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Part 1

Design of Engines for a New Efficient Aircraft

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CHAPTER 1 THE NEW EFFICIENT AIRCRAFT: REQUIREMENTS AND BACKGROUND

1.0 INTRODUCTION

This chapter sets out the background to the new airliner which is to form the basis of the first part of this book. The aircraft, to be called the New Efficient Aircraft (NEA), will be a large wide-body aircraft designed to give low fuel burn, in anticipation of the likely rise of fuel price and pressure to reduce CO_2 emissions. The aircraft will have two engines.

The costs and risks of a new aircraft or engine project are huge, but the profits might be large too. Some background is first discussed concerning the history and business of jet propelled aircraft and the impact of concerns for the environment. In explaining the requirements some of the units of measurement used are discussed. Design calculations in a company are likely to assume that the aircraft flies in the International Standard Atmosphere (or something very similar) and this assumption will be adopted throughout this book. The standard atmosphere is introduced and discussed towards the end of the chapter.

1.1 SOME BACKGROUND

The age of jet travel really got started when the Boeing 707 entered service in 1958. By the time this aircraft was initiated, Boeing had already acquired considerable experience of large multi-engine jet aircraft, bombers and tankers, so it was in a strong position to make good design choices. The 707 was conceived as a long-range aircraft, which in those days meant it was capable of flying across the Atlantic non-stop with a full load of passengers, typically 110 in a two-class cabin. The range with maximum payload was only 2800 nautical miles (nm), but the shortest distance between London and New York is 2991 nm and going west there are normally headwinds that increase the effective distance. Such flights would therefore operate with less than the maximum payload, which would mean less than maximum freight on board, if all seats were taken.

The Boeing 707 had four engines and very much set the trend for aircraft which followed it. The fuselage was circular for most of its length, the wings were swept and the turbojet (no bypass flow) engines were mounted on pylons to hang under and forward of the wing. Hanging the engines under the wing has many advantages, in particular their significant weight is close to where the lift is generated, which makes the structure lighter. Furthermore, in the case of an uncontained engine failure, the risk of catastrophic damage to the airframe or other engines is reduced. The under-wing engine arrangement has subsequently become the preferred for commercial aircraft. Other things

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about the 707 also came to affect later designs. The take-off field length was 11,000 feet (3353 m), which affected not only later aircraft specifications but also airport design around the world. The initial cruising altitude was 31,000 ft, and the cruise Mach number was 0.85, both of which strongly affected later designs. In the same year that the 707 entered service the Douglas DC8 had its first flight and the following year the Convair 880 flew for the first time; both these aircraft had similar features to the 707, but never achieved a similar market success.

Only twelve years after the Boeing 707, the Boeing 747 entered service. The 747 had a two-aisle layout in the cabin and initially could carry up to 366 passengers in three classes. The full payload range was under 3000 nm. The four engines were carried under the swept wings, but an important difference with the 747 is that now the engines were of the high bypass ratio type. For the initial 747 the engines were only made by Pratt & Whitney, who had also made the engines for the 707. The 747, like the 707, was conceived as a long-range aircraft and for that reason four engines seemed the rational choice. For the early engines achieving enough thrust for take-off was hard and the margins were small. At take-off the engines must be sized so that if one fails at the worst possible moment, just when the aircraft rotates prior to leaving the ground, the take-off can be continued and the plane can land safely. For a four-engine plane it means that take-off thrust is 4/3 times the minimum required, whereas for a two-engine plane (a “twin”) the thrust must be twice the minimum. For a turbojet or a low bypass engine sizing the engines to meet this double thrust requirement implies extra engine weight and excess capacity at cruise. The extra weight of this excess capacity would reduce the range and efficiency of the aircraft. As we will see, the situation changed considerably with the advent of modern high bypass ratio engines and the twin has now become the norm even for long range. In addition, in the early days of over-ocean travel the added security during cruise of four engines was deemed prudent and the use of four engines for long range persisted so that both the A340, entering service in 1993, and the A380, in 2007, had four engines. In the case of the A380, however, it is now size which makes four engines more attractive than two. Were the Airbus A380 to have only two engines they would be so large that it would be necessary to raise the wing to fit them under. Raising the wing is not considered practical since, if the wing were higher off the ground than current large aircraft, it would raise the cabin, and if the cabin were raised higher the existing passenger handling facilities at airports would be unusable. Raising the wing would also make the undercarriage much bigger and heavier. Furthermore, if the Airbus A380 were to have only two engines, these would be too large to be moved conveniently as air freight, which is occasionally necessary when an engine needs replacement or overhaul.

Shortly after entry into service of the four-engine Boeing 747, two “tri-jets” with three high bypass engines came into service: the Douglas DC10 and the Lockheed L1011. The engines were made by General Electric and Rolls-Royce respectively. These were conceived as intermediate-range aircraft (2350 nm for the DC10 and 2324 nm for the L1011) for which three engines gave a good mix of performance and added security. Like the 747 they were wide-body aircraft with two aisles in the cabin. There was also a general acceptance that shorter range would imply a smaller aircraft with fewer passengers, a view which still carries some weight today.

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The mould was broken by a new international company with headquarters in France: Airbus. As the name “Airbus” implies, they conceived of an aircraft to move many people a relatively short distance. The aircraft they designed was the Airbus A300, a wide-body aircraft with only two engines, often referred to as a twin, which entered service in 1974. Not only was it a wide-body aircraft with only two engines, the A300 was aimed at short range and initially had a full payload range of only about 900nm (see Table 1.1). The A300 could carry 220 passengers in a three-class layout and as many as 375 passengers in a one-class cabin. The Boeing 767, a wide-body two-engine plane, entered service eight years later with a full payload range of 2200 nm for the 767-200 but almost 5000 nm for the 767-200ER. Extensive use was made of the 767 for long-range flights and special regulations, referred to as Extended-range Twin-engine Operational Standards (ETOPS), were introduced to allow operation over oceans; ETOPS is briefly explained below. The 767-200ER established that the twin could be a long-range aircraft and meanwhile the original Airbus A300 range had also greatly increased. About a decade after the Boeing 767 Airbus introduced the A330 and Boeing the 777, both wide-body twins. Initial full payload ranges were relatively short (3700 and 3300 nm, respectively), and Airbus had little incentive to push the range because it almost simultaneously released the four-engine A340 for long ranges. However, range increased very rapidly with the Boeing 777, so that the 777-200LR has a full-payload range of about 7600 nm. The success of the A330 and 777 then form the background to the launch of the Boeing 787 programme in 2000 and the launch of the Airbus A350 in 2006. Problems with the 787 delayed entry into service until late in 2011 and the A350 entered service late in 2014.

Both Airbus and Boeing have embarked on a process of improving existing twin jets, starting with the single-aisle A320 and B737, but more recently including the large twin-aisle aircraft. The A330neo (new engine option) was announced in 2014 and is due to be delivered to airlines at the end of 2017. This will have a new, more efficient engine with a larger fan. The wings will be modified and lengthened, and together this is claimed to offer a fuel-burn savings of 10% at full payload and maximum range. (The engine improvements are estimated to save 10% fuel and aircraft aerodynamics another 3%, but the drag of the larger engine penalises the aircraft by 1% and the increased weight by 2%.) Airbus claims that the performance will match the B787, but the aircraft will be significantly cheaper. In 2013 Boeing launched the B777X, which is to enter service in 2019. It will also offer a new engine and improved wings. The wings will use the carbon-composite technology of the 787 and their span will be increased by 6.5 m, requiring the use of folding wing tips. The heavier version, the B777-9X, will have a capacity of 407 passengers, putting it where only the B747 would have been only a few years ago. These are very long range aircraft with the range for the B777-8X offered as 9300 nm and for the larger-payload B777-9X as 8200 nm.

The full payload ranges for both the 787 and A350, in the initial versions, are in excess of 5000 nm. The performance of both are shown in Table 1.1, together with some of the key two-engine aircraft that preceded them. Many of the parameters in the table are self-evident and others will be explained later. In the table a number of weights (or masses) are referred to. The take-off weight m_{TO} is made up of the empty weight m_E, the payload (which is the weight of passengers

Table 1.1 Salient characteristics of some large two-engine aircraft

	Airbus A300-B2	Airbus A300-600	Boeing 767-200	Airbus A330-300	Boeing 777-200	Boeing 777-200LR	Boeing 787-8	Airbus A350-900
Entry into service	1974	1983	1982	1993	1995	2006	2011	2014
Normal max. passengers	269	274	216	335	375	301	242	315
Range at max. passenger (nm)	1500	3100	4000	5400	4800	9100	7650	8100
Maximum range at max. payload, R1	900	1950	2200	3700	3300	7600	5500	5900e
Max. payload	30.6	43.3	33.2	55.2	54.6	64.0	40.2e	47.6
Max. take-off weight	137	165	143	233	243	348	228	268
Empty weight	86	87	80	120	136	145	122e	133e
Fuel burn at R1 (see Section 2.1)	15	29	24	49	42	124	60e	65
Cruise Mach no.	0.78	0.78	0.80	0.82	0.84	0.84	0.85	0.85
Cruise L/D (estimates)	16	16	18	20	20	20	21	21
Estimated engine *sfc* ($\mathrm{kg\,h^{-1}kg^{-1}}$)	0.64	0.63	0.62	0.58	0.57	0.54	0.52	0.51
Wing span (m)	45	45	48	60	61	65	60	65
Wing area ($\mathrm{m^2}$)	260	260	283	362			325	443

Note. All weights in tonne. Weights for the 787-8 are those given in November 2011 by Lyssis, (http://www.lissys.demon.co.uk/boeing787-2011) with empty weight significantly higher than the original design specification given by Boeing. All the values should be treated as indicative of the trend rather than exact, and ‘e’ indicates that this is estimated rather than from a published source. R1 is the range with maximum payload and maximum take-off weight. Fuel burn is fuel weight at take-off less reserves estimated at 4% of maximum take-off weight.

Note that numbers with ‘e’ indicates that they are only estimates.

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and freight) m_{PL} and the fuel m_F. The fuel weight can be divided into fuel which is expected to be burned, m_{FB}, and the fuel which is held in reserve for contingencies, m_{FR}, which is not expected to be burned. As a reasonable approximation, $m_{FR} = 0.04m_{TO}$, and the reserve may be treated as an addition to the empty weight.

As the table shows, the cruise Mach number and the range have increased over time, so the latest twins are designed to cruise at the same speed as the long-range four-engine planes, $M = 0.85$. It may also be noted that a full complement of passengers does not provide maximum payload: each passenger may be taken to weigh 95 kg with baggage. Typically the freight carried in the hold ("belly freight") is comparable in weight to a full load of passengers. In quoting range it is not uncommon to give the value when only a full load of passengers is carried, with no freight in the hold.

The growth in twin aircraft for long ranges could not have happened without several things. One is that the engines have become very much more reliable, so that long flights of two-engine aircraft can be allowed over the oceans with acceptable safety. Long-range flights of two-engine aircraft are now governed by the Extended-range Twin-engine Operational Standards (ETOPS), referred to above, which specify how much flight time (flying with only one engine in operation) they may be away from a suitable airport for diversion in case of a problem. The amount of time depends on the testing procedure they have been through, and experience of reliability in testing and operations to date. For the 787, for example, the ETOPS limit is 330 minutes and the A350 is intended to be 350 minutes. ETOPS has led to increased attention to reliability. Another reason for the use of twins for long range is the recognition that high bypass engines are quite well matched at take-off and cruise, meaning that, unlike the old engines, they operate at full capacity in both cases and are not carrying excess capacity (and weight) to ensure safe take-off capability. A key consequence of this is that long range flight with twins becomes efficient. This satisfactory match is a topic which will be discussed in more detail in later chapters. A further reason for the increase in twins is that engines are expensive items requiring maintenance and having two rather than four engines reduces operating cost. The New Efficient Aircraft (NEA) which is the object of the first ten chapters of this book, will therefore have two engines.

As already noted, large aircraft are usually intended for long-range operation, whilst small aircraft are for short range. The smaller aircraft have a single-aisle configuration in the passenger cabin; this category includes regional jets but is most conspicuous in the Boeing 737 and the Airbus A320 series. There is some variation in full-payload range between types of single-aisle aircraft, but most can carry a full load of passengers around 3000 nm, even though the majority of flights are much less than 1000 nm. Using relatively small aircraft for short flights allows the traffic to be handled with frequent flights and this is generally attractive to passengers. There are also efficiencies associated with short range aircraft due to their increased ratio of passenger to fuel weight. As noted above, the original Airbus A300 was a short-range, wide-body aircraft, but the majority of wide-body aircraft are primarily for long range. The aerodynamic performance of the single-aisle aircraft is perhaps 10–15% worse than the larger aircraft, measured in terms of drag per unit of weight. Likewise, the engine specific fuel consumption may be 20% worse

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than that of the best larger engines. The New Efficient Aircraft (NEA) will therefore be a wide-body aircraft capable of carrying about 300 passengers with a design range more like that of the current single-aisle aircraft, about 3000 nm. The aircraft aerodynamics and structural efficiency will be comparable to the latest twin aircraft, the 787 and A350, and engine performance will be comparable to those engines installed on these aircraft.

1.2 ENVIRONMENTAL ISSUES

When jet propelled passenger transport was initiated, little or no thought was given to the environment, either near the airports or in the upper atmosphere. By the late 1960s the situation near airports was becoming intolerable, mainly because of the noise, but also because of pollution. The pollution involved unburned hydrocarbons, smoke (i.e. small particles of soot, which is unburned carbon) and oxides of nitrogen (NO_x). Gradually steps have been taken to rein in the nuisance near airports by international agreement, with regulations both for combustion produced emissions near airports and for noise during take-off and landing.

The international agreements are reached so that the interests of various parts of the industry (from manufacturers of engines through to the airlines which operate rather old aircraft) are addressed. The net result is that the international agreements have lagged behind public pressure for amelioration so that local regulations at important airports around the world have tended to be more challenging for the makers of new engines to meet. The international limits on noise are so far above the noise produced by new aircraft with modern engines that the international limit serves merely as the benchmark from which the margin of lower noise is set. For noise the airport which tends to determine the level which new large aircraft have to achieve is London Heathrow. For products of combustion an airport which sets the level is Zurich, where charges are varied depending on the amount of pollution released in a standard landing and take-off operation. The issues and rules for emissions of pollutants are addressed briefly in Section 11.5. Noise is considered in an appendix at the end of the book.

Concerns about noise, particulates (small soot particles) and NO_x remain, but these have more recently been overshadowed by concerns about the impact of aviation on global warming. The principal motivation behind the introduction of the early jet aircraft, such as the Boeing 707, was higher speed and comfort and in terms of fuel burn, or CO_2 production, they were far worse than piston engines they replaced; indeed it is only recently that jet-propelled aircraft have achieved fuel efficiency as good as the later piston engine airliners. According to the Air Transport Action Group,[1] the global aviation industry currently produces 2% of the global CO_2 emissions, which is about 12% of the CO_2 from transport. In addition, oxides of nitrogen do make a contribution to global warming, as do the condensation trails left by aircraft when flying through an atmosphere which is supersaturated relative to ice. There is large uncertainty associated with both these factors, and they are sometimes described, quite inappropriately, as giving a multiplier to the effect of the carbon

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[1] http://www.atag.org/facts-and-figures.html.

dioxide generated. Certainly carbon dioxide has a well-recognised effect and persists much longer in the atmosphere, for times on the order of 100 years. In this book we direct attention at reducing the emission of carbon dioxide, whilst recognising that this is not the whole impact of aviation. The reduction in the amount of fuel burned automatically leads to a reduction in the emission of CO_2, and with this in mind the International Air Transport Association and the International Civil Aviation Organisation have set goals for fuel efficiency improvement of 1.5% per year to 2020 and 2% per year from then to 2050. It is hard to maintain year-on-year improvements like this. Indeed, the historical trend going back to the introduction of the Boeing 707 is about 0.7% per year, and it is widely thought that improvements are becoming harder to achieve.

Reducing fuel burn is an obvious saving in cost to any airline. At the time when *all* aircraft in service in 2015 were conceived, and designed, the cost of fuel was a relatively small fraction of the overall direct operating cost, typically no more than 20%. This meant that considerable inefficiency in the use of fuel could be allowed if the aircraft were to be more flexible in operation. So, in particular, a plane capable of long range could be attractive to an airline even if the requirement for long range was infrequent. This has driven the trend for range so apparent in Table 1.1. Likewise, the ability to carry significant belly freight was attractive, even if the amount carried on the majority of flights was well below the maximum possible, so the fuel burn penalty of the increase in aircraft structural weight and larger engine thrust to allow this freight capacity was accepted. Fuel is now more expensive and is expected to become more so, either because of a rise in the cost of unrefined petroleum or because of taxes or charges added to the fuel. Possible charges on emitted CO_2 are equivalent to a rise in the cost of fuel. Moreover, there are plans to introduce certification levels for CO_2 or fuel burn, broadly analogous with those currently for noise and NO_X, which will further drive aircraft towards lower fuel burn. This is the background for the proposed New Efficient Aircraft, a wide-body aircraft embodying the latest technology optimised for low fuel burn in the majority of operations.

1.3 COMMERCIAL ASPECTS OF NEW LARGE AIRCRAFT

It takes several years to design, develop and certify (i.e., test so that the aircraft is approved as safe to enter service) a new aircraft. It seems to take even longer to develop the engines, but until the specifications of the aircraft are settled, it is not clear what engine is needed. There are three major engine manufacturers (Rolls-Royce in Britain, Pratt & Whitney and General Electric in the United States). The costs of developing a wholly new engine are so high that it has been the ambition of each manufacturer to use, whenever possible, an existing engine, perhaps with some adaptation or uprating. On the Boeing 777 all three major manufacturers offered an engine, and the competition was fierce. Pratt & Whitney and Rolls-Royce offered developments of existing large engines, but in this case General Electric developed a wholly new engine, the GE90. Rarely does it serve the makers of new engines or new aircraft to give much information on the costs they have incurred. Nevertheless, the *Economist* of 18 September 1999 reported that the GE90 had cost General Electric \$1 million per day for four and a half years, in total about \$1.6 billion; it is not clear how much extra

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was spent by risk-sharing partner companies. This huge sum can be made more understandable if an average wage for an employee, with the appropriate overheads, is taken to be $150,000 per annum – the $1.6 billion cost then translates into over 10,000 man-years of work.

If engines are expensive, the airframe is even more so. The *Seattle Times* of 5 February 2011 quoted a Wall Street analyst who says that the original Boeing estimate for the cost of the new 787 was $5 billion, but that the problems Boeing encountered raised the cost by between $12 billion and $18 billion. The *Seattle Times* of 24 September 2011 gave a 'conservative estimate' that the cost to Boeing of producing the 787 was in excess of $32 billion. A spokesman, David Strauss, from the investment bank UBS, is quoted, who believes Boeing must sell between 1100 and 1900 787s to break even. An estimate by Reuters news agency on 22 October 2012 refers to Airbus having to spend $15 billion producing the A350, but it is not known how much has actually been spent in bringing the aircraft into service.

This is a business in which large financial risks are taken, which, in turn, leads to caution and conservatism. On the other hand, the developments evident in Table 1.1 point to a continuing increase in design range, which is now significantly greater than the overwhelming majority of flights; airlines have a liking for the flexibility that long design range brings, even if this comes at the costs of higher fuel consumption. So long as airlines want increased range in their new aircraft, it is difficult to get change in the style or operation of aircraft. It is even harder to get any radically new configuration, such as blended wing bodies or open rotors (two rows of propellers), and this book will be concerned with more conventional engine and aircraft configurations propelled by a turbofan engine. The New Efficient Aircraft considered here will be the conventional fuselage with wing (sometimes called tube and wing) and the engines will be mounted under the wings. Engines are large and heavy; for example, a Rolls-Royce Trent 800, which is the lightest engine to power the Boeing 777, weighs about 8 tonne when installed on the aircraft. Because most of the lift is generated by the wings, hanging the comparatively massive engines where they can most easily be carried makes good structural sense. This reduces the wing root bending moment and makes possible a reduction in the strength and weight of the whole aircraft.

Whilst discussions are going on between aircraft manufacturers and airlines, they are also going on between aircraft manufacturers and the engine manufacturers. As specifications for the 'paper' aircrafts alter, the 'paper' engines designed to power them will also change; many potential engines will be tried to meet a large number of proposals for the new aircraft before any company finally commits itself. The first ten chapters of the book will attempt, in a very superficial way, to take a specification for an aircraft and design the engines to propel it – this is analogous, in a simplified way, to what would happen inside an engine company.

1.4 SPECIFICATION OF THE NEW EFFICIENT AIRCRAFT

The New Efficient Aircraft (NEA) is to have a clear design objective of moving passengers with the least environmental impact, consistent with meeting the needs of passengers and airlines. The