

A Centennial Review of Sub-sonic Transport Aircraft

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From Wright Brothers 1903 to present day 2003, aeronautical technology has made a profound progress. This paper demonstrates the outcome of this progress in weight, wing area, and engine thrust in three categories of transport aircraft of short to long range, regional jets, and turbo-prop commuter aircraft. Also the paper includes those aircraft with distinct jump in aeronautical technology. Few of the technologies that have contributed to this progress are elaborated too. An average of four to three times progress in aerodynamic sciences, three to four times in weight reduction for material science, and system design, and two to one and half times progress in propulsion of turbo-fan, and turbo-prop engines are concluded.

INTRODUCTION

Loftin, at NASA has made a wonderful report [1] about transport aircraft progress from 1903, to First World War, and years between the wars, as well as post Second World War. The emergence of jet propulsion was reported as the most critical turning point in aeronautical sciences. He also considered the retraction of landing gears, firing of gun through rotating blades of propeller engines, monoplane victory over bi, and tri-plane, and last but not the least, semi-monocoque all metal skin aircraft are also specified as key progress issues. Other authors reported the emergence of more effective avionics, engine system instruments, aircraft materials, and in-flight entertainment. Further elaboration in the progress of transport category aircraft occurring since the post Second World War, especially in the last 25 years, are the prime target of the author in this paper.

SETTING THE SCENE

It may be possible to go through every detail of the progress in the field of aircraft design, structure and systems in the past hundred years. However, each topic may require a single paper in order to demonstrate the progress. Readers may have to explore several papers and reports to make their own conclusions. It may

be necessary to establish a methodology to explore the progress in its integration form, i.e. the transport aircraft itself. In this methodology aircrafts were found with numbers of matured technologies to make them the technology hub.

The criteria for progress in wing loading and thrust loading will not be repeated here, as other authors in other review approaches have successfully used them. Also direct operating cost reduction progress was not considered as the basis. This approach is prone to many biased data. The author considered passenger kilometer as the denominator for the reduction of aircraft weight, wing area, and thrust required for trend analysis of the chosen aircraft at which the technology jump was found. The reduction of the ratio of takeoff weight and passenger kilometer is “an indication of progress in aircraft structure design, and aeronautical alloy, as well as progress in aircraft systems (more functions, higher reliability, lower weight) and aircraft interior (beauty, ergonomics, and lower weight)”, and the ratio of wing area and passenger kilometer is “an indication of the progress in design, and technology of airfoil, wing, high lift devices, as well as in use of advanced methods in computational fluid dynamics (CFD), and stress analysis finite element software” and the ratio of thrust and passenger kilometer is “an indication of lower fuel consumption, and lower engine weight (helping the first trend), lower aerodynamic drag, as well as development of higher thermodynamic efficiency, and innovative cycle”. In order to provide confidence in the above methodology, the author in-

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cluded all the base jet transport aircraft from the birth to B777 in Table 1. Sub-sonic transport aircraft are categorized according to their own historical progress: 1) Transport aircraft of short to long range i.e. range: 3500 to 16000km, seats: 120 to 600 pax (passenger). 2) Regional transport jets: Range: 1500 to 3500km, seats: 35 to 100 pax. 3) Propjet commuter aircraft i.e. range: 500 to 2000km, seats 18 to 70 pax.

TRANSPORT AIRCRAFT

The following aircraft were found by the author in which the technology jump occurred and made them distinguished and appropriate candidate for comparison.

1. DAKOTA, DC-3: First flight took place in July 1933, before the Second World War. Douglas DC-3 continues to fly today, see Figure 1. More than 13000 were produced, 2000 of them in Soviet Russia. This is the aircraft that changed history, first by opening the era of modern air transport in mid-1930s, and then by becoming the mainstay of the Allied air transport effort in World War II. The author considers DC-3 as the perfection of aeronautical technology progress from Wright Brothers till the birth of jet engines. With retracting landing gears, trailing edge flaps, reliable engines under the wings, which all later designers considered the best place for them, pressurized, air-conditioned, adequate avionics, matured electric system, cabin interior designed for safety and comfort, DC-3 could be treated as the last advanced technology tail dragger aircraft, since the Wright Flier'. Table 1 shows take-off weight, wing area, with respect to passenger/kilometer for Dakota DC-3.
2. Boeing 707, Figure 2, was the second turning point in the development of jet transport aircraft happening twenty years after DC-3 in 1954. Although this

was the second jet transport aircraft in the history after the British De Havilland Comet (1949), it incorporated all the technology that was necessary for a safe long-range air transport. By close study of subsequent jet transport aircraft such as Boeing 727 (1963), 737 (1967), French Caravel (1955), British BAE one-eleven (1963), BAE Trident (1967), BAC VC-10 (1962), American Douglas DC-8 (1958), Holland Fokker F-28 (1967), Russian Ilyushin-62 (1963), Tupolev Tu-124 (1960), Tu-154 (1968), no significant breakthrough has been made superior to B707 in the technology and design methodology. All of them followed their peers B707 being single aisle short to medium range aircraft. The engines followed B707 low by pass ratio famous JT-3d model. Most of the systems of present jet transport aircraft were first introduced in B707 aircraft which still fly in more than 300 examples. Followings are few examples of innovation in aircraft systems used in matured stage in B707: Pressurization by intelligent out flow valve / Air cycle unit for air-conditioning with innovative use of engine bleed / Ice protection of wing leading edge by economical cyclic use of engine bleed / Inertial navigation in conjunction with radio navigation, and radio com. integrated with intercom / Passenger comfort with modern galleys, toilets, ergonomic interior / Novel four engines under the wings (this idea is pursued by Airbus A340 forty years later in 1991) for safe operation across the Atlantic. Table 1 shows a significant progress from Dakota to B707 in twenty years i.e. seven times reduction in takeoff weight, 25 times reduction in wing area with respect to passenger/kilometers. Boeing 707, the initiator of the global tourism industries, is by far the author's best candidate for the second grand advances in the jet passenger technology progress.

3. Boeing 747 (Figure 3) is yet the third turning point



Figure 1. Dakota DC-3

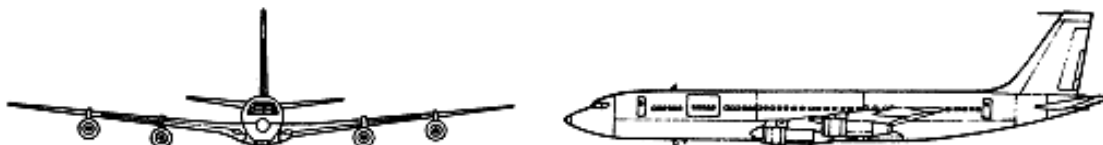


Figure 2. Boeing B707

Table 1. Jet transport aircraft listed as per date of their first flight.

Table 1	Country	Year	Pax (a)	Range (b)	Total Thrust (T)	Wing Area (S)	$W_{t_{max}}$ (c)	$W_{t_{max}} / (Pax \times Range)$	$S / (Pax \times Range)$	$T / (Pax \times Range)$	
Units				Km	lbf	m^2	Kg	$1000 * Kg / (Pax * km)$	$10000 * m^2 / (Pax * km)$	Lbf / $(Pax * km)$	
1	2	3	4	5	6	7	8	9	10	11	12
1.	DC-3	USA	1933	24	563	2x1200 hp	91,7	11430	846	67.87	
2.	B707	USA	1954	189	5835	4x 19000	283.4	151320	136	2.57	0.069
3.	DC-8	USA	1958	117	9950	4x 17000	266.5	147415	126	2.26	0.058
4.	VC10	UK	1962	187	7600	4x 21800	272.4	151950	106.9	1.916	0.061
5.	B727	USA	1963	125	4500	3x 15000	157.9	95027	169	2.807	0.080
6.	BAC111	UK	1963	119	2726	2x 12550	95.78	47400	146.1	2.95	0.077
7.	IL62	Russia	1963	168	6700	4x 23150	279.6	162000	143.9	2.48	0.082
8.	B737	USA	1967	119	3851	2x 14000	91.5	52390	114.32	1.98	0.061
9.	Trident	UK	1967	139	3965	3x 11960	135.26	65317	118.5	2.554	0.065
10.	Tu-154	Russia	1968	128	5280	3x 20950	201.45	90000	133.1	2.98	0.093
11.	B747	USA	1968	350	8023	4x 43500	511	356070	126.8	1.82	0.061
12.	LI011	USA	1970	345	4629	3x 42000	320	195045	122.13	2.0	0.079
13.	DC-10	USA	1970	380	6875	3x 51000	364.3	251744	96.36	1.394	0.058
14.	Mercure	France	1971	155	750	2x 15500	116	65500	563.44	9.978	0.266
15.	A300	Europe	1972	281	1668	2x 51000	260	142000	302.96	5.542	0.217
16.	DC-9	USA	1974	139	3323	2x 15500	92.97	54885	118.82	2.012	0.067
17.	IL-86	Russia	1976	350	3600	4x 28635	320	206000	163.5	2.54	0.091
18.	MD-80	USA	1979	137	3306	2x 18500	118.8	63503	140.2	2.623	0.083
19.	B767	USA	1981	200	3700	2x 44300	283.3	128030	173.01	3.828	0.12
20.	B757	USA	1982	186	2000	2x 37400	181.25	99880	268.5	4.872	0.20
21.	A310	Europe	1983	214	4815	2x 48000	219	132000	117.15	1.94	0.085
22.	A320	Europe	1986	150	5650	2x 25000	122.4	77000	90	1.44	0.059
23.	A340	Europe	1991	239	14816	4x 31200	325.2	275000	77.66	0.918	0.035
24.	A330	Europe	1992	335	9300	2x 74000	325	230000	73.82	1.043	0.0433
25.	B777	USA	1994	305	13241	2x 74000	427.8	286895	71	1.06	0.0366

(a) Pax: No. of passengers,

(b) Range with maximum payload and or number of passengers in previous column appropriately,

(c) $W_{t_{max}}$: Maximum all up weight,**Figure 3.** Boeing B747

that the Americans achieved in the field of design and manufacture of jet transport aircraft in just 15 years after Boeing 707. A first double decker, first wide-body, first two aisle aircraft, first to carry more than 350 passengers in three classes, B747 aircraft flown in 1969 was the third aeronautical technology jump offered to air transport civilization. From B707 to B747, no aircraft exceeded take-off weight of 150 tons. The highest span experienced was 44 m; the highest wing area was 285 m^2 . With the Boeing 747, aeronautical industry experienced a takeoff weight of 350 tons, 230% rise.

Wing area rose to 511 m^2 , a 200% increase, and wing span rose to 60m. There was a revolution in all disciplines of aviation business. The grand size of the aircraft contributed to the technology of building very large hangers. The runways of most major airports were strengthened for higher LCN values. The production line of this giant aircraft at Boeing Seattle was so spacious that it soon became a tourist spot. Boeing 747 was the beginning of the American supremacy in the jet transport business, being sold to North and South America, Europe, Africa, and Asian airlines. Only Soviet,

and pro-Soviet countries purchased Ilyushins, and Tupolevs. The only competitor to Boeing wide body was American Mc Donald Douglas DC-10, and Lockheed Tri-star. As regards the engine technology, a great progress also occurred in the bypass ratio from 2 to 5, lowering the specific fuel consumption by 25 to 35%. Turbine blade cooling and uni-directional vacuum investment casting as well as long fan blade technologies were among the technology jumps that happened at jumbo-jet. Boeing 747 was a flying village, with a lot of change taking place in the airport passenger, and cargo handling system, and aircraft emergency evacuation systems.

Boeing 747 helped tourist industry to flourish to its peak high, due to more than 20% reduction in direct operating cost (DOC). This allowed millions of European, and American tourists to travel to long distances to China, and South East Asia, where these countries could promote their economy. Also millions of tourists from everywhere in the world visited Europe, and United States. As the initiator of wide body aircraft, a new culture in aircraft design methodology promoted the subsequent wide body aircraft such as DC-10, Tri-star, Airbus A300, and A310, and Ilyushin Il-86. Boeing 747, one of the major contributors of the global business, is by far the author's candidate for the third grand advances in the jet passenger technology. Table 1 shows that B747 systems, interior, and body structure weight reduction produced only 7% improvement compared with B707. The reason for such a minor improvement may lie in the unnecessary rise in the fuselage diameter of B747. This aircraft was designed originally to carry high volume cargo in competition with Galaxy C-5. As a cargo aircraft, it required large fuselage diameter, but as a passenger aircraft, not only large volume was more than necessary for passengers, but it caused an increase in weight of life support systems as well as structural weight. This extra weight penalty outweighed the benefits of speciously comfortable interior for passengers. On the other hand, wing area reduction i.e. aerodynamics achievement since B707 is 30% improvement. Engine thrust requirement, also improved by 12% in 15 years.

4. Airbus A320: Since her emergence, Airbus Industries has pioneered twin-engine wide body aircraft and twin-engine permission to cross Atlantic by enhancing the reliability of engines. The birth of Airbus no doubt was a great achievement in the history of aviation. This permitted air transport to be relieved from Boeing and Mc Donnell Douglas world dominance, letting the talented thousands of European aeronautical engineers and scientists to materialize their ideas of transport aviation. No matter how important such achievements may be; it may not be treated as grand turning point in the history of jet transport aircraft, until Airbus designed A320 Aircraft. A320 (Figure 4) is the fourth turning point in the history of jet transport technology, first flown in 1986. For the first time electric wires performed the flight control system, abandoning the hydraulic piping, cables, and push-pull rods except for landing gears, brakes, and steering. A320 is no more a statically stable aircraft in which horizontal tails, produce positive lift, reducing the total lifting surfaces.

The incorporation of fly by wire system with parallel computers / full digital avionics system with liquid crystal multi-function display / a considerable amount of weight reduction due to use of composite material / systems reliability enhancement with large reduction in the cost of maintenance are few examples of technology jump in A320. The super critical airfoil of A320 wing with considerable contribution to aircraft lift drag ratio for the first time challenged the ever-successful Boeing 737 family of classic as well as new generation to the extent that it now holds higher orders than that of Boeing. A320 set the standard for common flight deck for the first time, allowing cross currency for the pilots. Side stick technology, disregarding the pros and cons was first introduced in A320.

The engine technology has also experienced the fully autonomous electronic fuel control system. For the first time a joint efforts of the American, and European, as well as Japanese engine makers united their talents and specialization to produce a low specific fuel consumption, highly reliable, and maintainable family of jet engines for the family of A320 aircraft known as CFM, and IAE. A320

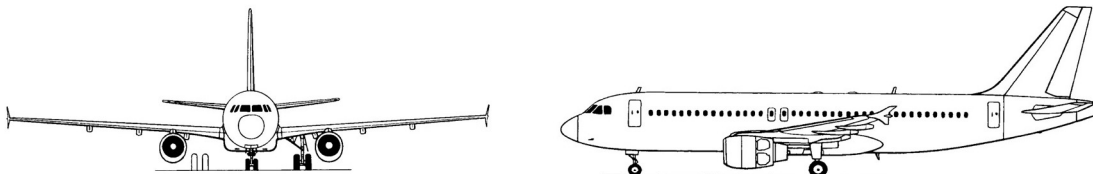


Figure 4. Airbus A320

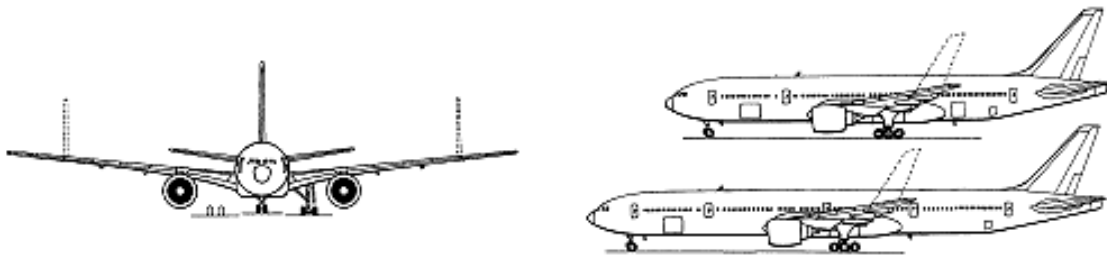


Figure 5. Boeing 777

Aircraft was first to introduce composite material in its primary structure, as well as the first aircraft to include centralized maintenance system. Flight safety in A320 reached yet another peak with the introduction of computers that does not allow pilots to exceed aerodynamic and structural limitations. Airbus A320, a genuine fuel-efficient aircraft, is by far the author's candidate for the fourth grand advances in the jet passenger technology progress. Table 1 shows A320 achieved a 29%, 21%, and 2 to 3% improvement in weight, wing area, and thrust requirement per kilometer-passenger over B747 respectively.

5. Boeing 777: (Figure 5) is indeed the fifth, and the last turning point in the history of transport aircraft. The airplane design offers features, innovations and approaches to airplane development that set the standards for delivering value to airlines. Since the wonderful A320, many aircraft were designed and developed by Airbus, such as A321, A319, A330, and A340. Boeing also designed and delivered successful aircraft since B747, such as B757, B767, B717, and B747-400. Russian developed Tupolev Tu-204, Tu-214, Tu-224, Tu-234, Tu-324, and Tu-334, and Ilyushin-96. But, Boeing 777 is the first jetliner to be 100 percent digitally designed using three-dimensional computer graphics. Throughout the design process, the airplane was "pre-assembled" on the computer, eliminating the need for a costly, full-scale mock-up. Boeing 777 is the first jetliner to be designed allowing the airline specialists to participate in the design process. It

was also first aircraft, that encouraged the design and development of turbo-fan engines of the by-pass ratio jumping from 5 to 10. Boeing 777 achieved to carry 50 more passengers, to a 1000 to 2000 km longer range with 100 ton less take-off weight, 100 m² less wing area, and two engines instead of four, with 20 to 30 thousands pounds less required thrust, with 30% less fuel consumption, and more than 35% less maintenance cost than early B747. Table 1 shows that B777 is 21% weight improved than A320, proving the point that intelligently chosen two aisle single deck diameter of 5.6 to 5.8 meters is a better solution for a wide body aircraft, requiring less weight in life support system, and still offering satisfactory comfort for the passengers. A 26% wing area reduction, and 40% engine thrust requirement per passenger-kilometer of B777 as compared with A320 is another victory for the aerodynamicist, and twin engine philosophy. This aircraft is indeed qualified by the author as the last and the fourth grand advances in the jet passenger technology progress.

Note 1: In Table 1, all the aircraft mentioned above at which technology maturity occurred are shadowed. It may be argued that for example why VC10 for which columns 10, 11, and 12 shows the lower value than B707 and even B747 were not considered by the author as a technology jump. VC10 was produced in less than 50 numbers and perhaps few military air-refueling versions are still flying, whereas B707 with date of birth 8 years older still carry passengers in more than 100 examples. VC10 like all aft fuselage engine mounted aircraft suffered

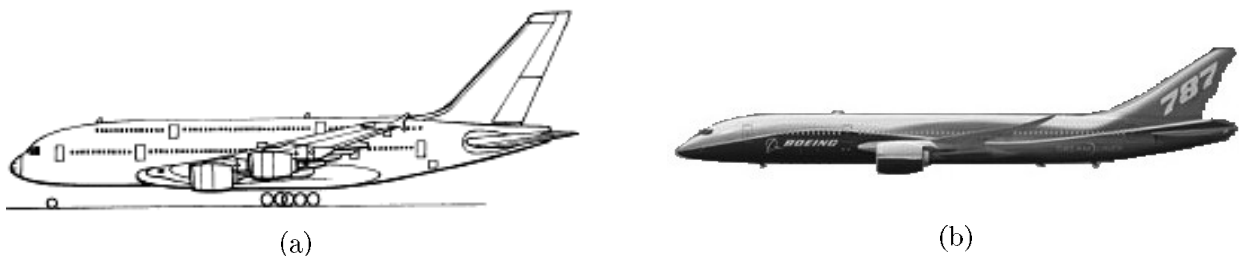


Figure 6. (a) A380, (b) B787

from heavier wing weight. This may be traded with lower noise and hidden engine appearance to passenger, but being a long range airliner, higher fuel consumption, T tail maintenance burden made the aircraft less economical and less acceptable to the market as compared to B707.

6. A380, and B787: The next turning point in jet passenger aircraft may be A380, and B787 but to be investigated in later years. However few of the advanced and wonderful technologies achieved in above aircraft deserve to be mentioned in this paper.
 - Passenger comfort, with innovative business seats in A380,
 - All electric aircraft system, specially no bleed air-conditioning system in B787,
 - Passenger safe evacuation equipment from upper deck in A380,
 - Aggressive use of composite material in primary structural members in B787,
 - New fast and grand passenger handling system developed at airports for A380,
 - Highest transonic cruise speed claimed for B787,

REGIONAL JET AIRCRAFT

1. Caravelle: On the contrary to the impression that regional jet is a new phenomenon in air-transport industries, French were the pioneers in design and development of regional jet half century ago. When the British designed and flown the first jet transport aircraft Comet in 1949, and the American were successful in flying the second jet transport Boeing 707, the French were doing a design to be quite different from the above two. They pioneered



Figure 8. Tupolev 124



Figure 7. Caravelle

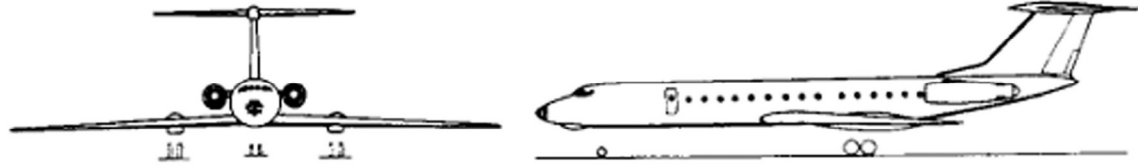
not only in regional jet but also they were first to design a rear fuselage mounted engine regional jet aircraft. Caravelle which was flown first time in 1955, indeed possessed new features that may be treated by the author as the first turning point in the history of regional jet. France was and still is the largest tourist attraction place in the world. The French designers were considering the regional passengers who are brought by B707 to main hubs in Europe i.e. London, Paris, Rome, etc. may be moved to all places of tourist attraction by an aircraft with capacity, and range such as Caravelle. Designers in Caravelle not only for the first time placed the engines at the rear fuselage, but also were able for the first time to design a near to T-tail empennage i.e. cross tail. They were also most probably the first nation to design and install APU in the fuselage tail section. Table 2 shows the weight, wing area, and thrust requirement with respect to passenger-kilometer of the world first regional jet for subsequent comparison.

2. Tu-134: The second aircraft to join the regional jet fleet of the world were that of the Russian Tupolev Tu-124 (Figure 8) to fly in 1960. This aircraft placed the engine within the wing root, a methodology that was soon abolished. The Russian were still unable to retract the landing gears into the wing root/fuselage bay to keep the wing clean.

The British also made an attempt not to lose the competition and designed the BAE one-eleven and flown it in 1963. An aircraft that was superior to Caravelle, but were made not withstand hot and high climate. Regional jet transport technology (unlike jet transport that was solely produced by the Americans) from the beginning were dominated by many participants i.e. many countries out side American continent designed this type of aircraft. The Dutch Fokker who were amongst the aircraft design pioneers developed F-28 to fly in 1967. The technology improvements were significant, but no visible innovation as compared with Caravelle. They produced 240 of these aircraft. Fokker became most known regional jet maker in the Western world. One year later the Russian designers inspired by Caravelle and F-28, improved their design of Tu-124, and placed

Table 2. List of successful regional jet.

Table 2	country	Year	Pax (a)	Range (b)	Total Thrust (T)	Wing Area (S)	Wt _{o max} (c)	Wt _{o max} / (Pax x Range)	S / (Pax x Range)	T / (Pax x Range)	
Units				Km	lbf	m ²	Kg	1000*Kg / (Pax*km)	10000*m ² / (Pax*km)	Lbf / (Pax*km)	
1	2	3	4	5	6	7	8	9	10	11	12
1	Caravelle	France	1955	64	2000	25000	150	50000	390	11.7	0.2
2	Tu-134	Russia	1968	80	2000	30000	127.3	47000	296	7.96	0.187
3	F-100	Holland	1986	107	2000	27500	94	41500	193	4.3	0.13
4	ERJ-170	Brazil	2003	70	3889	28000	85	36000	132	3.12	0.10

**Figure 9.** Tupolev 134

the engines at the rear fuselage in Tupolev Tu-134 (Figure 9) regional jet flown in 1968. They produced 700 of these aircraft, and although the landing gear bay was still stored under the outer section of the inner wing, the weight, wing area, and thrust improvement exceeded that of F-28 (see Table 2). Author considered Tu-134 as the second best regional jet emerged 13 years after Caravelle.

3. F-100: The French after their successful Caravelle made the second attempt by an innovative regional jet Mercure 100. This regional jet aircraft for the first time placed the engines under the wings. But due to probably miss-calculation in range (150 pax for 750 km) it received no market support what so ever. The third turning point in the history of regional jet was probably scored by the Dutch design of Fokker F-100 (Figure 10). The aircraft was the first regional jet to be equipped with full glass cockpit and FMS autopilot link with GPS/INS. F-100 made the first flight in 1986. By this time the regional jet technology was pursued by Netherlands in the Western world who designed and flight tested F-70 later. Table 2 shows F-100 further improvements compared with early designs.
4. ERJ-170: Fokker was the last amongst the Euro-

pean, and the Russian to have designed regional jet. The art of making regional jet became quite unattractive due to emergence of advanced turbo-prop aircraft, during eighties, and until mid-nineties. When the progress in 7000 to 15000 lb thrust turbo-fan engines occurred during the mid nineties, and also when the great improvement in the noise, and avionics and interior of turbo-prop aircraft resulted in the rise of their price to close to jet aircraft, the revival in regional jet took place, but this time in South and North America. The Brazilian and Canadian picked up the flag, and up to now they have produced wonderful regional jets.

- Canadian CRJ200 (CRJ700) with 50 pax (70 pax), and 1824 km (3124 km) range, flown first in 1991 (1999), with engines installed at the rear fuselage (Figure 11).
- Brazilian ERJ145 with 50 pax, and 2963 km range, flown first in 1995, with engines installed at the rear fuselage.
- Brazilian ERJ135 (140) with 37 (42) pax, and 3148 km range, flown first in 1998, with engines installed at the rear fuselage (Figure 12).

In all above aircraft a real turning point did not occur for technology innovation. All of them were

**Figure 10.** Fokker F-100



Figure 11. CRJ 200, 700

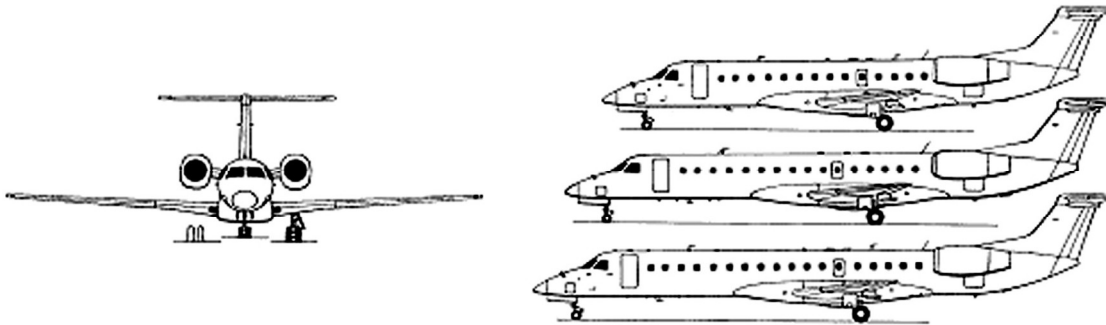


Figure 12. ERJ 135, 140, 145

rear fuselage mounted engines, fuselage body was taken from their predecessor executive jet, and all of them were equipped with digital avionics system. The real turning point happened in 2003, when Brazilian Embraer designed ERJ-170 (see Figure 13). The advanced fly by wire regional jet, for the first time with engines at the right place under the low wings, ERJ-170 is the latest, and perhaps the last matured sub-sonic regional jet could become the mainstay of regional jets for years to come.

The range and the capacity is such that it may cover most of the regional roots in many rich and tourist populated countries of the world such as North America, Europe, and China. Table 2 shows for ERJ-170 weight saving per passenger-kilometer is three folds, wing area is also three folds, and thrust saving is nearly two folds against first regional jet Caravelle in less than 50 years. Europe and American Dornier Fairchild aircraft manufacturing industry tried to design a similar aircraft 728 jets with even more advances in special intelligent electric system, but due to cash crisis, they were unable to complete the aircraft beyond roll out stage.

TURBOPROP COMMUTER AIRCRAFT

Turbo-prop families of commuter aircraft also have undergone profound progress. The only type of passenger aircraft whose progress was the source of its diminishing. Unlike jet transport, the author would rather deal with their progress on the generation basis.

1. The First Generation Turbo-props (1951-1960): British are considered the first nation to produce the first turbo-prop aircraft, with highest variety,

and quantity of early propjet aircraft. The story of the propjet aircraft begins with the development of turbo-prop engine, and British are again the pioneers in this field, developing Rolls Royce Dart. All the early British, American, Netherlands, and Japanese turbo-prop aircraft were equipped with Dart engines. The following aircraft are considered the early turbo-props (first generation), who are designed and flight-tested from early fifties to early sixties.

- UK, BAE Viscount 810, 1951, Pax: 65, Range: 2757 km, 440 produced,
- UK, Handley Page Herald 200, 1955, Pax: 44, Range: 1786, 50 produced,
- Netherlands, Fokker F.27, 1955, Pax: 36, Range: 2070, 581 produced,
- USA, Grumman Gulfstream 1-C, 1958, Pax: 37, Range: 2500 km, 200 produced,
- UK, BAE HS748, 1960, Pax: 58, Range: 1455, 381 produced,

They are either high or low wing, but no distinctive technological superiority can be found among them in order to choose the one that could be called a turning point. BAE Viscount 810 (Figure 14), due to being the first world turbo-prop aircraft, and also subsequent first generation aircraft could not exceed this aircraft in any of the technology criteria, is treated the first turning point in the history of propjet aircraft.

2. The Second Generation Turbo-props (1960-1983): Many propjet aircraft were designed and developed by number of nations since the creation of early turbo-props. Turbo-prop aircraft proved to be more

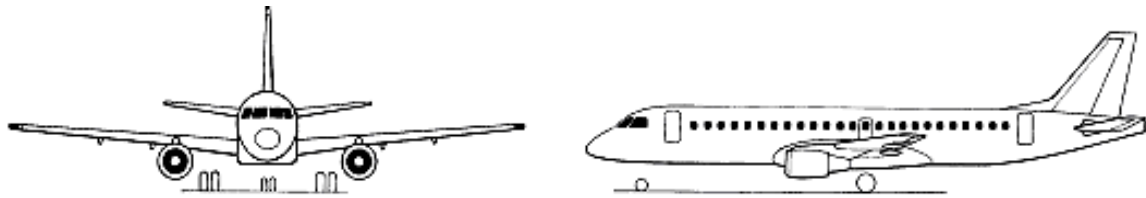


Figure 13. ERJ 170



Figure 14. BAE Viscount 810

economical, and more applicable to short ranges than early jet transport. The turbo-prop engines were 20 to 35% less fuel thirsty, and they were able to land and takeoff from short runways of towns all over every country, hence they provided an air commuter between towns, and major cities. The second-generation propjets were able to offer capacity range from less than 18 to nearly 50 Pax. It gradually proved to the operators that a profitable capacity might be 50 to 70. The reduction of propeller noise, and to fly faster close to jet aircraft soon becomes the challenge to propjet designers. The following aircraft are considered second-generation turboprops. They are designed and flight-tested from early sixties to early eighties:

- Soviets, Antonov An-24, 1960, Pax: 50, Range: 1000 km, 1100+ produced,
- French, Aerospatial, Nord 262, 1960, Pax: 25, Range: 1000 km,
- Japan, NAMC YS-11A, 1962, Pax: 60, Range: 1000 km, 110 produced,
- Canada, De-Havilland Twin Otter, 1965, Pax: 20, Range: 1300 km, 834 produced,
- UK, Jetstream 31, 1967, Pax: 18, Range: 1519 km, 150 produced,
- Brazil, Embraer EMB-110, 1968, Pax: 21, Range: 2000 km, 500 produced,
- Spain, CASA C-212, 1971, Pax: 19, Range: 480 km, 389 produced,
- USA, Beech Super King Air B200, 1972, Pax: 10, Range: 1400 km, over 2000 produced,
- Canada, De-Havilland Dash 7, 1975, Pax: 20, Range: 1300 km, 114 produced,
- Canada, De-Havilland Dash 8, 1975, Pax: 20, Range: 1300 km, over 500 built in all versions of -100, -200, -300, -400,

- Czechoslovakia, LET L-410, 1975, Pax: 15, Range: 800 km, 650+ produced,
- USA, Cessna Model 208 Caravan, 1982, Pax: 14, Range: 2326 km, over 500 built in all versions,
- Brazil, Embraer EMB-120, 1983, Pax: 30, Range: 2000 km, the number produced is included in EMB-110,
- Sweden, Saab SF 340, 1983, Pax: 35, Range: 1191 km, over 400 built in all versions,
- France/Italy, ATR-42, 1984, Pax: 46, Range: 2420 km,
- France/Italy, ATR-72, 1985, Pax: 72, Range: 2778 km, over 500 built in -42, and -72,

It took nearly twenty years since the first generation turbo-props in order to arrive at a genuine technology best propjet. It is evident that the European companies designed more propjets. The French /Italian ATR family and Swedish Saab 340 may be the best high and low wing aircraft emerged from above mentioned propjets. The author prefers to select ATR-72 (Figure 15) as even the better aircraft among the second-generation turbo-prop. The technology of retracting landing gears of a high wing aircraft into the side fuselage fairing was perfected in ATR. The challenge that none of the first and second-generation high wing propjet aircraft were able to break. ATR were able to moderately modernize their avionics system to the level of most jet transport aircraft of their time, having all necessary VOR-DME-NDB-ILS-GPS-VHF-HF in place. For the first time ATR were able to install a full composite wing box in the aircraft. The aircraft speed was increased to 10% higher than any of their contemporary turbo-prop aircraft. The noise decibels inside the cabin were reduced efficiently to less than 85. Although the most near to ATR aircraft such as Saab 340,

Table 3. List of successful turboprop commuter aircraft

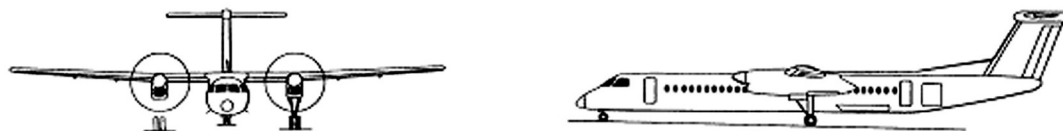
Table 3	Country	Year	Pax (a)	Range (b)	Total Thrust (T)	Wing Area (S)	Wt _{0max} (c)	Wt _{0max} / (Pax x Range)	S / (Pax x Range)	T / (Pax x Range)	
Units				Km	lbf	m ²	Kg	1000*Kg/(Pax*km)	10000*m ² /(Pax*km)	Lbf / (Pax*km)	
1	2	3	4	5	6	7	8	9	10	11	12
1	Viscount	UK	1951	65	2757	8400	89.46	32886	183.5	4.99	0.0468
2	ATR-72	France/Italy	1985	74	1685	5000	61	22000	176.4	4.90	0.040
3	Q400	Canada	1998	70	2400	10142	63.08	27329	162.67	3.755	0.060
4	Do328	Germany	1991	30	1556	4360	40	13640	292.2	8.56	0.093
5	Saab2000	Sweden	1992	50	2639	8250	55.7	22000	166.73	4.22	0.0625
6	An-140	Ukraine	2001	52	2300	5000	56.5	21500	179.7	4.72	0.042

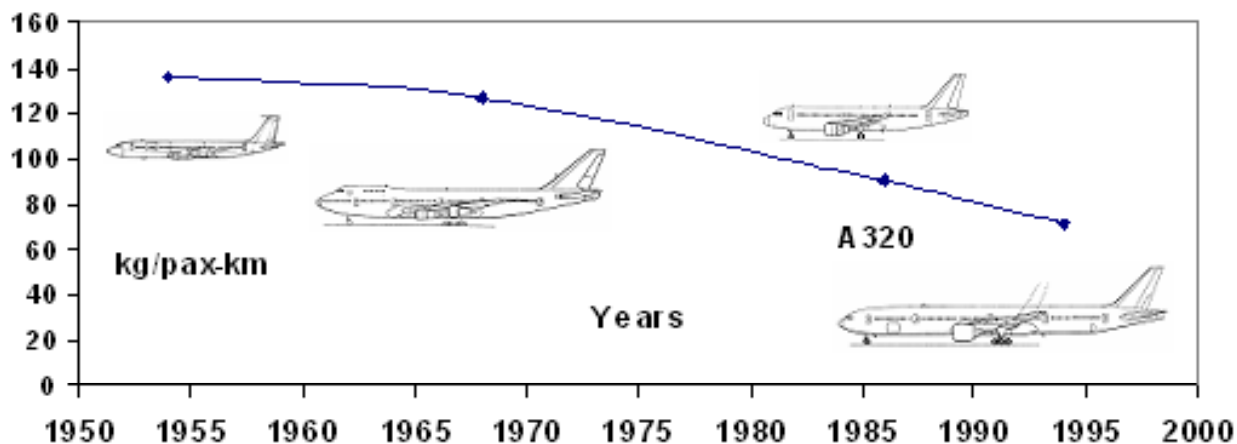
**Figure 15.** ATR 72

and Canadian Dash-8 were equally modernized, but ATR-72 were more successful in market as well as in technology achievement (see Table 3).

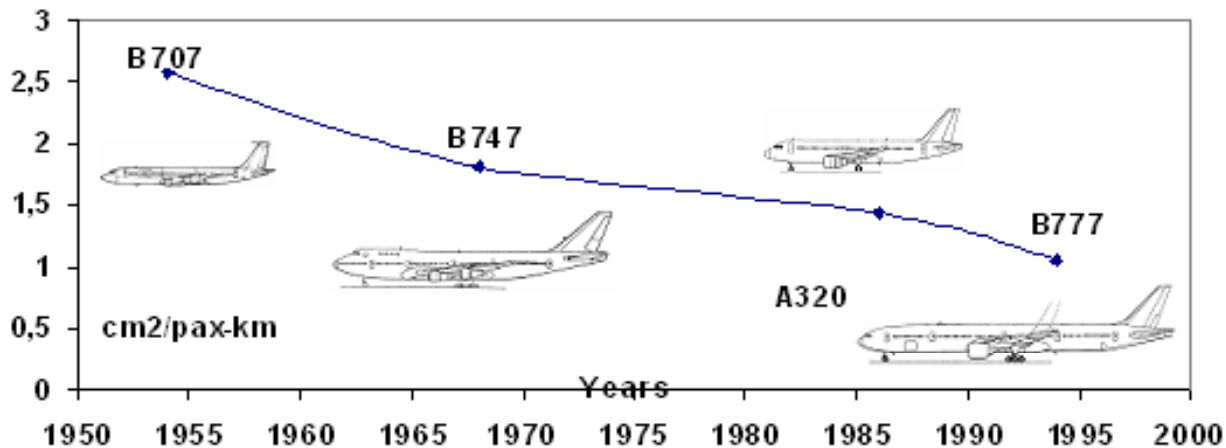
- Third Generation Turbo-props (1983-2003): Indeed the fate of this type of transport aircraft is amazing, and deserves deep scrutinizing. The speed of progress begins with the emergence of new ideas to develop as quiet, as fast, as comfortable, and as advanced avionics as jet transport aircraft. The competition drives the Canadian, Swedish, and German to heavily investing for Dash-8-400, Saab-2000, Dornier-328 respectively. The British, and Dutch followed them with caution, and rather least investment for up grading HS 748 to ATP (Advanced Turbo-prop), and Fokker F-27 to F-50. The French and Italian ignored this upheaval and progressively modified ATR-42, and 72 to new avionics and produced versions of ATR-42-500, and ATR-72-500. The Indonesian also entered this business and designed N-250, a seventy seat advanced turbo-prop that could not reach end of its flight tests due to financial, as well as political problems of Indonesia. Russian Ilyushin designed a new low wing twin turbo-prop IL-114, and Ukrainian designed a totally new twin turbo-prop aircraft An-

140. Both design Bureaus targeted the replacement of second generation An-24. It was apparent that An-140 having superior performance as well as using advanced technology, and selecting Western critical system components would lead the competition, which ended with An-140 being selected by Russian, Ukrainian, and Iranian serial production industries. An-140 was intelligently equipped with old and new system components to keep the cost as low as being distinctly away from regional jets. Table 3 shows the performance of the best of third generation turbo-prop. Indeed Dornier 328, and Saab-2000, and Dash-8-400 were wonderful turbo-props. They were all equipped with full glass cockpit. All necessary investment in interior design was incorporated as fancy as jet transport. Active and passive noise suppression methodologies were put into operation so that noise level was down to less than 85 decibels at prop sections of passenger cabin. Dornier used advanced wings and extra powerful engines to go as fast as 600 km per hour (kmph), 100 kmph higher the rest of existing turboprops except Saab-2000. Saab-2000 used far extra powerful engines twice more than any twin turboprop in the world so that speed reached higher than 650 kmph. Saab-2000 had to invest heavily

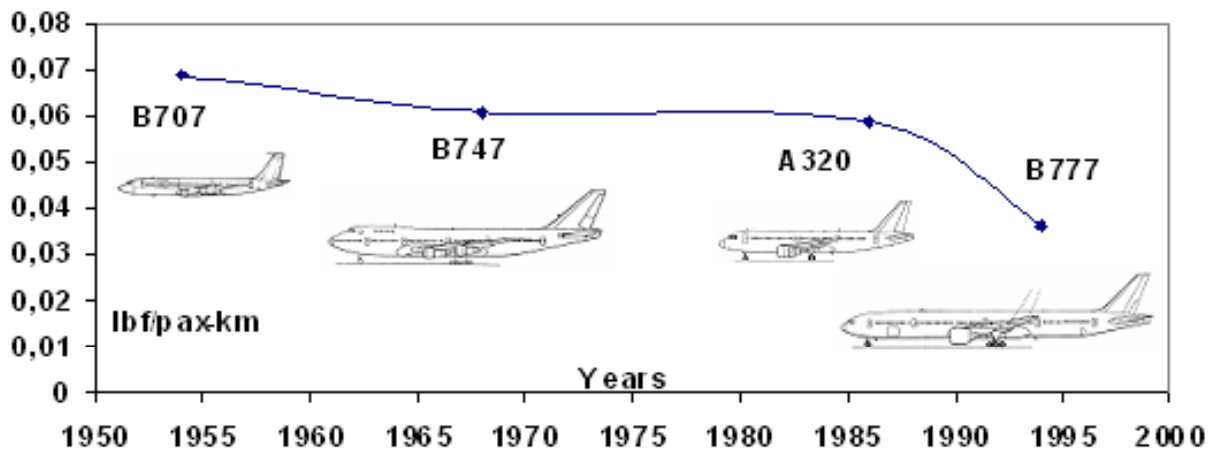
**Figure 16.** Dash8-Q400



(a)

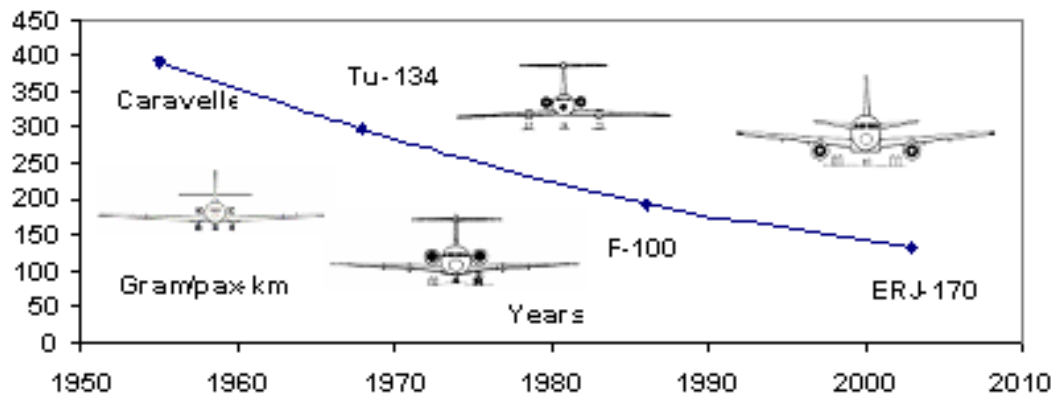


(b)

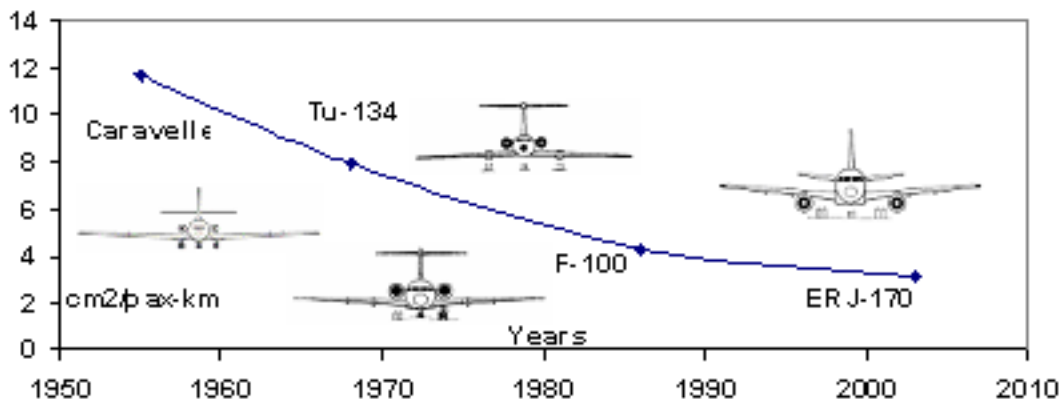


(c)

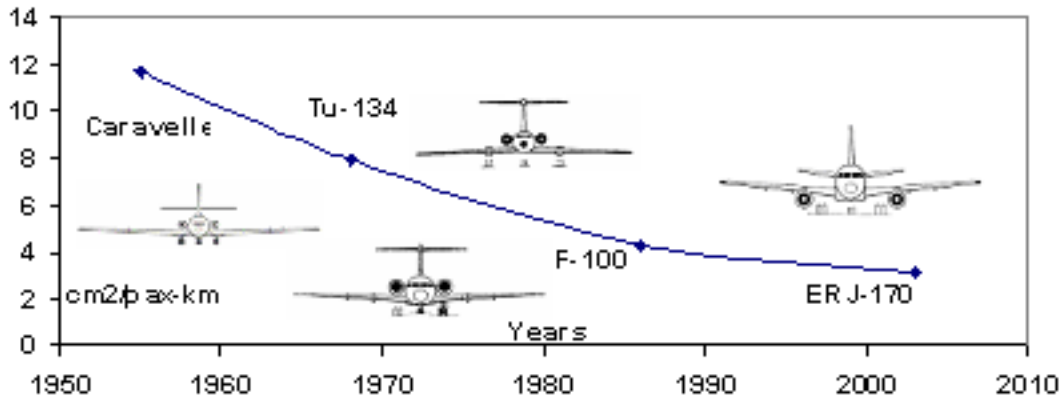
Figure 17. Progress Trend for Jet Transport Aircraft, (a) Take-off Weight Progress Trend, (b) Wing Area Progress Trend, (c) Engine Thrust Trend.



(a)



(b)

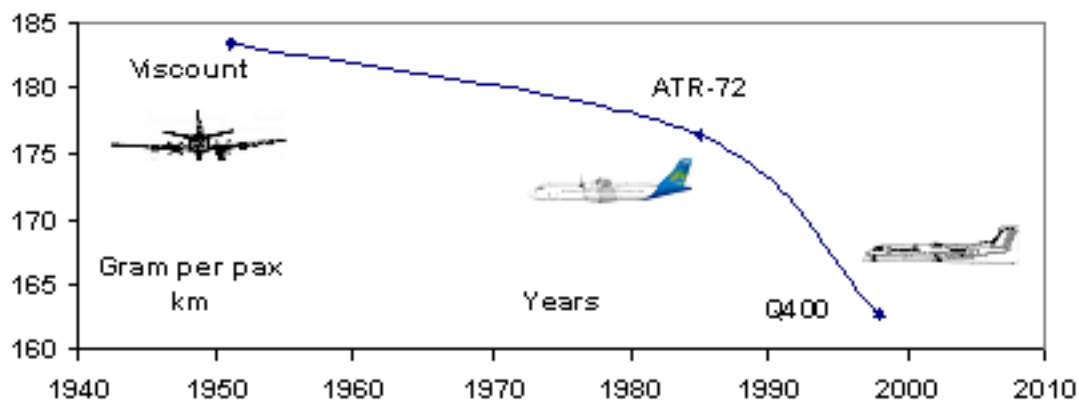


(c)

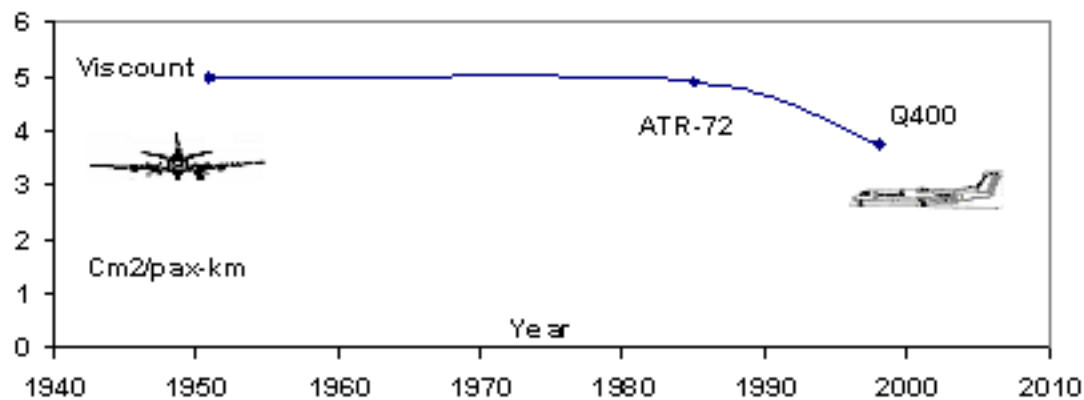
Figure 18. Progress Trend for Regional Jet Aircraft, (a) Regional Jet Take-off Weight Progress Trend, (b) Regional Jet Wing Area Progress Trend, (c) Regional Jet Thrust Requirement Progress Trend.

in weight and cost to reduce engine noise inside and outside aircraft to meet the ICAO regulations. Due to advanced nature of Dash-8-400, Dornier 328, Saab-2000, airlines did not welcome ATP, and Fokker F-50. The British BAE Jetstream, and ATP, and Dutch Fokker F-27, and F-50 due to above reasons closed their turbo-prop production line forever. Due to the cost escalation of Dornier 328, and Saab 2000, both companies had to raise

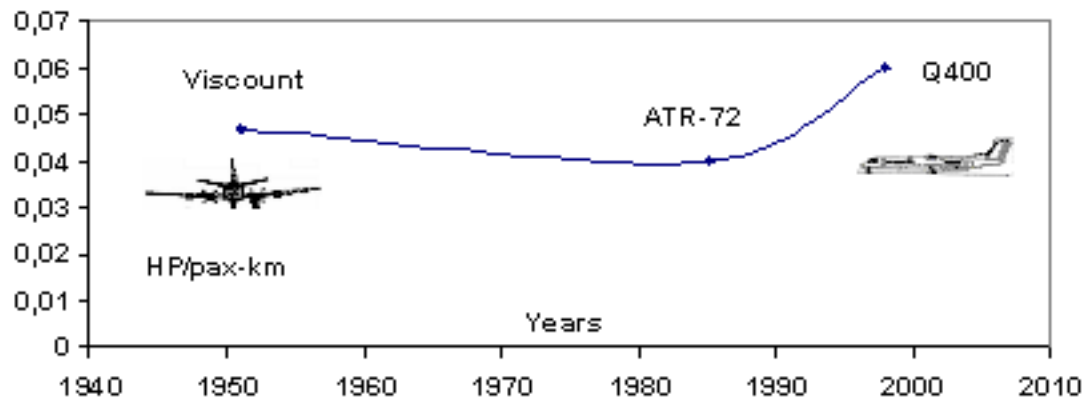
the price of their aircraft to nearly equivalent jet aircraft. This led to the ideas of designing new generation regional jet. Competing Brazilian Embraer and Canadian Bombardier immediately made use of recent advances in 7000 to 15000 lbf turbofan engine with further lower specific fuel consumption, and embarked upon designing lower cost and higher efficient regional jet, beating Dornier 328, and Saab 2000 out of the Market. Both German and



(a)



(b)



(c)

Figure 19. Progress Trend for Propjet Aircraft, (a) Propjet Take-off Weight Progress Trend, (b) Propjet Wing Area Progress Trend, (c) Propjet Horse Power Requirement Progress Trend.

Swedish companies went broke, and closed their most ever sophisticated and advanced turbo-prop aircraft production line. Embraer also closed their second-generation turbo-prop production line such as EMB-110, and EMB-120, leaving the Western World with two left propjets, Bombardier Dash-8-400, and 300 family, and French/Italian ATR

family. The former has had many difficulties in market approval, and has experienced intermittent production closure, leaving ATR the only player in the Western propjet family. An-140 Aircraft also remained as the only propjet family survived in the non-Western countries. Author considers Canadian Bombardier Q400 (Figure 15) as the best turbo-

prop of the third generation to be in the production line in spite of market difficulty, and regional jet threat. Although An-140 is just slightly behind, the An-140 price per seat of 163,000/- US Dollar is far below 242,000/- US Dollar for Q400. On the other hand Q400 (Figure 16) possesses a full glass cockpit avionics offering much comfortable, and passenger appeal interior. There is distinct improvement in weight, and wing area of Q-400, a third generation turbo-prop compared to ATR-72 of second generation, except for engine. The engine power per passenger and per kilometer of third generation turbo-prop aircraft has risen as compared to second generation. However it is not a bad news, as turbo-prop aircraft since their birth have struggled to reach higher speeds. It was proved that without higher engine power, they could not reach speeds as high as 600 kmph. Although engine power has gone up per pax-km, the overall weight, and wing area per pax-km, has fallen due to improvement in turbo-shaft engine performance and weight. The rise and fall of the best third generation turbo-prop occurred in less than 15 years.

CONCLUSIONS

- Transport aircraft from short to medium range have made a tremendous progress since Wright Brothers to the matured pre-second World War technology as Dakota DC-3, and then moved for 70 years to Boeing 777 (see Figure 17). Author would place Dakota out side the final trend analysis, since the changes that followed was quantitatively out of proportion. From Boeing 707 to Boeing 777 (see Table 1):
 - The amount of take-off weight per passenger per km has fallen from 136 kg to 71 kg, resulting in 48% improvement.
 - The progress in aerodynamics was incredible. The amount of wing area has fallen from 2.57 Cm² to 1.06 Cm² per passenger per km, more than 2.5 times.
 - The amount of thrust lbf required per passenger, per km was improved from 0.069, to 0.0366 for almost two times. But in real terms, due to standing to hot and high condition and single engine failure reliability extended range (ETOP) with twin engines, the real reduction is of the order of four times.
- Regional jets (see Figure 18) also have made a great progress since their birth. From Caravelle to ERJ-170 (see Table 2):
 - The amount of take-off weight per passenger per km has fallen from 390 gram to 132 gram, a three times reduction in 50 years.
 - The progress in aerodynamics was incredible. The amount of wing area has fallen from 11.7 Cm² to 3.12 Cm² per passenger per km, nearly four times.
 - The amount of pound force thrust required per passenger per km was reduced from 0.2 to 0.1. But in real terms, due to the same reason as jet transport aircraft, the real reduction is of the order of three times.
- Turbo-prop commuter aircraft (see Figure 19) have also made a progress that unfortunately did not result in its survival in the market. The first time that technology incorporation was counter-effective. On the whole, one or two types of propjet were more cautious in rapid technology incorporation and opted for incremental progress. These were Antonov An-140 for Eastern side, and ATR-72, and 42 from Western manufacturers, and it seems that these two will remain in the market for the foreseeable future, except that Q400 may survive only with large cash insertion in the production line. The progress of propjet commuter aircraft from British Viscount to Canadian Q400 can be described as follows (see Table 3):
 - The amount of take-off weight per passenger per km has fallen from 183.5 gram to 162 gram, an 11% reduction in 50 years. Although this seems very little as compared to other types of transport aircraft, but the number of new system equipment that was added to this type of aircraft in this 50 years were incredible. These are extra navigation and flight instrument dual VOR, ILS, DME, advanced FDR, TCAS, EGPWS and weather radar, extra equipment for fire alarm system in the passenger cabin, 16 G passenger seats, hydraulic operated control surfaces, APU as part of empty weight, etc.
 - The progress in aerodynamics, from the amount of wing area 4.99 Cm² to 3.755 Cm² per passenger per km is almost 25%. The progress could have been more if the cost of wing design were not in the mind of designers. Also the lower stall speed of the propjet aircraft did not necessitated the importance of using super critical airfoils. On the other hand the short take of and landing requirement compelled the designers to equip

It is to be noted that the regional jet would have to invest more in empty weight than transport aircraft of short to medium range. The reason is that they ought to equip themselves for the same system capability, and safety reliability, but have to carry fewer passengers per kg of the empty weight.

the wing with heavier double slotted flaps, and proportionately larger wing area.

- The progress in horsepower per passenger per kilometers quantitatively reversing. From British Viscount it has fallen from 0.0468 down to 0.040, but it has gone up to 0.06 for Q400. This rise has occurred for almost all latest commuter turboprops. The designers were compelled to increase the engine power as the only mean to fly and climb faster, while providing more bleed air to life support systems. This led to increase in engine horsepower, with little improvement in specific fuel consumption.

FUTURE PREDICTIONS

1. Subsonic jet transport aircraft may face two turning points in future. One is for ultra high capacity aircraft such as Airbus A380, a European aircraft with complete two floor passenger cabins, and large number of system advancements. The aircraft design community excitedly followed the flight tests of this aircraft that happened few weeks ago. The other turning point may belong to the Boeing 787. A first jet passenger aircraft is claimed to be super economical, and mostly fabricated with composite material. The Author is quite excited to read further about this aircraft in future.
2. The regional jet aircraft may not see a tremendous jump in technology in a foreseeable future. This class of aircraft has already gone too far to gain the reward from the market before the designers invest for much advanced technology.
3. The turboprop commuter aircraft will be perhaps subjected to cost effective incremental progress in order to stay at much lower price than regional jets. In fact for propjet aircraft the progress is to survive in the market for the coming years.

The following references have helped the author to establish his views but they were not directly connected to any of the above topics.

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