A View of the Future of Civil Transport Aircraft Propulsion Systems

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Background

• Civil transport aircraft are designed to meet the requirements of the airlines that operate them, in particular: performance and operating costs.
• The environmental impacts (especially related to global warming), and the huge increase in fuel cost, have affected aircraft design substantially.
• Airlines contribute to 2-4% of environmental impacts today (pollution, CO₂ emissions, etc.), and it is expected to rise to 10-15% or more in the next 30 years, if no major improvements are made.

Innovation is a key to CO₂ reduction
Direct Operating Cost (DOC)

- **DOC target**: usually 15% to 20% less than current operating aircraft.

- **Example**: the DOC target for the A380 was set to be 15% to 20% better than Boeing 747-400.
Advisory Council for Aeronautical Research in Europe (ACARE)

Objectives 2020/2050
- Noise reduction by 50%.
- Fuel consumption and CO₂ emission reduction by 50%.
- NOx emissions reduction by 80%.

Engine Contribution
- Noise reduction by 6 dB per operating point.
- Specific fuel consumption (SFC) Reduction by 15% to 20%.
- NOx emission Reduction by 60% to 80%.
Bréguet Range Equations

The fundamental Bréguet Range Equations:

\[
Range = H \frac{g}{\eta_{thp}} \cdot \left(\frac{L}{D}\right) \cdot \ln\left(\frac{W_{initial}}{W_{final}}\right)
\]

Where:

\[
W_{initial} = W_E + W_P + W_F, \quad W_{final} = W_E + W_P
\]

therefore,

\[
\frac{W_F}{W_P \cdot R} = \frac{1}{X} \left(1 + \frac{W_E}{W_P}\right) \left(1.022e^{\frac{Rg}{X}} - 1\right)
\]

where,

\[
X = H \eta_{thp} \left(\frac{L}{D}\right)
\]

- \(H\) = Fuel heating value
- \(H \eta_{thp}\) = \(V/\text{SFC}\)
- \(L/D\) = Lift over drag ratio
- \(R\) = Range
- \(V\) = Aircraft Velocity
- \(W_E\) = Aircraft empty weight
- \(W_F\) = Fuel weight
- \(W_P\) = Payload weight
- \(\eta_{thp}\) = Thermo-propulsive efficiency
- 1.022 = Factor (additional fuel used in takeoff, climb, approach and landing).

Use of carbon fibre reinforced polymer (CFRP) leads to significant reduction of the A350 XWB fuselage weight.
Lift Over Drag Ratio (L/D)

\[ C_D = C_{D_0} + k \frac{C_L^2}{\pi AR} \]
\[ \frac{D}{L} = \frac{C_D}{C_L} = \frac{C_{D_0} + k \frac{C_L}{\pi AR}}{C_L} \]

Differentiating \( D/L \) for \( C_L \) and equaling to zero, getting \( (D/L)_{\text{min}} \)

\[ \frac{d}{dC_L} \left( \frac{C_{D_0} + k \frac{C_L}{\pi AR}}{C_L} \right) = - \frac{C_{D_0}}{C_L^2} + k \frac{1}{\pi AR} = 0 \]
\[ (L/D)_{\text{max}} = \frac{1}{(D/L)_{\text{min}}} = \frac{1}{\frac{C_{D_0}}{k} \frac{\pi}{\pi AR}} \]
\[ C_L = \sqrt{\frac{C_{D_0} \pi AR}{k}} \]

At point A the lift-to-drag ratio is maximum:

\[ C_D = C_{D_0} + k \pi AR \frac{C_{D_0}}{k \pi AR} = 2C_{D_0} \]
\[ (L/D)_{\text{max}} = b \sqrt{\frac{\pi}{4kSD_0}} \]

- \( C_L \) = Lift coefficient
- \( C_D \) = Drag coefficient
- \( C_{D_0} \) = Zero-lift drag coefficient = \( S_{D_0}/S \)
- \( S_{D_0} \) = Surface zero-lift drag coefficient (\( \Sigma C_{D_0} \))
- \( k \) = Induced drag factor (or \( 1/e \))
- \( e \) = Oswald efficiency
- \( D \) = Drag
- \( L \) = Lift = \( W \)
- \( W \) = Weight
- \( S \) = Surface area
- \( AR \) = Aspect ratio = \( b^2/S \)
- \( b \) = Span
Airbus indicates that the A350 XWB will:

- Reduce fuel consumption by 25% compare with B747-400.
- Lower operating cost by 8% compared to B787.
- Reduce number of scheduled maintenance tasks by 55% compare with A330.
CFM LEAP-X and P&W PurePower PW1100G engines are ready for near-term adoption by airframe manufacturers.
These engines promise approximately 15% fuel-burn improvements over their predecessors in addition to 50% less maintenance hour (MH) over 12 years.

The A320neo is a retrofit option. The A320neo versions will have over 95% airframe commonality with the 320ceo (current engine option) versions, enabling it to fit seamlessly into existing A320 Family fleets.

The 737 MAX is not a retrofit option. It is a new airplane.

There is a size limit for high BPR turbofan in conventional airplanes.
Narrow-Body Aircraft Re-Engine (cont.)

**CFM LEAP-X**
- Twin annular premixing swirlers (TAPS) increase oxygen in the combustor.
- Thrust range 18,000 to 35,000 lbf.
- Bypass ratio (BPR) of 10 - 11 versus 6 on the CFM 56.
- Utilize technology from the GENx engine developed for the B787/B747-8.
- Extensive carbon fiber development.
- 18 fan blades rather than 24 on the CFM 56.

**P&W PurePower PW1100G**
- Fan geared configuration allow the fan tips to operate in sub-sonic conditions.
- Thrust range 24,000 to 33,000 lbf.
- Bypass ratio (BPR) of 12.

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![Fuel Consumption Improvement vs. Bypass Ratio (BPR)](image)
Rolls-Royce Civil Large Engine Key Technology

**Advance**

- Bypass ratio: 11+
- Overall Pressure ratio: 60+
- Improved efficiency over Trent 700: 20%
- 2 & 3 shaft engine configurations.
- Carbon composite-titanium (Cti) fan systems.
- 20% reduction in CO₂ and NOx emissions.
- Light & efficient turbo-machinery components.
- Advanced materials and seals.
- Adaptive technology (turbine tip clearance and cooling flows control system).
- Advanced controls, monitoring and electrical systems integration.

**UltraFan**

- Technology readiness: 2025.
- Bypass ratio: 15+
- Overall Pressure ratio: 70+
- Improved efficiency over Trent 700: 25%
- Variable pitch fan system.
- Slim line nacelle.
- Power gearbox.
- Multi-stage intermediate pressure (IP) system.
- Further use of advanced materials.
- 25% reduction in CO₂ and NOx emissions.
Engines operate at materials physical limits, and face a variety of constraints and operational requirements, including:

- Inlet flow distortion and separation,
- Compressor surge and stall,
- Combustion instabilities,
- Flow separations on airfoils,
- Flutter and high cycle fatigue,
- Engine emissions and noise.

However, it is clear that both high pressure turbine (HPT) entry temperature (TET) and overall pressure ratio (OPR) of aircraft gas turbine engines will keep increasing, leading to a further improvement of specific fuel consumption (SFC) and specific thrust. Consequently, there will be an increased use of bleeds, variable stator vanes and turbine tip clearance. This in turn will result in increased control systems complexity and enhanced safety schemes to prevent turbine overheat and rotor over-speed.
Thermal efficiency is improved by increasing OPR & TET. Traditionally, this has been achieved by new materials, improved turbine cooling and smaller, high-speed cores.

However, at current technology level, where cooling flow increases with OPR & TET, and component efficiency deteriorates as engine cores become smaller, SFC gains may not be achieved from further OPR & TET increases.

Improvements in propulsive efficiency arise largely through increases in bypass ratio (BPR) partly due to the OPR & TET increase.
Aircraft Gas Turbine Engine Environment

Sensors and actuators have to operate reliably under extreme gas path pressure and temperature conditions.
Electric wing ice protection
Electric environmental control system (ECS)
Electric engine starting system
Electric power distribution and management systems (power on demand)
Electro-mechanical actuators (EMAs), electro-hydrostatic actuators (EHAs) / electrical backup hydraulic actuators (EBHAs)
Electric nitrogen-generation-system compressor used for fuel-tank inerting
The More Electric Engine (MEE)

- Electric braking
- Electro-mechanical thrust reversing actuation
- Electro-mechanical variable stator vanes (VSVs) actuation
- Electric fuel pump, metering and control system
- Electric oil pump and scavenge system
- Distributed engine control using deterministic CAN buses
- Advanced diagnostics and prognostics
Centralized and Distributed Engine Control Systems

Current Centralized Engine Control Architecture

Distributed Engine Control Architecture

Future Extended Distributed Engine Control Architecture
Active Tip Clearance Control

Tip clearance, the radial gap between rotating blades and compressor casing, varies significantly during different operating conditions due to centrifugal forces and thermal expansion.
Between 1960 and 2010, technology progress enabled reducing aircraft fuel consumption and reduction of CO₂ emissions by 60%. ACARE objective is a further 50% reduction by 2020!
Constant NOx Pollutants and Noise Reduction

- 1st CFM engine brought a 60% reduction
- 35% further benefit through Double Annular Combustors
- New technologies bring further 50-60% benefit

Noise ground footprint divided by 7
90% reduction in neighborhood impact
Over the last 25 years, engine reliability as measured in terms of in-flight shutdown (IFSD) rate, has improved by more than tenfold, mainly due to the increased maturity of electronic engine controls (EECs) and enhanced testing procedures during the development phase.
Engine Overall Efficiency ($\eta_{thp}$)

$\eta_{thp}$ Thermo-propulsive efficiency
$\eta_{th}$ Thermal efficiency
$\eta_{pr}$ Propulsive efficiency

$\eta_{thp} = \eta_{th} \cdot \eta_{pr} = \frac{PW_{\text{Aircraft}}}{PW_{\text{Fuel}}} = \frac{FN \cdot V_0}{W_f \cdot FHV}$

$\eta_{th} = \frac{PW_{\text{Airflow}}}{PW_{\text{Fuel}}}$

$\eta_{th} = 1 - \frac{1}{OPR^\frac{\gamma-1}{\gamma} \cdot \left(1 + \left(\frac{\gamma-1}{2}\right) M_0^2\right)}$

$\eta_{pr} = \frac{PW_{\text{Aircraft}}}{PW_{\text{Airflow}}}$

$\eta_{pr} = \frac{FN \cdot V_0}{\frac{1}{2} W_9 V_9^2 - \frac{1}{2} W_0 V_0^2}$

Increase OPR & TET:
- Modify engine thermal cycle
- Modify combustor operation
- Modify combustor and turbine cooling system

Decrease exhaust velocity (decrease fan pressure ratio FPR)
- Decrease inlet velocity seen by the engine (reduce SFC)

$SFC = \frac{W_f}{FN} = \frac{W_f \cdot FHV}{FN \cdot V_0} \cdot \frac{V_0}{FHV} = \frac{V_0}{\eta_{thp} \cdot FHV}$
Thermal Efficiency ($\eta_{th}$)
Increase OPR & TET

Increasing OPR & TET provides **thermal efficiency improvement**...

...but increases **constraints on engine technology**:
- Core size decrease → high pressure (HP) core components feasibility (sealing, increased clearance penalties, decrease compressor and turbine efficiencies).
- Increased engine temperatures → need for higher cooling airflows → partially offsets SFC benefit due to higher OPR.
- Increase compressors exit temperature $P_3$ → last stages material.
- Compressors stage count → weight, length, overall dimensions.
- Hot air takeoff → increased relative airflow amount.
Thermal Efficiency ($\eta_{th}$)
Modify Thermal Cycle - Intercooled Engines

The compressed air is bled of the combustor case. It is lead through the heat exchanger matrix and cooled by bypass air. Partially or fully bypass of the heat exchanger, control the cooling air temperature. The cooled air is then delivered to the compressor rear cone and the HPT airfoils.

Heat exchanger (intercooler) between primary and secondary airflow

Intercooler integration challenges:
- Dimensions, weight, severe architecture modification
- Pressure losses (can offset benefit)
- Mostly valid for high thrust class engines
Compression air cooling, at constant pressure

\[ T_3 = \text{High pressure compressor (HPC) exit temperature} \]
\[ P_3 = \text{High pressure compressor (HPC) exit pressure} \]
Thermal Efficiency ($\eta_{th}$)
Modified Combustor & Turbine Cooling System

Overall combustor requirements

High pressure turbine cooling arrangement and effectiveness
Propulsive Efficiency ($\eta_{pr}$)
Fan Pressure Ratio (FPR) vs. Bypass Ratio (BPR)

The propulsive efficiency is dominated by the capability of the low pressure fan system to accelerate a lot of air slowly, thereby minimizing shear layer losses and reduce noise emissions. Therefore, increase fan blade diameters (“more air”) and reduce fan pressure ratio (“slower”). However, low FPR requires higher BPR to maintain thrust performance.

- Best propulsive efficiency can only be achieved through FPR 1.02 to 1.2
- For BPR > 20, fan pressure ratio (FPR) influence on propulsive efficiency is very small

$F_N = W \times \Delta V$
$F_N \rightarrow$ Constant requirement
$W \rightarrow$ Need for increased mass flow
$\Delta V \rightarrow$ Decreased for better propulsive efficiency (decreasing airflow velocity is achieved through fan pressure ratio FPR reduction)
Propulsive Efficiency ($\eta_{pr}$) Bypass Ratio (BPR) vs. Fan Blade Diameter

Fan airflow rate is limited
→ Need for higher fan blade diameters to increase BPR

Engine front section increased
→ Propulsion power system (PPS) drag increase

Centrifugal constraints (fan blade containment)
→ Increase fan module mass

Fan module weight and drag penalties are significant increased for BPR greater than 15
Propulsive Efficiency ($\eta_{pr}$)
Conventional Propeller vs. Counter Rotating (CR) Dual Propellers

**Counter-rotating dual propellers advantages:**
- $2^{nd}$ rotor improves propulsive efficiency
- Higher overall pressure ratio (OPR)
  - Lower diameters
  - lower required airflow rate while maintaining high bypass ratio (BPR)

**Single propeller weaknesses:**
- Low airflow capability
  - Required high diameters
- Poor efficiency at high flight velocity
  - Required high flight velocity specific design

![Graph showing propulsive efficiency comparison between CR Dual propellers and Single propeller.](image)
Overall Propulsion Efficiency ($\eta_{thp}$)
Open-Rotor (Un-Ducted Fan) vs. Turbofan

Open-rotor engines provide better fuel efficiency but are significantly noisier than turbofans.
E-Thrust - “hybrid” electric propulsion system combined of electric fans and battery charged by an onboard gas power unit.

**Year 2040**

**Blended Wing Body (BWB)**

The Ultra Green Intermediate Range (300-Seat)

- Ducted aft-fan engine
- Counter-rotating turbofan (CRTF) engine
- Open-rotor engine

30% reduction in “wetted” surface area

Gas Turbine Engine Road Map

- High bypass ratio turbofan
- Ultra high bypass ratio advanced turbofan
- Counter rotating turbofan engine
- Open rotor

Today 2016 2019 2025 2035+

Entry into Service target

Disruptive HP cores, engine integration to fuselage, …