Technology Speed of Civil Jet Engines

Stefan Frei, Urban Mäder

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Abstract. In this paper, the speed of technology of civil jet engines is investigated. A fundamental limit is found to exist by the second law of thermodynamics, but it is not reached yet. A technology measure based on airplane efficiency is derived and applied to jet airlines of different sizes and time periods, ranging back to the 1960's.

1. Introduction

Since the dawn of modern aviation, when Wilbur and Orville Wright performed the first powered flight of mankind on the 17th December 1903, aviation has particularly been driven by technology and innovation. It was the invention of aerodynamic flight control and the availability of the new, powerful combustion engines that ultimately allowed the Wright's flyer to take off from the ground and stay in the air.

Civil mass aviation started to be popular in the 30ies, much assisted by technologically ground-breaking planes, such as the DC-3. The two world wars further expedited technological advances in aviation. At the end of WW II the first jet-powered fighter aircrafts had already flown. Only few years later, the first jet-powered commercial airliners doubled the speed of then established, propeller-driven designs.

Soon, focus was shifted from "faster, larger, further" to economical- and ecological considerations. This paper aims to investigate improvements made in these areas. The time examined time period ranges from early 60ies to today, thus comparing the first modern airliners (Boeing 707 and DC-8) with today's flagships.

The paper is organised as follows: In Section 2, the history and the working principle of jet engines are discussed. In Section 3, main technology drivers and limits are discussed. In Section 4, a measure for technology speed is proposed, while this measure index is applied to real data in Section 5. The paper finally concludes in Section 6.

2. History of Jet Engine Technology

Piston engines turned out to be a major bottleneck for more powerful airplanes in late 30ies [1]. The power (or thrust) they could deliver was limited, since the tips of a propeller must not rotate faster than the speed of sound, the efficiency decreases rapidly. Also, a propeller system is limited in the maximum speed it can achieve, since thrust decreases relatively quickly at higher aircraft speeds.

To overcome these difficulties, several alternatives to the turbojet were under consideration, most notably the thermojet, which employed a piston engine for compressing the air, which would then be burned

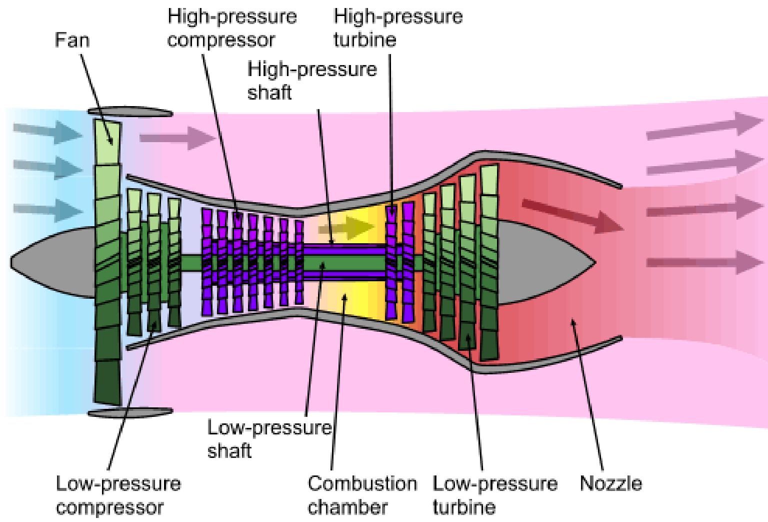

Figure 1. Turbofan Jet Engine, from [2]

continuously in the combustion chamber. The turbojet on the other hand, draws power for the compression directly from the exhaust gas stream. This design soon proved to be superior to the thermojet and thus soon prevailed.

In Figure 1, a modern jet engine is depicted [2]. The principle still is very similar to the original designs: Air is collected by the intake, then compressed by a multi-stage compressor. In the combustion chamber, fuel is added to the compressed air; the mixture is then continuously ignited. The pressurised gas leaves the engine through the turbine, which collects energy to drive the compressor stage.

A notable design feature is the large fan which precedes the low-pressure compressor stage. Some of the air the fan accelerates bypasses the engine and joins the hot air stream leaving the turbine stage. The ratio of bypassing- to combusted air is called bypass-ratio. Turbofans have a larger mass flow than turbojets, but at lower velocity. This leads to more thrust, but restricts the engine to lower airspeeds; it can thus be seen as compromise between propellers and pure turbojets. Typical bypass-ratios for large engines in sub-sonic airliners are usually higher than 5, while supersonic (military) jets have ratios around 2.

Today, there are three large manufacturers of jet engines left: General Electric, Rolls-Royce plc and Pratt & Whitney. After more than 50 years, the business can be considered mature.

3. Technology and Limits

In the early days of jet propulsion, innovation pace was fast, as fundamental new design ideas where found to drastically boost performance. Such radical design innovations where

- Transition from radial- to axial compressor. This greatly reduced the diameter of the engine while increasing thrust.
- Invention of turbofan. The first turbofans had an increase in thrust of over 50%, while fuel consumption was equal to the old designs.

In the 70ies, engine design matured; innovation became more subtle. Efficiency and performance of turbofans are mainly governed by two main factors:

1. Combustion temperature and overall compression (i.e. air pressure before the combustion chamber). The higher, the more efficient the thermodynamic combustion process. Combustion is mainly limited by available material technology, since turbine and engine casing must be able to withstand these conditions. Also, cooling techniques are applied to remedy for this.
2. Bypass ratio. By increasing the ratio, thrust (and efficiency) is increased. However, as with propellers, the blade tips must rotate with subsonic velocities. Hence, the diameter cannot be increased arbitrarily.

Hence, there are two fundamental technological limits for jet engines; one being defined by the second law of thermodynamics, the other by the trade-off between high velocity / low thrust and low velocity / high thrust. Both limits are not “absolute”. For instance, there is no absolute maximum temperature for the combustion chamber. The discovery of new materials and the invention of better cooling mechanisms will allow to increase efficiency further.

4. Assessment of Technology Speed

It is difficult to assess the technology level of jet engines directly, as too little information is available for comparison. Furthermore, it is not easy to extrapolate data of a single engine – probably from ground tests – to performance in an actual airplane. Moreover, it is unclear how to compare older turbojet- to modern turbofan engines, or small- to large ones directly.

We thus decided to employ an indirect measure: airplane efficiency. Though engines are not the only parts to influence airplane performance, they are the most important one. In [4], 69% of improvements between 1960 and 2000 are accredited to the engines, only 27% to aerodynamic improvements.

The performance measure chosen is *fuel needed per range payload*, or *APK* (available payload kilometre). That is, how many kilograms of fuel does a specific plane take to move one kilogram of payload for one kilometre. This value can be calculated for many airplanes from freely available performance charts of the Aircraft Operations Manual (AOM). However, this measure is typically not constant for every configuration of fuel, payload and range. For instance, Figure 2 shows a typical payload / range diagram. The diagram shows the attainable range of a Boeing 707 for any combination of payload and fuel. Note that the feasible area is bounded by various constraints, such as maximum structural payload, maximum fuel and maximum takeoff weight.

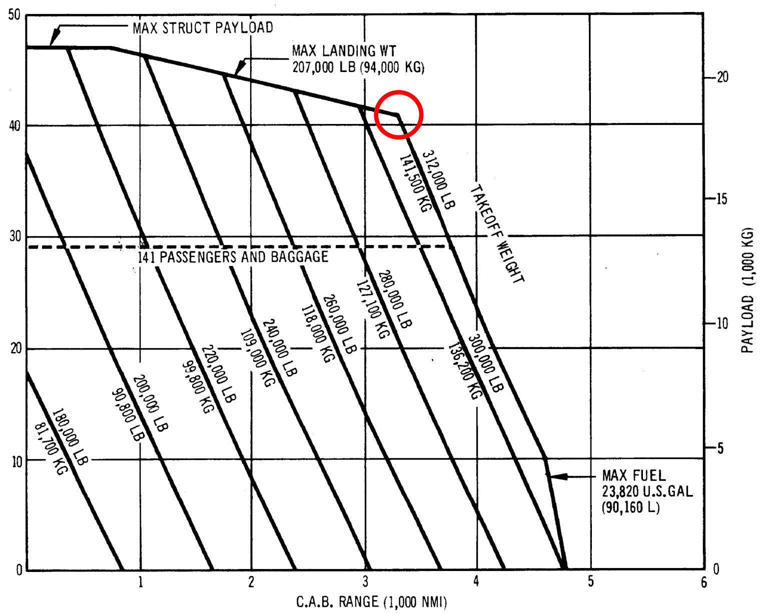

Figure 2. Range / Payload Diagram for Boeing-707-320 [3]

In order to consistently compare airplanes, similar working points must be chosen for each of them. We chose the point where the airplane is at maximum takeoff weight, with as much payload as is still feasible (red circle). The APK factor can then be computed using the data from these diagrams by the formula[1]:

APK = Fuel / (Payload x Range) [kg/(kg x km)]

5. Results

Airplanes from several manufacturers in several variants have been considered. The year of first appearance on the market was decisive. The oldest airliner is the Boeing 707-120 from 1957, the newest the Airbus 380-841 from 2005. Table 1 contains a list of all airplanes, with the calculated APK. In Figure 3, the data samples are plotted, along with a polynomial least-squares fitted curve.

6. Conclusion

The data samples suggest a technology speed of at about 2.2% per annum. Due to the fundamental limits mentioned above, it is not clear whether this development will be persistent in the future, without another technological breakthrough.

[1] Operational Empty Weight OEW and Maximum Takeoff Weight MTOW used are given in the Aircraft Operators Manual AOM

Model	Year	APK (scaled)
B707-120B Domestic	1957	78.88%
B707-320 Passenger	1959	100.00%
B707-320B Advanced Intl	1959	78.69%
B747-100	1969	42.72%
B747-200	1970	35.32%
B767-200	1981	42.87%
A310-200	1982	50.08%
B767-300	1986	32.59%
B747-400	1988	43.28%
MD-11 Passenger	1990	39.74%
A340-300	1994	37.58%
A330-300	1995	30.75%
B777-200	1995	38.08%
B777-200-IGW	1997	30.52%
B717-200	1998	61.69%
B737-800 Winglet	2002	38.75%
A380-841	2005	35.58%

Table 1. Airplanes, year of service entry and APK (scaled to worst)

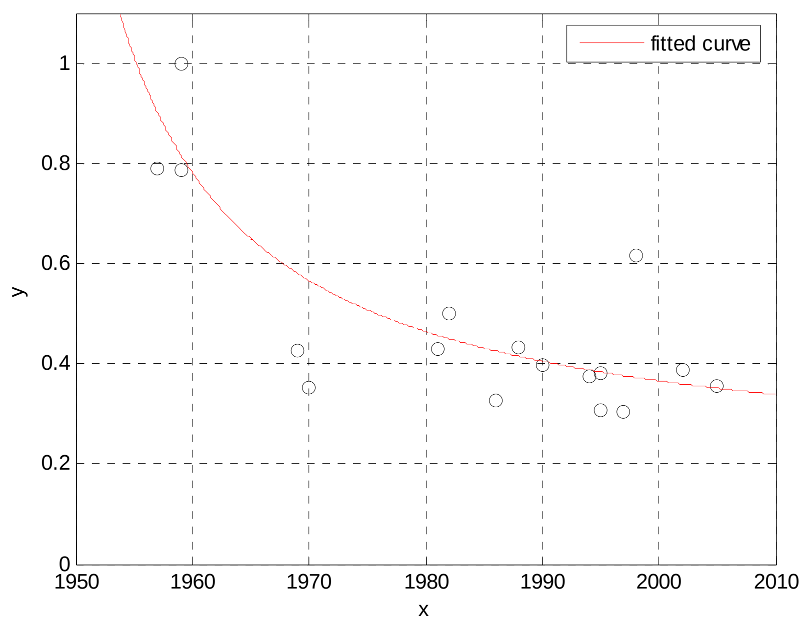

Figure 3. APK for different aircraft (scaled to worst)

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