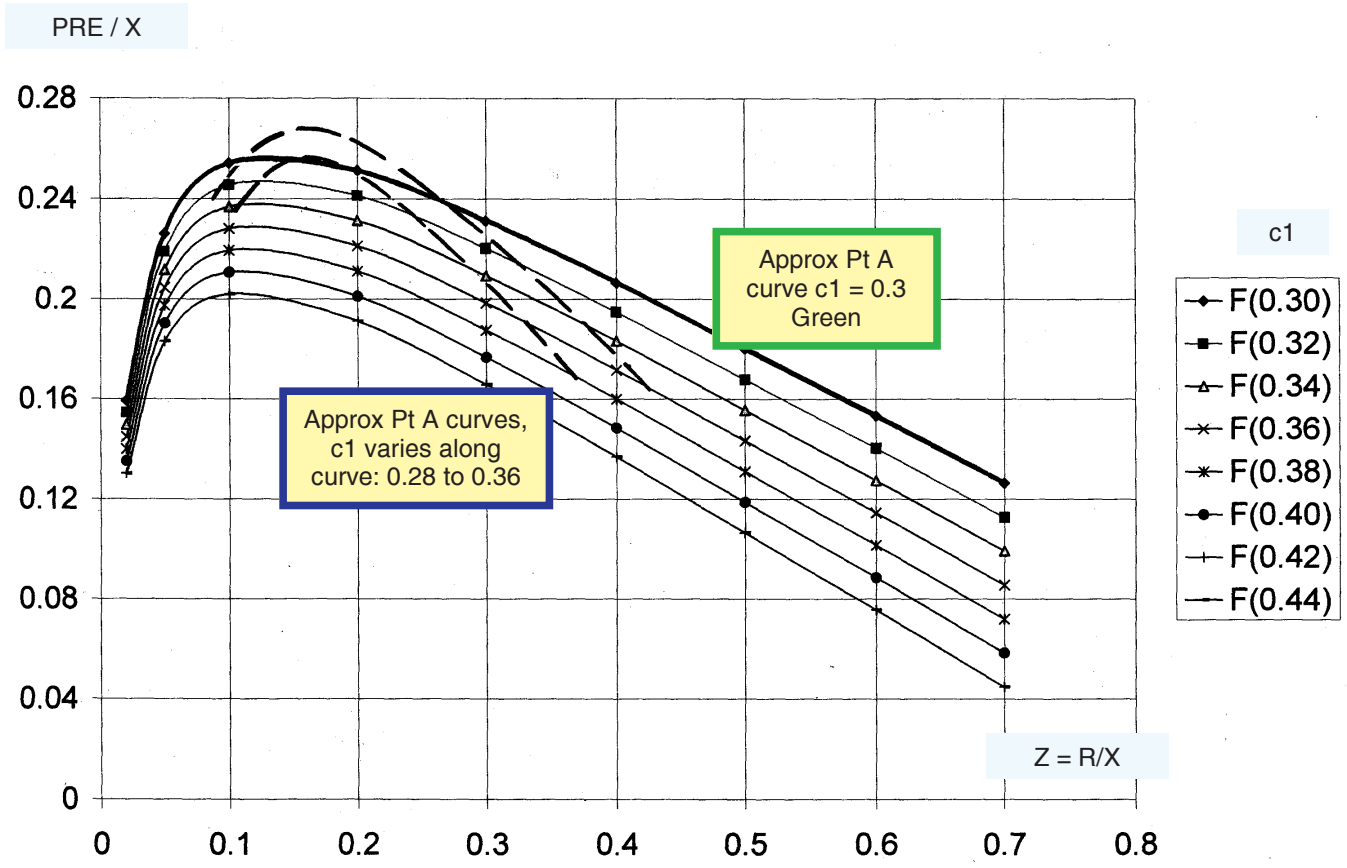
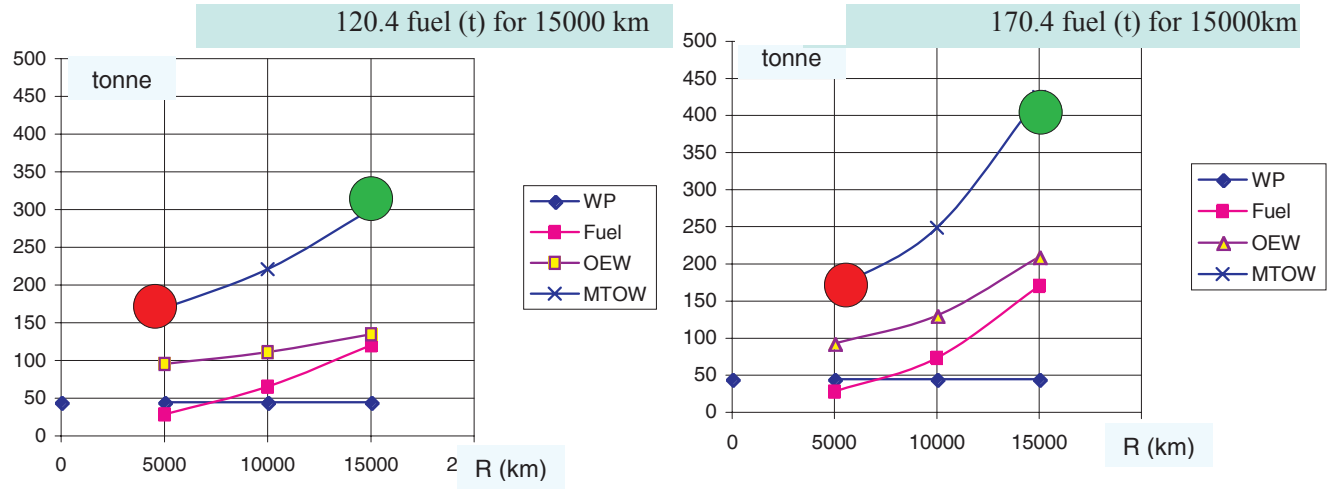


Figure 16. *PRE*/*X* and *Z* = *R*/*X* relationships, Pt A, *c*1 varying, *c*2 = 2·0.
Note: *c*1 = 0·3 represents Green's curve.

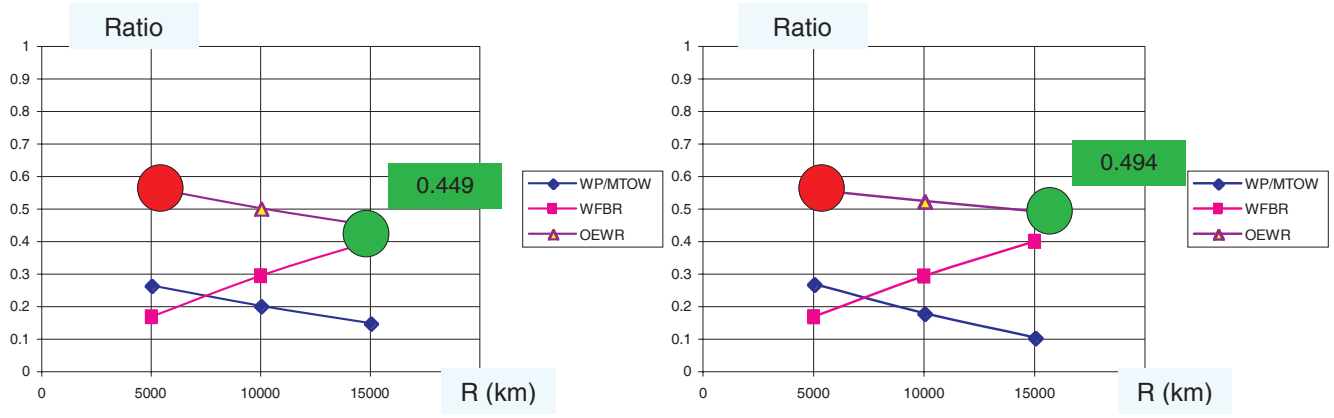


(a) As per Green. Fuel reserves omitted.

(b) Based on Figs 15 and 16. Including fuel reserves.

Figure 17. 5,000km and 15,000km designed aircraft compared, 470 seater. Payload, *OEW*, block fuel, *MTOW* (all in tonnes).

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(a) As per Green. Fuel reserves omitted.

(b) Based on Figs 15 and 16. Including fuel reserves.

Figure 18. 5,000km and 15,000km designed aircraft compared, 470 seater.
Ratios, payload, *OEW*, block fuel.

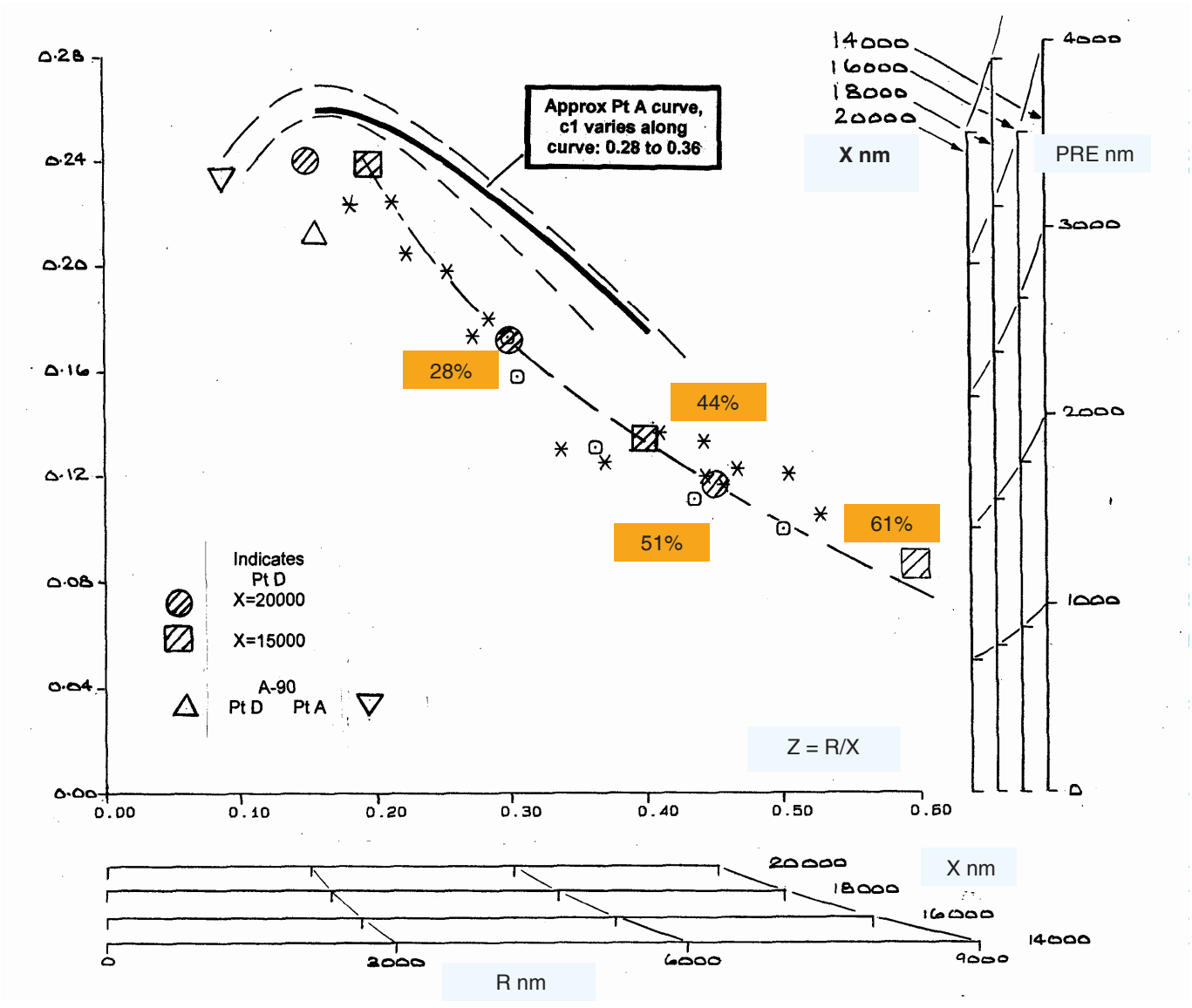


Figure 19. Commercial aircraft, *PRE*/*X* and *Z* = *R*/*X* relationships, Pt D.
Note: Parallel scales of *R* and *PRE* implied for different *X* values.

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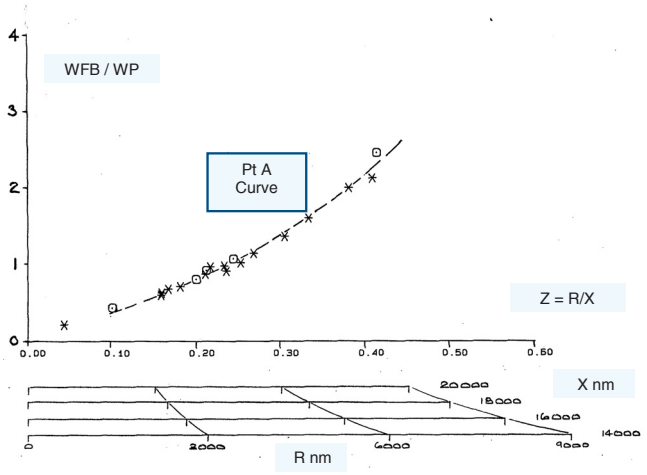


Figure 20. Commercial aircraft, *WFB*/*WP* and *Z* = *R*/*X* relationships, Pt A.
Note: Parallel scales of *R* and *PRE* implied for different *X* values.

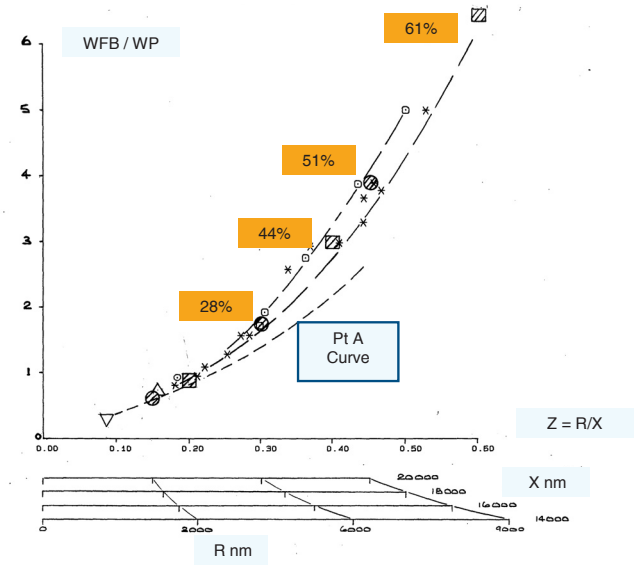


Figure 21. Commercial aircraft, *WFB*/*WP* and *Z* = *R*/*X* relationships, Pt D.
Note: Parallel scales of *R* and *PRE* implied for different *X* values.

	6,000nm	9,000nm
***PRE*: % decrease**	28-44	51-61
***PRE*: % improvement required**	39-78	105-159
***WFB*/*WP*: % increase**	28-44	51-61

An efficiency improvement of 159% would be required for a 9,000nm range aircraft (at $X = 15{,}000$) to achieve the same *PRE*/*X* level as a 3,000nm range aircraft.

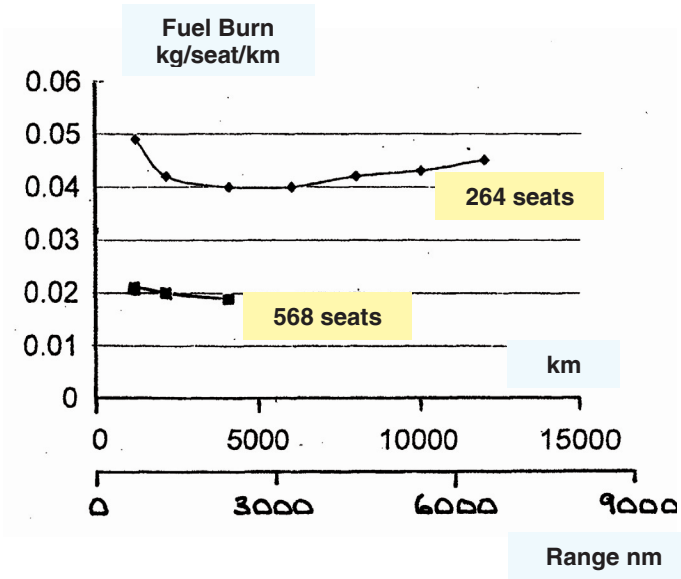
The % changes (penalties) for using long-range aircraft are large. This is considered very significant. We can save considerable quantities of fuel by employing a 3,000nm range aircraft with hops or with in-flight refuelling (allowing of course, in the latter case, for the fuel used by the tanker — this will be expanded upon in a further paper).

The A-90 was an academic project[5] for a large aircraft design carrying 500-620 passengers over shorter ranges. Using the design study data, derived PRE/X and WFB/WP information is shown in Figs 19 and 21. This correlates reasonably well with the trends. Although based on paper studies, this goes some way towards confirming that the major efficiency trends are nearly independent of aircraft size.

5.1 An interesting example

From Ref. 3, data for JAL B747-400 aircraft operated as either long-range, 264 seat or short-range high density 568 seat are shown in Fig. 22. The left figure shows fuel burn rate (kg/seat/km) against range (km). The data have been re-interpreted into *PRE* (lb.nm/lb) variation with range (nm) in the right figure. The high density, short-range operation is more than twice as efficient as the long-range operation. The decrease in *PRE* at short ranges is probably due to the greater part of the flight profile being 'off design' in climb, descent etc. The decline in *PRE* at long-range is due to the extra fuel mass carried. Both range and payload have a big effect on *PRE*, all else being constant.

It is worth mentioning that with 568 passengers at 210lb, the *WP* is 119,280lb. This payload weight is still less than *WPmax* of about 150,000lb (depending on engine type). With passenger payload only it appears difficult to reach the *WPmax*!



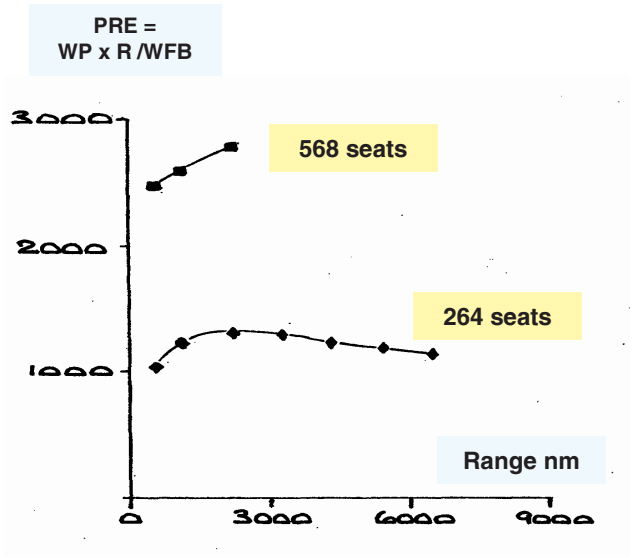


Figure 22. Fuel burn and payload efficiency variation with range,
JAL data for B747-400 long range (264 seats) and high density (568 seats), Ref. 3 (Green).

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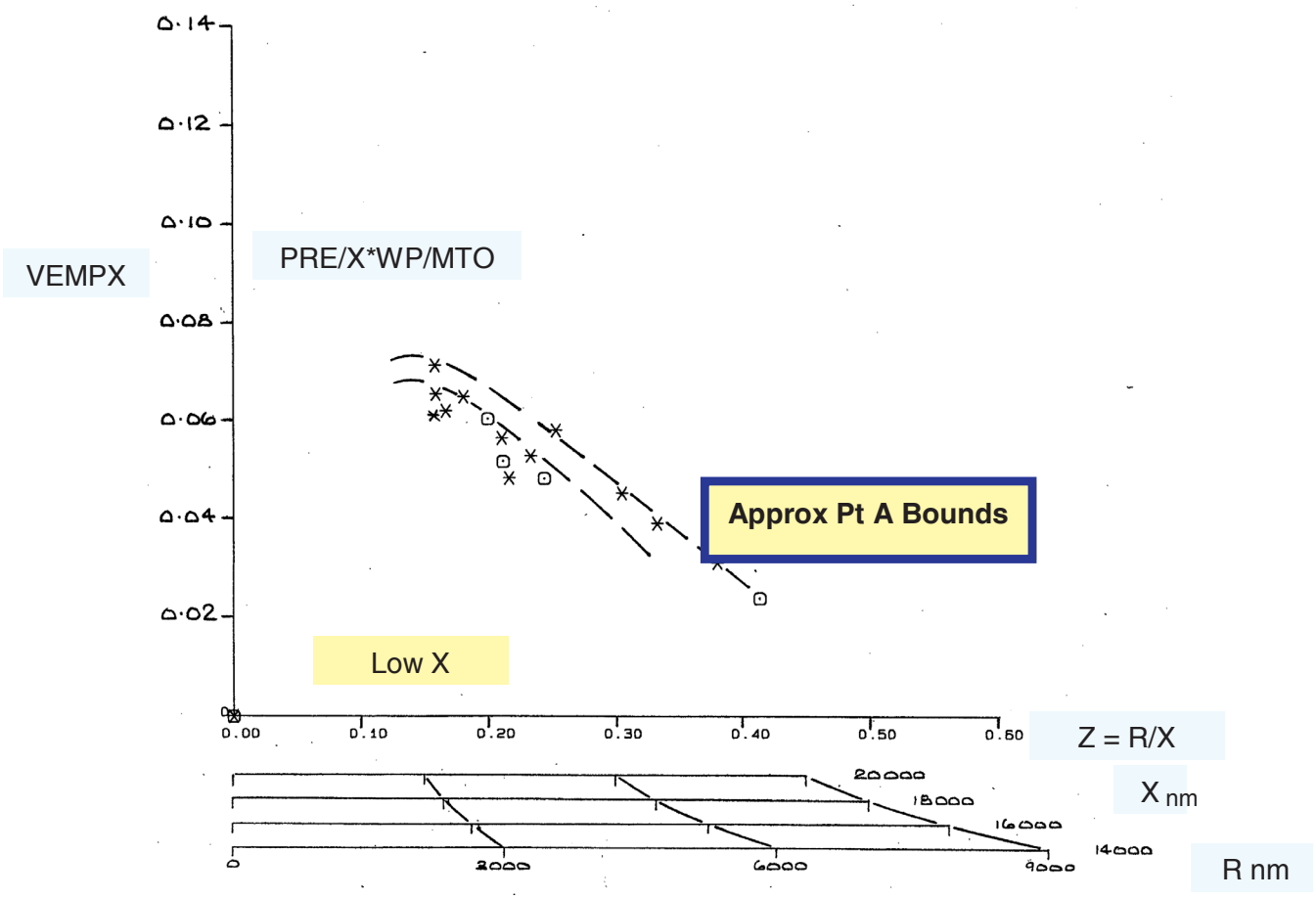


Figure 23. Derived Nangia emissions efficiency *VEMPX* variation with *Z*, Pt A curve.

6.0 EMISSIONS & 'NANGIA VALUE (COST) & EMISSIONS EFFICIENCY FACTORS'

The *PRE*/*X* graphs hide information about aircraft structure and size (hence noise and cost) implications. To include these we need to look at the value-efficiency trends. We can define *VEM* = *PRE*/*MTOW* (nm/lb of aircraft) and *VEO* = *PRE*/*OEW* (nm/lb of aircraft).

From Fig. 11, it can be deduced that, 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. The factor *OEW*/*WP* is related to the cost of ownership per unit payload (Fig. 8).

Relating the non-dimensional fuel efficiency *PRE*/*X* (Section 4) and the factor *OEW*/*WP*, we can define a non-dimensional 'Nangia value efficiency' parameter *VEOPX*:

$$VEOPX = (PRE/X) / (OEW/WP) = (PRE/X) \times (WP/OEW).$$

This parameter denotes the fuel efficiency per structure weight per unit payload, which can be related to the purchase cost per unit payload using the cost (price) *vs* OEW relationship of Fig. 8. It is interesting to note that the parameter *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 emissions efficiency parameter *VEMPX*:

$$VEMPX = (PRE/X) / (MTOW/WP) = (PRE/X) \times (WP/MTOW).$$

This parameter denotes the fuel efficiency per total weight per unit payload. It is interesting to note that the parameter *VEMPX* also serves a measure of airport and other fees. Higher value is better for lower noise emissions and operating costs.

For Point-A, Figs 23 and 24 show *VEMPX* and *VEOPX* variations with *Z* = *R*/*X*. Figs 25 and 26 refer to *VEMPX* and *VEOPX* variations with *Z* = *R*/*X* for Point-D. As may be expected, the curves are higher for the lower ranges as *WP*/*MTOW* and *WP*/*OEW* are higher at the lower ranges.

Thus for a given *X* value, using Fig. 11 and Figs 25 and 26, we can now determine various efficiency correlations. This makes the approach very much more concise and hopefully elegant. We have shown points for 3,000, 6,000 and 9,000nm for *X* = 15,000 and 20,000 and for the A-90.

We note that the small range aircraft is strongly favoured. This confirms the significant inference that a 6,000nm aircraft provides a value-efficiency of only about 25 -30% of that for a 3,000nm design. A 8,000nm design offers a figure of 20% compared with a 3000nm design. Such a graph is a realistic measure of the value-efficiency *VEM* of a given configuration as all the components of *MTOW* are included.

Further work can obviously be done to instil more of the finer detail in such figures, e.g. passenger/cargo proportions and so on.

Figure 27 shows that *VEM* and *VEO* will vary with payload carried over a given range. Figure 27 assumes a value of *X* = 16,000. Smaller aircraft fare better. Such parameters remain useful for comparative analyses with given (fixed) staged flight or in-flight-refuelling.

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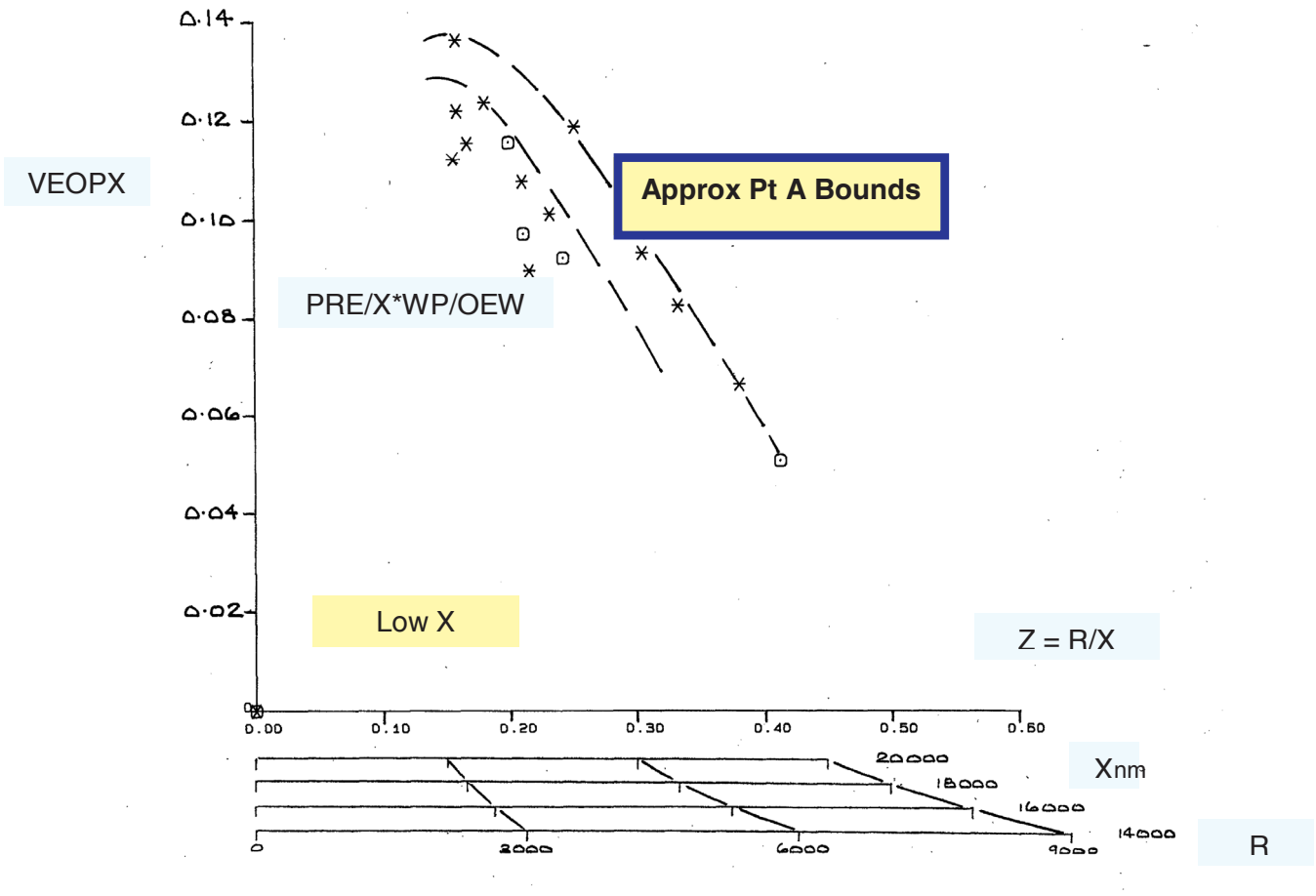


Figure 24. Derived Nangia value efficiency *VEOPX* variation with *Z*, Pt A curve.

6.1 An interpretation using VEM and VEO, example of 200 passengers flown over 6,000nm

Take a journey for 200 passengers over 6,000nm: Two possible options (systems) are:

	One aircraft flying 6,000nm	One smaller aircraft flying two 3,000nm stages	Ratio
VEM	0·0064	0·0175 or 0·0087 per stage	
Noise	~ 1/0·0064	~ 1/0·0175	2·73/flight
Emissions	~ 1/0·0064	~ 1/0·0087	1·36
VEO	0·0124	0·0305 each or 0·0152 (two aircraft)	
Cost	~ 1/0·0124	~ 1/0·0152	1·23

We infer that compared with a 3,000nm aircraft system, the 6,000nm non-stop system could be 23% more costly, produce 1·36 times more emissions and 2·73 times the noise.

Next, we take a journey for 200 passengers over 9,000nm: Two possible options (systems) are:

	One aircraft flying 9,000nm	One smaller aircraft flying three 3,000nm stages	Ratio
VEM	0·0026	0·0175 or 0·0087 per stage	
Noise	~ 1/0·0026	~ 1/0·0175	6·73/flight
Emissions	~ 1/0·0026	~ 1/0·0058	2·23
VEO	0·0055	0·0305 each or 0·0102 (three aircraft)	
Cost	~ 1/0·0055	~ 1/0·0102	1·854

We infer that compared with 3,000nm aircraft system, the 9,000nm non-stop system could be 85% more costly, produce 2·23 times more emissions and 6·73 times the noise.

We now have a reasonably good idea of the costs and environmental benefits, using a 3,000nm aircraft. In future, it will be worthwhile taking a further general look at efficiency implications and how, in some cases, benefits can be taken, using current aircraft.

Many factors may contribute towards improved efficiency. These include more advanced materials, improved manufacturing techniques, design improvements and better design methods and improved

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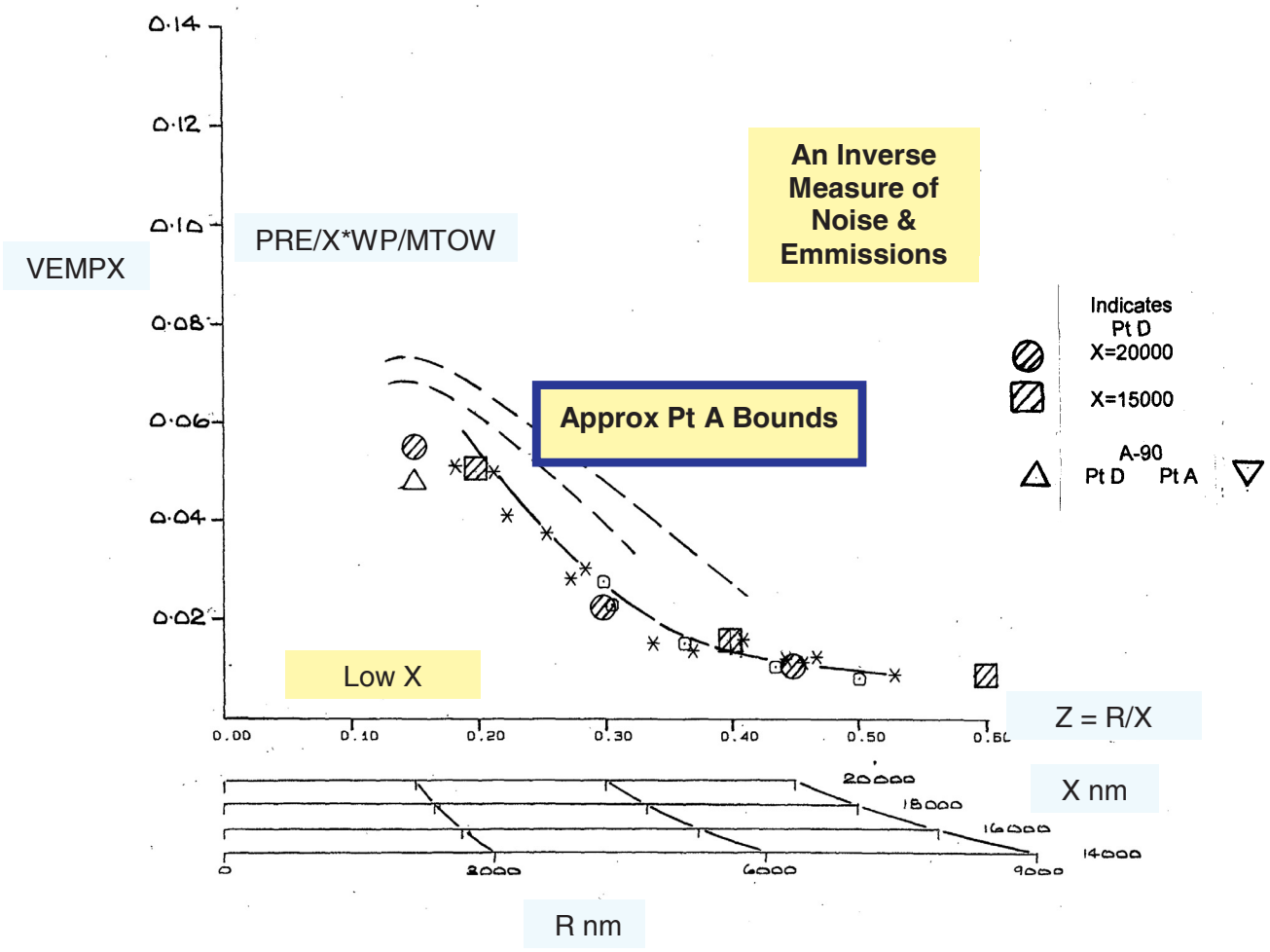


Figure 25. Derived Nangia emissions efficiency *VEMPX* variation with *Z*, Pt D curve.

operating procedures. These will continue to have an impact during the life cycle of a given type.

7.0 CONCLUDING REMARKS

There are many ways of describing productivity/efficiency of a given transportation system depending on the perspective required. In aviation, and as direct result of the quest for speed, people have defined productivity in one particular way. Now, environmental issues and costs (financial) play a very much more significant role. Therefore we need to address efficiencies in a different way. Indeed, a most important aspect is the dilemma between small short range aircraft and large long range aircraft in terms of efficiency. The environmental issues are then not limited to fuel burn considerations but also noise, congestion at airports, etc. This paper has laid out the foundations for studies on which current and future generations of aircraft and indeed propulsion systems might be judged and designed for.

Our analysis started with current flying aircraft. It is appreciated that it is no mean task to obtain consistent information. However, we have been able to establish some very distinct and useful trends that can provide a level of 'confident' extrapolation. These provide the guidelines for achieving the levels of efficiency that will be demanded in future. This could enable designers to rapidly assess the impact on future designs of new and innovative technologies, e.g. laminar flow, blended wing bodies, etc.

In passing, we have also been able to improve upon some of the deficiencies and update important results of the Greener By Design reports.

The efficiency results are based on payload capacity. Passengers, of course, do not constitute an 'efficient' load to transport over long distances by air. The requirement for adequate leg-room, convenient seating layout, sufficient overhead clearance, etc., results in relatively low density payload. Double-deck fuselage configurations improve the density payload for large aircraft.

Due to fuselage structure limitations, payload capacity cannot always be converted totally into passenger capacity. To maximise productivity it is necessary to carry the largest number of passengers over the greatest distance at the greatest speed. This goal is achieved at the expense of dramatically reduced cost and fuel efficiency. Efficiency decreases with increasing range but there will always be a demand for long-range flight. Consequently there is a 'price to pay' for market forces.

By demanding long ranges, the present trend seems to be going against fuel burn efficiency. This obviously depends on the technology and market constraints of today. If we want to transport a given payload over a given distance then the efficiency is a direct function of aerodynamics (L/D), structural mass and engine SFC.

Value efficiency varies for a specific aircraft by up to +30% depending upon how that aircraft is operated. Short-range, high-density payload operations are more efficient than long-range, reduced payload operations.

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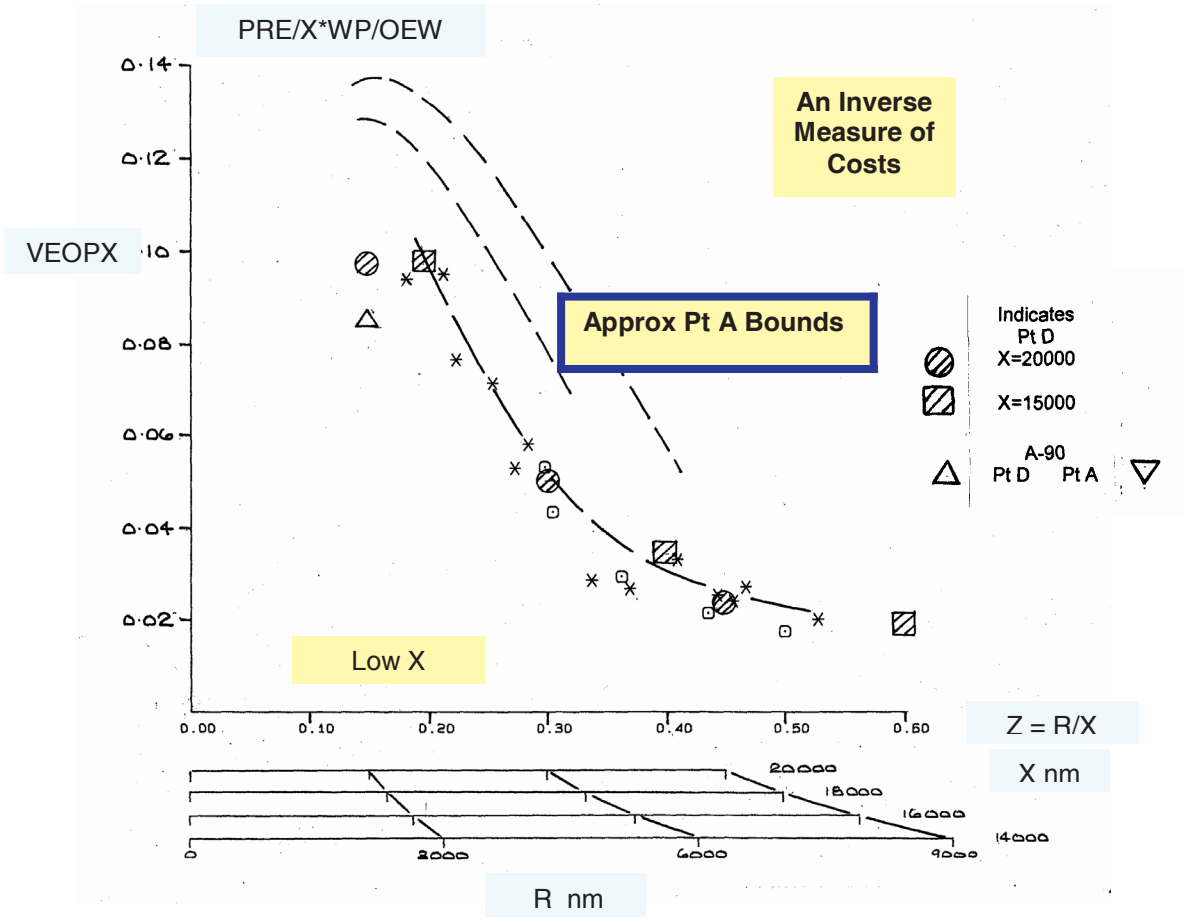


Figure 26. Derived Nangia value efficiency *VEOPX* variation with *Z*, PT D curve.

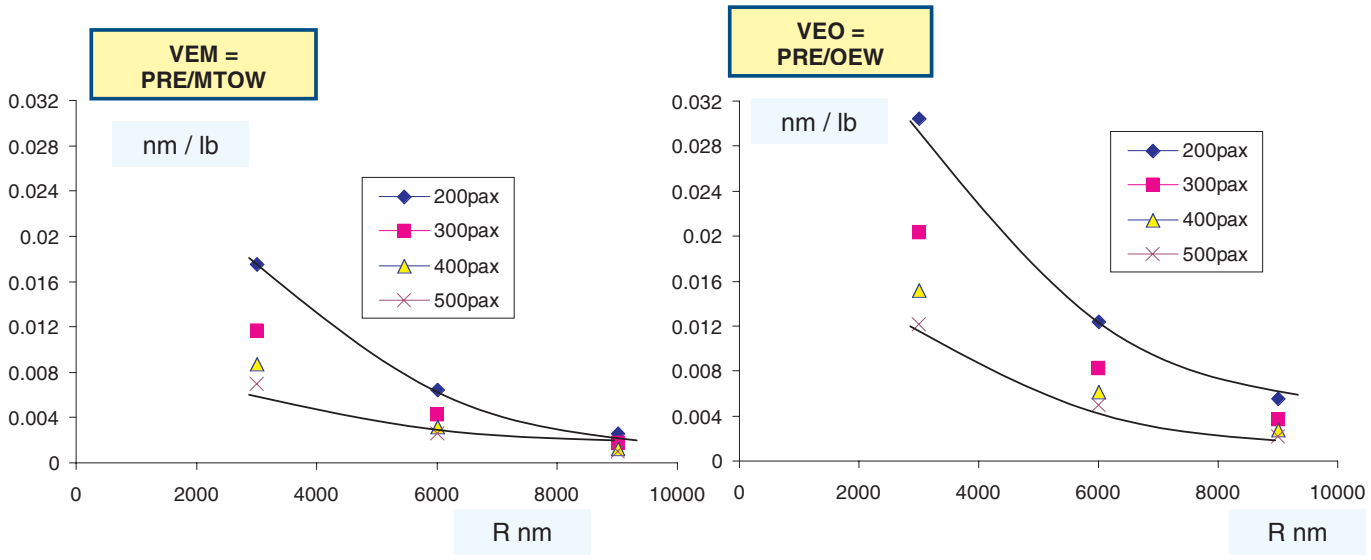


Figure 27. Derived value efficiency *VEM* and *VEO* for 200-500 seat aircraft with accounting for *X* = 16,000.

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Some of the conclusions deduced from the established trends may be controversial in view of the current practices and will no doubt be debated amongst aircraft and engine manufacturers alike. Policy makers will be involved. Further work is required in many areas. Environmental and economic considerations will, in future, demand greater value efficiency in preference to productivity. One solution for long-range services is to use short-range hops. Another solution is via air-to-air refuelling. This will be addressed, in more detail, in an imminent further paper. Relatively smaller aircraft with smaller propulsion systems could lead to greater efficiencies in manufacturing and less types of aircraft to be maintained in operator fleets.

ACKNOWLEDGEMENTS

The author has pleasure in acknowledging helpful technical comments and discussions at various times with Les Hyde, Dr Ray Kingcombe, Ian Wilson, Richard Pitman, Peter Newton and Dr John Green. The technical assistance of Dr Michael Palmer is appreciated. Currently, these studies remain unfunded and are therefore a part of in-house R&D activities. It will be appreciated that this has amounted to a major undertaking, all in the spirit of the quest for knowledge and wider understanding. Some of the inferences and conclusions may come as surprise and be controversial. We do hope that a healthy debate will ensue in view of the well documented, and real, environmental pressures on the aviation scene. Co-operation and sponsorship on the work programmes is warmly invited.

Lastly it should be mentioned that any opinions expressed are those of the author.

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