# FUEL CONSUMPTION DUE TO SHAFT POWER OFF-TAKES FROM THE ENGINE

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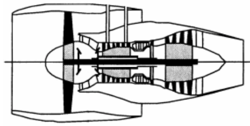

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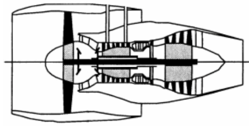
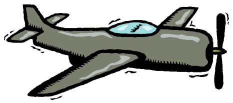


# Research Question

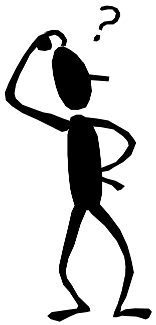


- Aircraft **performance** and **direct operation cost** (DOC) estimation depending on subsystems (design):

  Knowledge of ΔSFC due to secondary power (shaft power / bleed air)

  needed for:

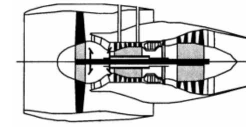
- Aircraft sub-systems benchmark: architecture trade-off between:
  - **power demand**
  - **weight**
  - initial & maintenance costs
  - safety & reliability





- Future trends due to advanced engine technology level and raised secondary power demand

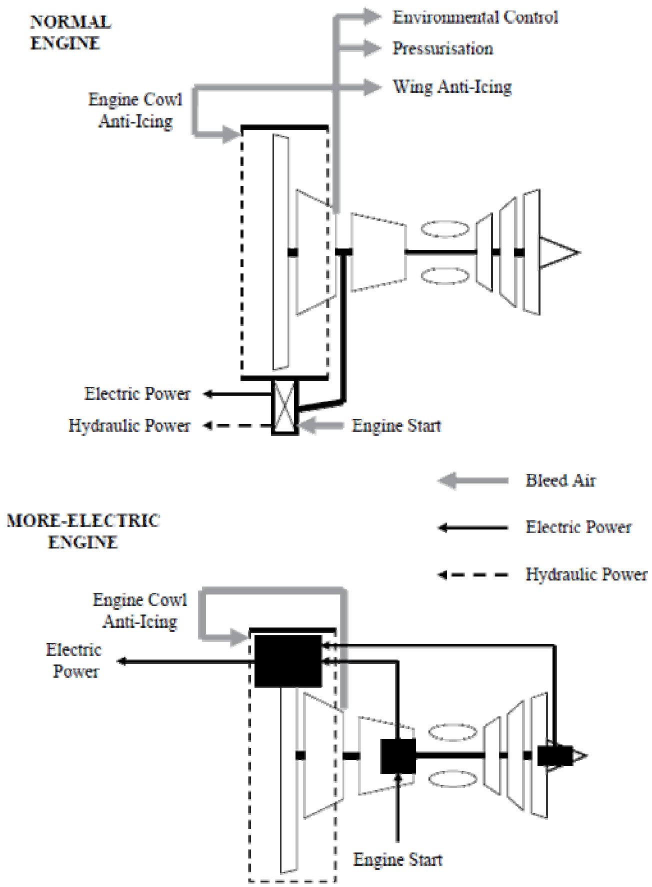
- **Target: Wide-range valid ΔSFC estimation model with *"as few as possible"* significant input parameters**



# Secondary Power Off-Takes

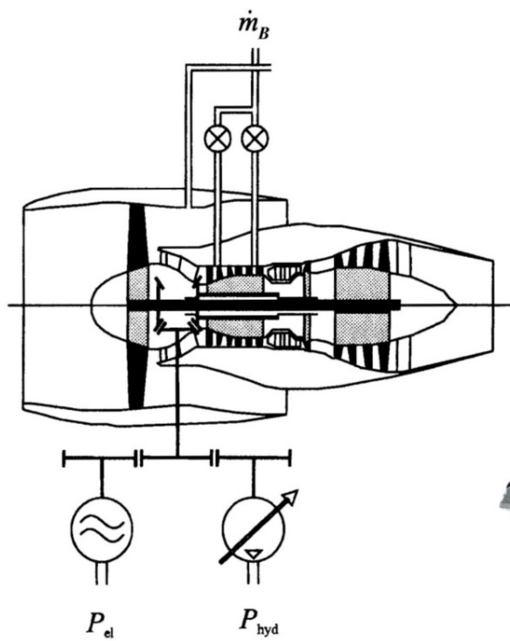
- Two off-takes sources:

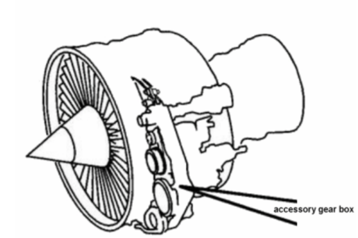
**Bleed air** or **Shaft power**



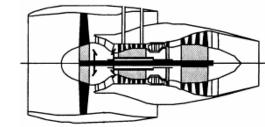

High-Power demanding systems:

- ECS (bleed air)
- Anti-ice (bleed air, el.)
- Cabin: IFE, Galley (el.)
- Control Actuator System (shaft, el.)
- Cockpit & Flight Control System (el.)



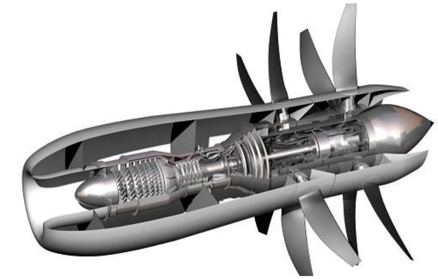



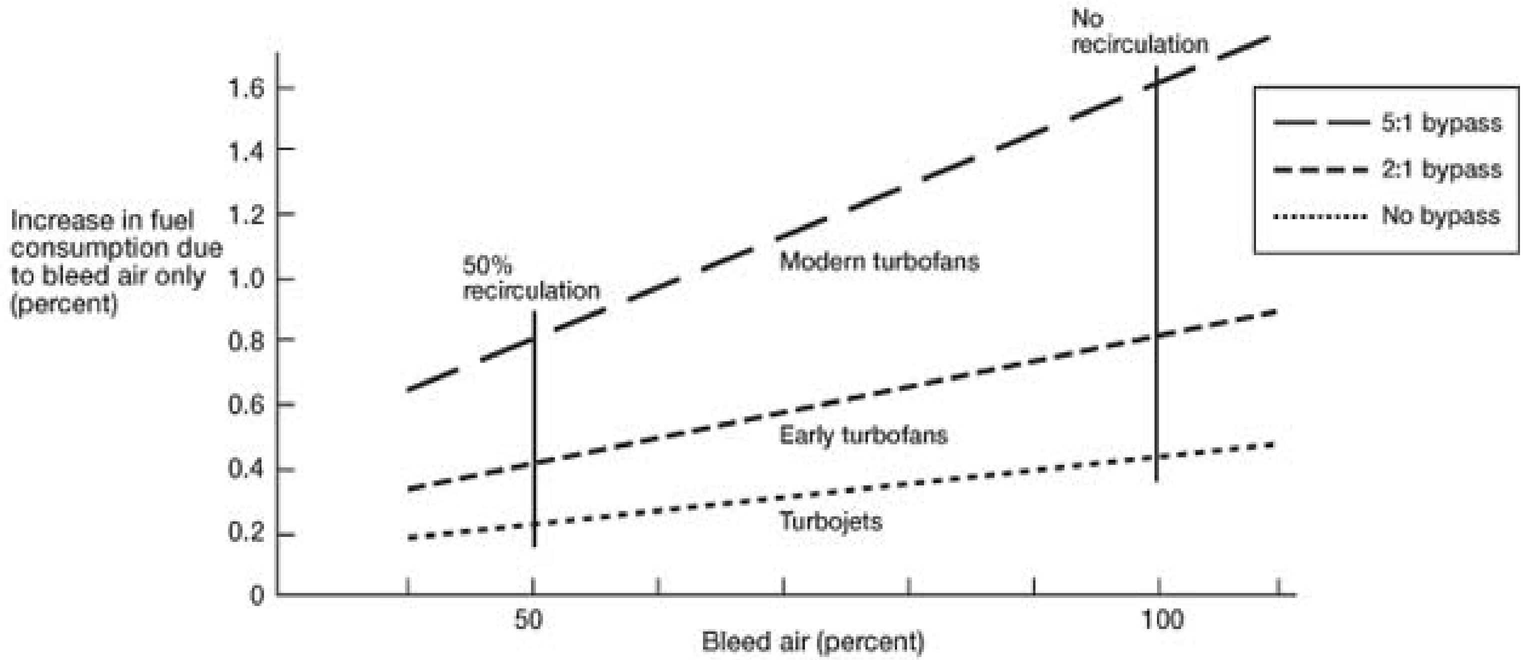

external accessory gearbox



# Literature: Power Off-Takes

- Increased influence of ΔSFC due to secondary power off-takes:
  ECS (bleed air) influence on different engine technology designs

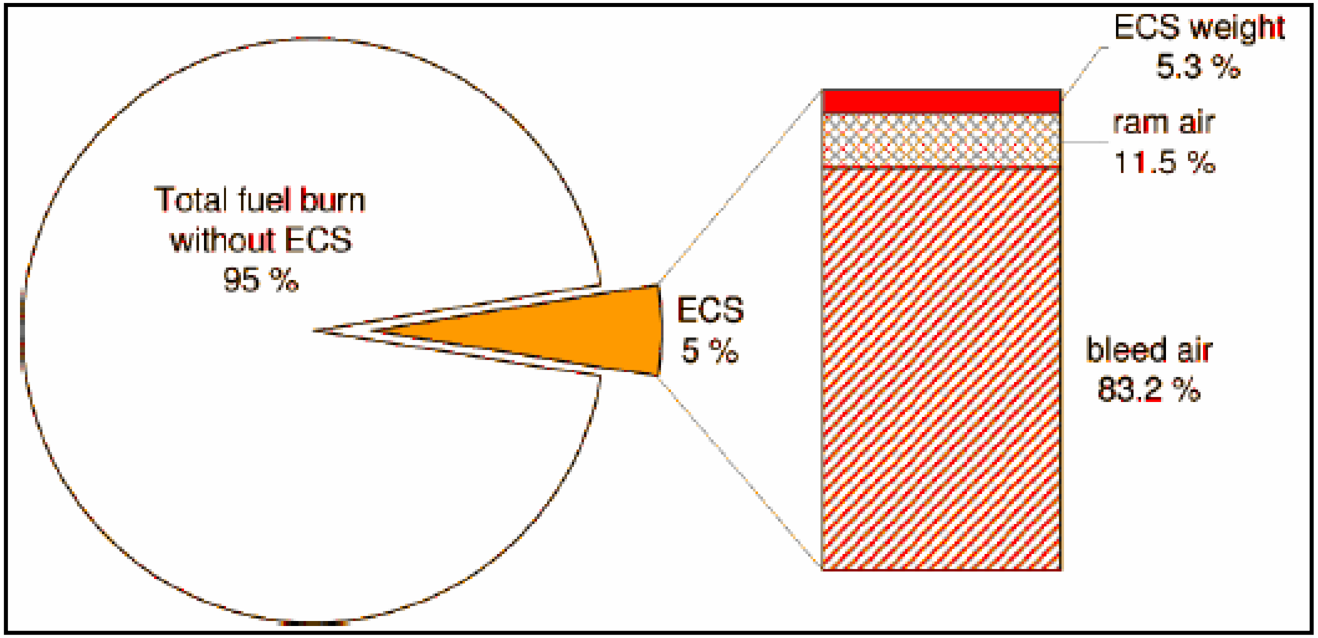





NOTE: Fuel consumption based on average performance for two engines at continuous cruise.

# Literature: Power Off-Takes

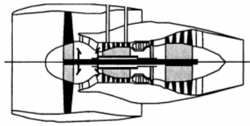
- Example: Fuel burn due to conventional ECS system:
  - **bleed air (83%)**
  - ram air (12%)
  - system weight (5%)



# Literature: Power Off-Takes

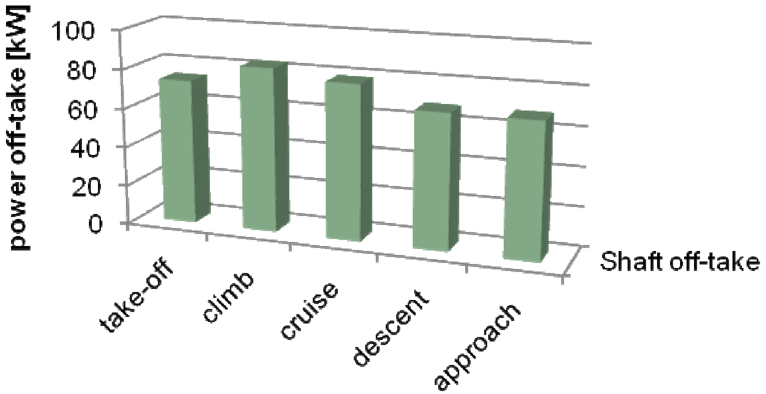
- Future secondary power demand trends:

| **Secondary power demand lowering effects** | **Secondary power demand increasing effects** |
|---|---|
| More efficient sub-systems (mainly due to feedback control power adaption) | Higher comfort level:<br>• IFE (power consumption)<br>• Cabin pressure level |
| Electric <u>**de-**</u>/anti-ice systems instead of bleed anti-ice system | High density seat configuration |
| | Enhanced safety assessment (e.g. anti-ice active in cruise ) |
| | Higher BPR of the engines → less core flow → higher adverse effects → limitation of bleed air amount |

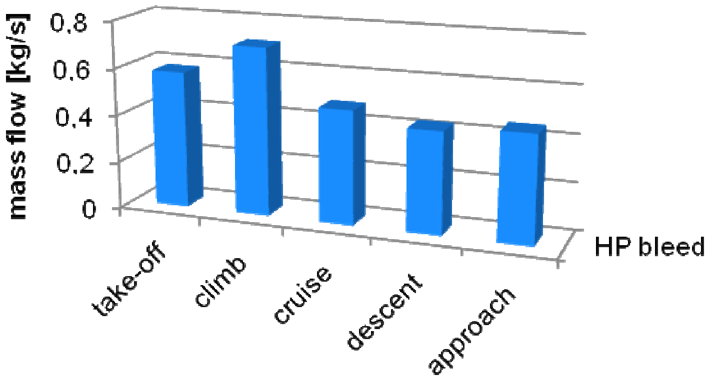


# Measurements: A320 Power Off-Takes

| Thrust rating | | Shaft power off-take [kW] | Max. bleed air off-take from fan [kg/s] | Max. bleed air off-take from HP compressor [kg/s] |
|---|---|---|---|---|
| take-off | (to 1500 ft) | 73.8 | 0.463 | 0.579 |
| climb | (to 31000 ft) | 83.5 | 0.308 | 0.710 |
| cruise | (in 31000 ft) | 79.0 | 0.186 | 0.481 |
| descent | (to 1500 ft) | 68.6 | 0.332 | 0.429 |
| approach | | 68.6 | 0.453 | 0.453 |

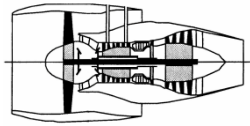



| Thrust rating | Fuel [kg]: no off-takes | Fuel [kg]: max. shaft power no bleed air | Fuel [kg]: no shaft power max. bleed air | Fuel [kg]: max. shaft power max. bleed air |
|---|---|---|---|---|
| take-off | 71 | 71 | 72 | 72 |
| climb | 491 | 496 | 501 | 505 |
| cruise | 1504 | 1528 | 1542 | 1565 |
| descent | 54 | 55 | 57 | 57 |
| approach | 7 | 7 | 8 | 8 |
| total fuel | 2127 | 2157 | 2180 | 2207 |
| off-take fuel | | 30 | 53 | 80 |
| **relative off-take fuel** | | **1.4 %** | **2.5 %** | **3.8 %** |




- Engine limitations:

  V2527-A5 shaft power limit: 131 [kW] (total)



# $k_P$ versus $k_P$* Approach

## “Classic” $k_P$ definition:

$$k_P = \frac{\Delta SFC / SFC}{P / T}$$

$$with\ k_P \approx 0.002 \left[\frac{N}{W}\right]$$

$$\dot{m}_{F,P} = k_P \cdot SFC \cdot P$$

## Scholz $k_P$* approach:

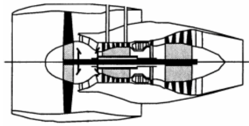
$$k_P{}^* = \frac{\Delta SFC / SFC}{P / T_{TO}}$$

$$with\ k_P^* \approx 0.0094 \left[\frac{N}{W}\right]$$

$$\dot{m}_{F,P} = k_P{}^* \cdot \frac{T}{T_{TO}} SFC \cdot P$$

$$k_P = k_P{}^* \cdot \frac{T_{req}}{T_{TO}} \approx k_P{}^* \cdot 0.2$$

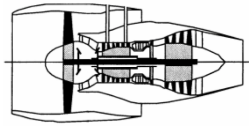
A $T_{req}/T_{TO}$ of 0.2 is valid in cruise condition only.
The cruise sector time is dominant, therefore
$k_P$ is usually given for cruise conditions.



# Literature Summary: Values for $k_P$ Factor

| Author / organization / engine | Source | Shaft power Specific Fuel Consumption $SFC_P$ [kg/(kW·h)] | Engine Specific Fuel Consumption $SFC$ [kg/(N·s)] | Shaft power factor $k_P$ [N/W] |
|---|---|---|---|---|
| SAE | [21] | 0.304 | $4.25 \cdot 10^{-5}$ | 0.00199 |
| CF6-80C2 | [2] [14] | 0.125 | $1.64 \cdot 10^{-5}$ | 0.00212 |
| EPI TP400-D6 | [2] [15] | 0.167 | $1.07 \cdot 10^{-5}$ | 0.00434 |
| SCHOLZ [1, 4] | [17] | | | see (15): ≈ 0.00188 |
| YOUNG [2] | [24] | | | |
| Trent 775 [4] | [23] | | | 0,00204 |
| CF6-80C2-A2 [4] | [23] | | | 0,00177 |
| CFM-56-5C-2 [4] | [23] | | | 0,00182 |
| RB211-22 [4] | [12] | | | 0,00182 |
| RB211-535E4 [5] | [24] | | | 0,00177 |
| Trent 772 [5] | [24] | | | 0,00147 |
| AHLEFELDER [3, 5] | [1] | | | new evaluation: |
| 3 shafts, mixed nozzle | | | | 0.00296 |
| 3 shafts, unmixed nozzle | | | | 0,00213 |
| 2 shafts, mixed nozzle | | | | 0,00226 |
| 2 shafts, unmixed nozzle | | | | 0,00308 |
| DOLLMAYER [3] | [7] | | | LP shaft: 0.00256<br>HP shaft: 0.00320 |
| LAWSON | [10] | | | |
| BR 715-38 | | | | 0.00175 |
| Adour | | | | 0.00175 |
| **Average** | | 0.199 | | **0.00226** |

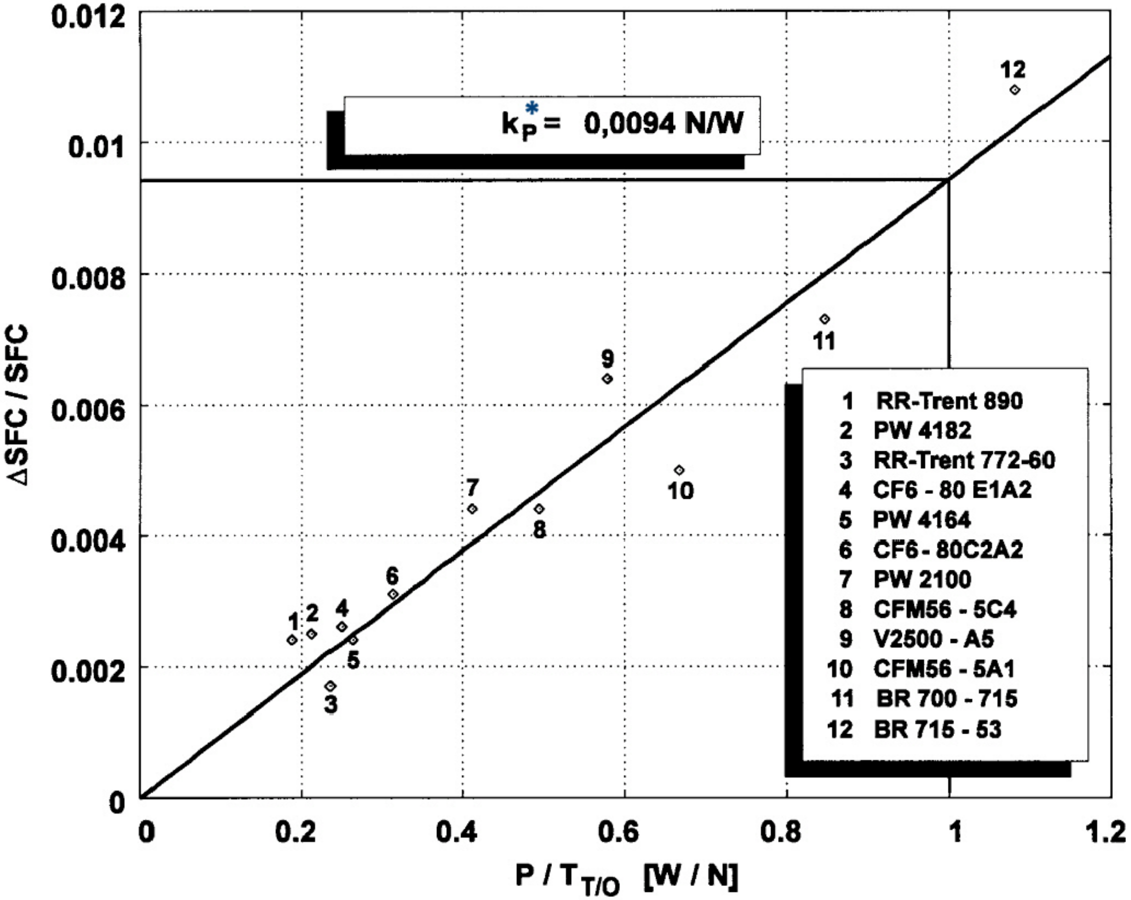
1 data from engine decks, average of different altitudes and Mach numbers
2 data generated with TURBOMATCH (Chapter 5)
3 data generated with GasTurb [8]
4 data generated at maximum cruise thrust
5 data generated at normal cruise thrust

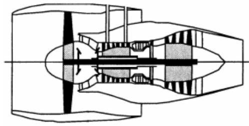


# $k_P$* Value of Different Engines

- Valid for wide range of engine $T_{TO}$

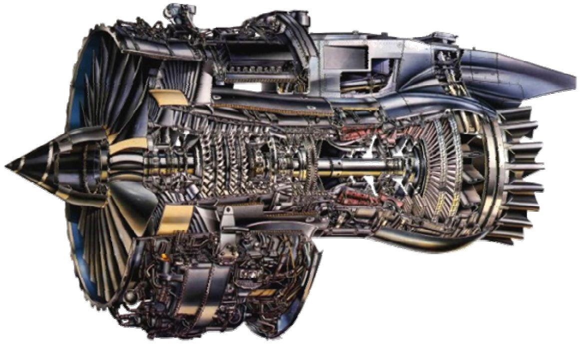
$$k_P{}^* = \frac{\Delta SFC / SFC}{P / T_{TO}}$$





# Jet Engine Shaft Power Off-Take Performance Model

- Used tool: TURBOMATCH (Cranfield University)
  - “0-D-simulation” tool (comparable to GasTurb, GSP)
  - based on component efficiency/operation point performance maps
  - Analyze of design point and off-design conditions



**Examined engine**

- 3 spool engine:

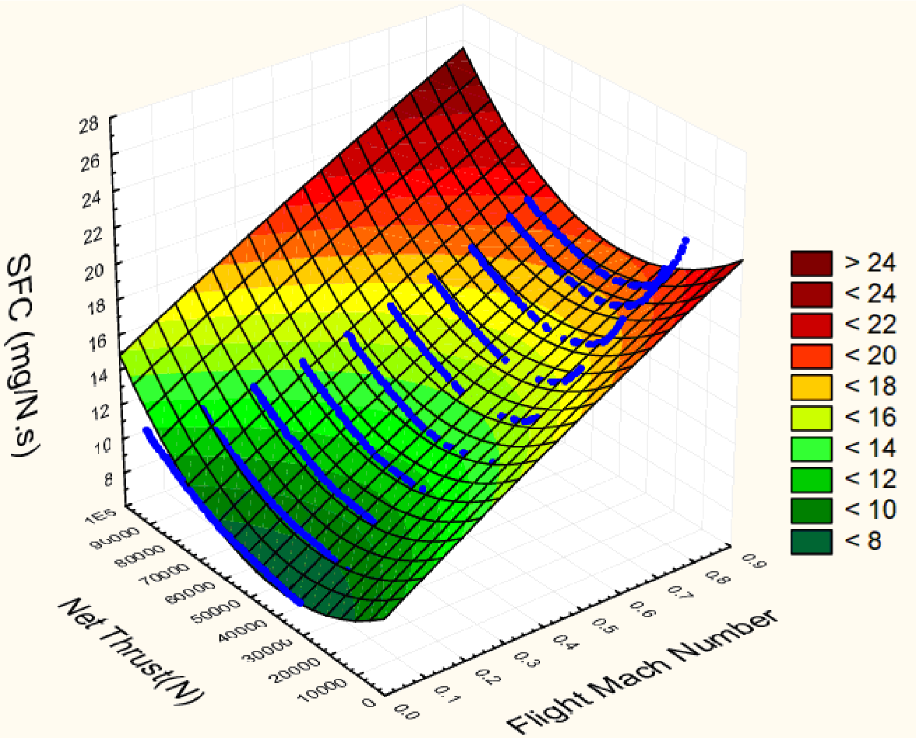
| Rolls-Royce | RB211-524D4 |
|---|---|
| application | B747-200<br>B747-300 |
| BPR | 5.0 [-] |
| OAPR | 29.5 [-] |
| FREF | 231 [kN] |
| SFC | ca. 0.392 [lb/lbf/h] |

- model parameter deviation < 5% of published engine data
- shaft power off-take on LP spool

# Model Investigation: Reference SFC Performance Map

**Parameter deviation:**

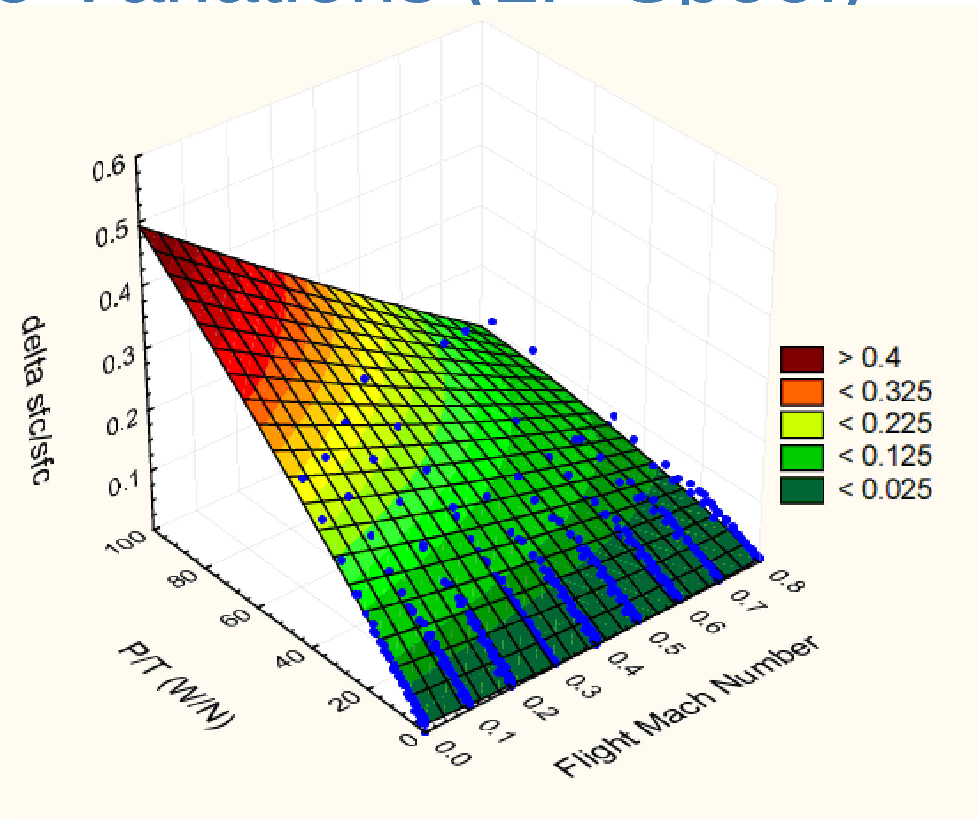
- Altitude 0; 5,000; 10,000m
- M = 0…0.8
- Turbine inlet temperature: 1100K…1600K
  - → Total mesh size: 64 points
- **Engine control: constant turbine entry temperature [K]**
- Shaft off-take: 0…1600 kW
  - → thrust deviation



altitude: 10.000m

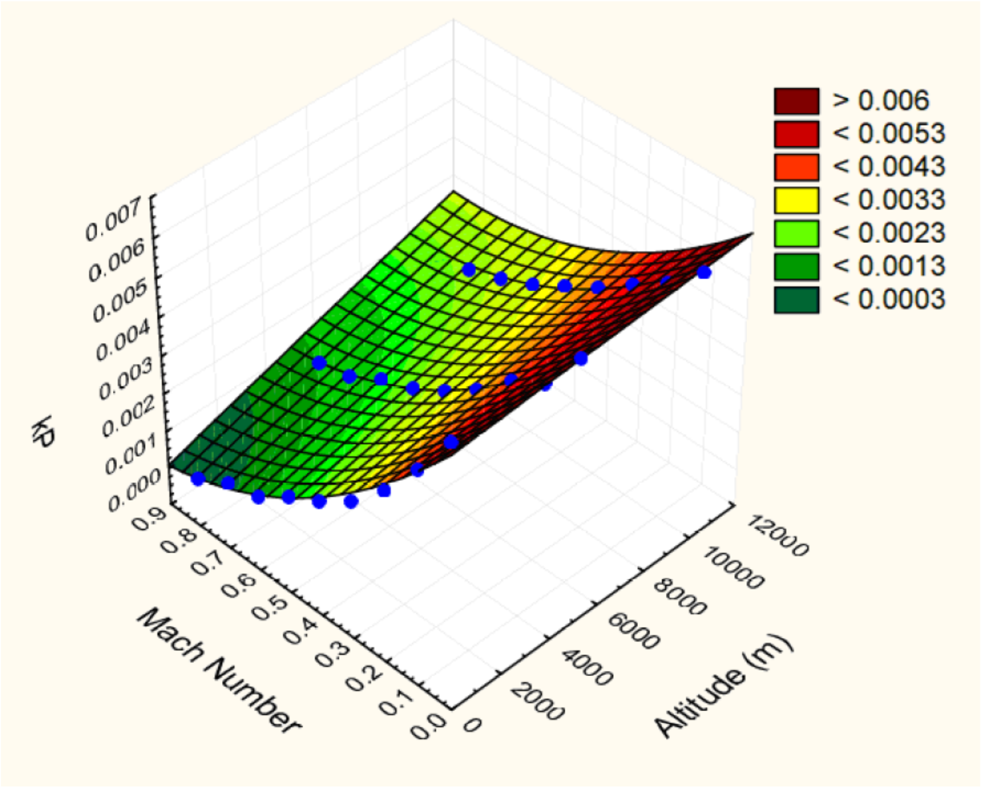
# Shaft Power Off-Take Variations (LP Spool)

- Almost linear behavior of ΔSFC against power off-take ratio at flight condition
- Slope is a result of the absolute SFC value at the flight condition and the shaft off-take efficiency




data for flight altitude of 5000m

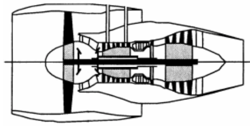
# Proposed Unified Equation for Estimation of Fuel Consumption due to Power Off-Takes (1/3)



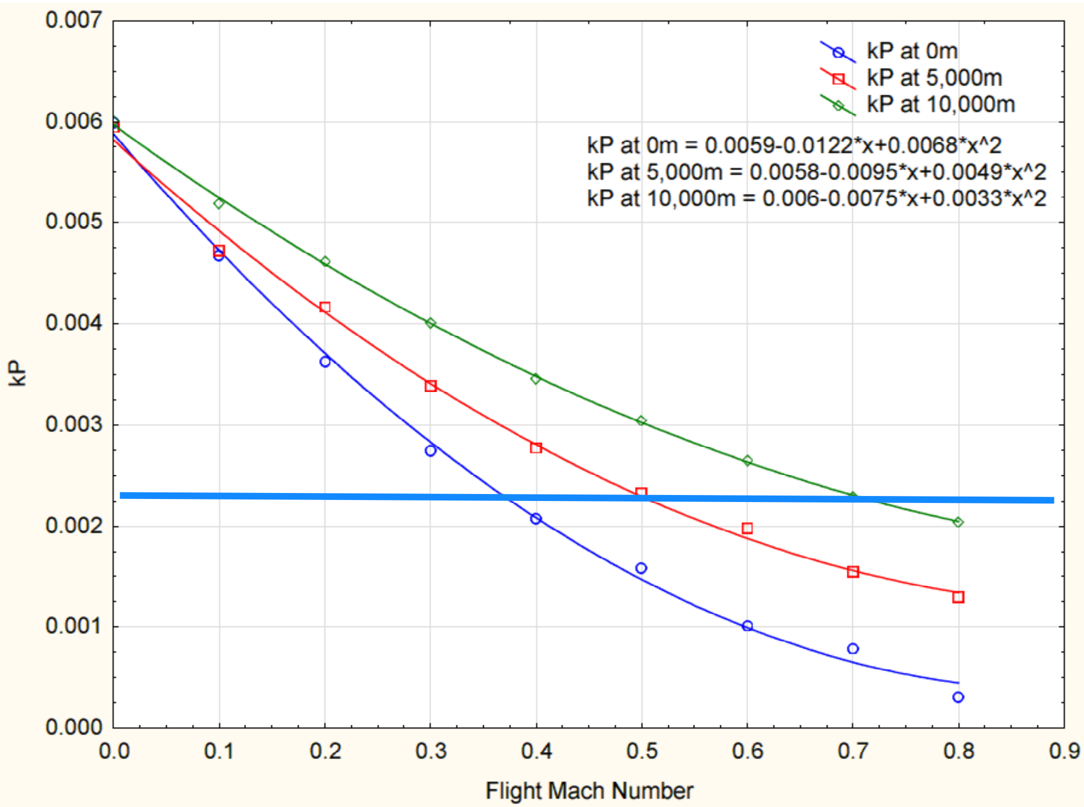

Unified $k_P$ factor as function of **Mach number** and **altitude** calculated using RB211-524-D4 engine

$$\dot{m}_{F,P} = k_P \cdot SFC \cdot P$$

$$k_P = 0.0057 + 4.60 \cdot 10^{-8} \frac{1}{\mathrm{m}} h - 0.0106\, M - 4.44 \cdot 10^{-13} \frac{1}{\mathrm{m}^2} h^2 + 1.85 \cdot 10^{-7} \frac{1}{m} h \cdot M + 0.0049\, M^2$$



# Proposed Unified Equation for Estimation of Fuel Consumption due to Power Off-Takes (2/3)




Unified $k_P$ factor as function of Mach number and altitude calculated using RB211-524-D4 engine

$$\dot{m}_{F,P} = k_P \cdot SFC \cdot P$$

$$k_P = a(h)\,M^2 + b(h)M + c(h)$$

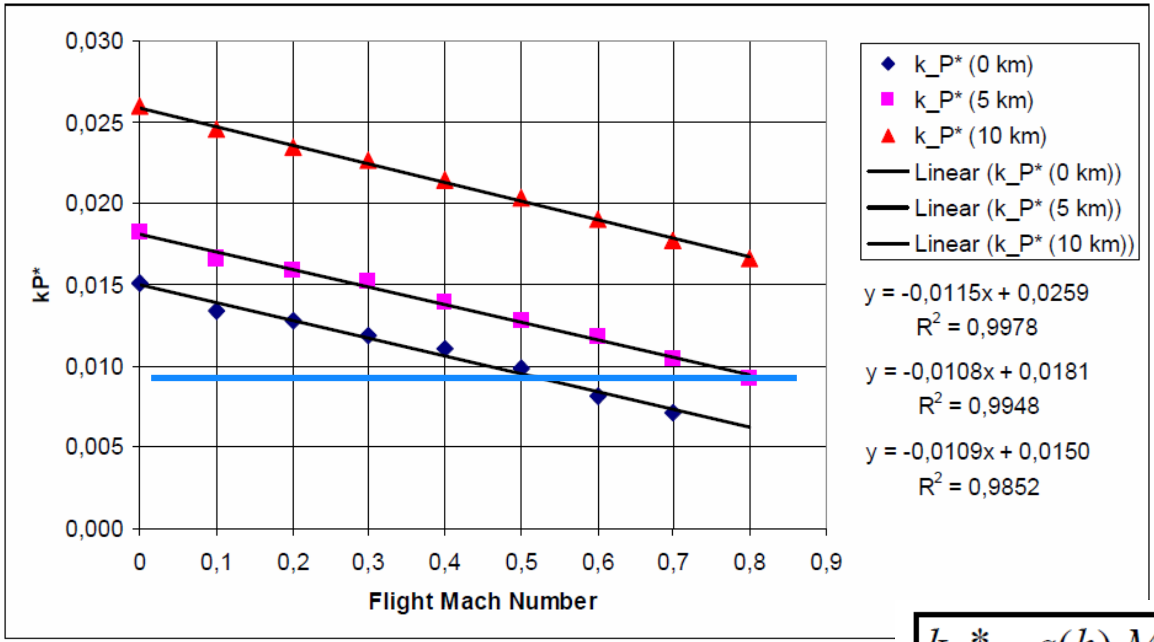
with

$$a(h) = -3.5\cdot 10^{-7}\,\frac{1}{\mathrm{m}}\,h + 6.75\cdot 10^{-3}$$

$$b(h) = 4.7\cdot 10^{-7}\,\frac{1}{\mathrm{m}}\,h - 1.208\cdot 10^{-2}$$

$$c(h) = 1.0\cdot 10^{-8}\,\frac{1}{\mathrm{m}}\,h + 5.85\cdot 10^{-3}$$

# Proposed Unified Equation for Estimation of Fuel Consumption due to Power Off-Takes (3/3)




Unified $k_P$* factor as function **of Mach number** and **altitude** calculated using RB211-524-D4 engine.

$$\dot{m}_{F,P} = k_P{}^{*} \cdot \frac{T}{T_{TO}} SFC \cdot P$$

$$k_P{}^{*} = a(h)\,M + b(h)$$

with

$$a(h) = -6.0 \cdot 10^{-8} \frac{1}{\mathrm{m}} h + 1.08 \cdot 10^{-2}$$

$$b(h) = 9.4 \cdot 10^{-11} \frac{1}{\mathrm{m}^2} h^2 + 1.5 \cdot 10^{-7} \frac{1}{\mathrm{m}} h - 1.5 \cdot 10^{-2}$$

# Why calculating $\Delta$SFC related to $k_P$ respectively $k_P^*$?

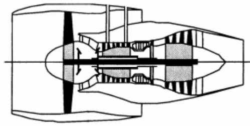
**Benefits:**

- Universal: engine technology/efficiency already captured in SFC
- Good agreement with simulations:
  SFC rise linear in common off-take power/thrust ratios (to be shown in case of bleed air)
- SFC often known
- Good knowledge of SFC alterations with the flight conditions
- Simplicity favorable for case-studies/conceptual design

$$\dot{m}_{F,P} = k_P \cdot SFC \cdot P$$

$$\dot{m}_{F,P} = k_P^* \cdot \frac{T}{T_{TO}} SFC \cdot P$$

→ *SFC based shaft power off-take penalty estimation seems to be a good way of representation*



# Insert: SFC Estimation

fidelity

- Engine deck data
- simulation tools (e.g. GasTurb, GSP)
- Thermodynamic/physics calculation
- Statistical/Empirical estimation methods; e.g. updated Torenbeek

- in combination with Breguet, SAE AIR 1168/8 or mission simulation

→ **mission fuel estimation / fuel weight penalty**

$$SFC = \frac{0.697\sqrt{\frac{T(h)}{T_0}}\left(\phi - \vartheta - \frac{\chi}{\eta_{comp}}\right)}{\sqrt{5\,\eta_{noz}\,\left(1+\eta_{fan}\,\eta_{turb}\,BPR\right)\cdot\left(G + 0.2\,M^2\,BPR\,\frac{\eta_{comp}}{\eta_{fan}\cdot\eta_{turb}}\right)} - M\,(1+BPR)}$$

$$G = \left(\phi - \frac{\chi}{\eta_{comp}}\right)\cdot\left(1 - \frac{1.01}{\eta_{gasgen}^{\frac{\gamma-1}{\gamma}}\cdot(\chi+\vartheta)\cdot\left(1-\frac{\chi}{\phi\cdot\eta_{comp}\cdot\eta_{turb}}\right)}\right)$$

$$\vartheta = 1 + \frac{\gamma-1}{2}\cdot M^2 \;;\quad \phi = T_{TE}/T(h) \;;\quad \chi = \vartheta\cdot\left(OAPR^{\frac{\gamma-1}{\gamma}} - 1\right) \;;\quad \eta_{gasgen} = 1 - \frac{0.7M^2(1-\eta_{inlet})}{1+0.2M^2}$$

Turbine entry temperature in cruise: $T_{TE} = \frac{-8000\text{ K}\cdot\text{kN}}{T_{TO}} + 1520\text{ K}$

$$OAPR = 2.668\cdot 10^{-5}\;1/\text{kN}\cdot T_{TO} + 3.517\cdot BPR + 0.05566$$

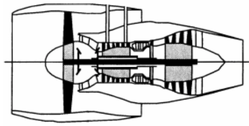
$$\eta_{comp} = \frac{-2\text{ kN}}{2\text{ kN} + T_{TO}} - \frac{0.1171}{0.1171 + BPR} - M\cdot 0.0541 + 0.9407$$

$$\eta_{turb} = \frac{-3.403\text{ kN}}{3.403\text{ kN} + T_{TO}} + 1.048 - M\cdot 0.1553$$

$$\eta_{inlet} = 1 - (1.3 + 0.25\,BPR)\cdot \Delta p/p$$

$$\eta_{fan} = \frac{-5.978\text{ kN}}{5.978\text{ kN} + T_{TO}} - M\cdot 0.1479 - \frac{0.1335}{0.1335 + BPR} + 1.055$$

→ **Target:** SFC as a function of PR, TET, BPR and $T_{TO}$ (representing engine technology level and scale)



# Shaft Power Off-Take Efficiency

- Shaft power off-take efficiency:

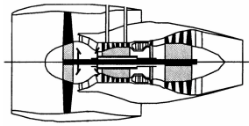
$$\eta_P = \frac{P}{\dot{m}_{F,P} \cdot H} = \frac{1}{k_P \cdot SFC \cdot H} = \frac{1}{0.002 \cdot 16 \cdot 42.5} = 74\,\%$$

- Compare with Carnot/Ericsson/Ackerer-Keller cycle
- Praxis values:
  - Stationary ”combined cycle” (gas & steam turbine): ≈ 0.58
  - Stationary gas turbine: ≈ 0.38
  - Aviation turboprop shaft power (A-400M) with $SFC_{shaftP}$ = 0.167 [kg/kWh] but $SFC_{propP}$ = 0.213 [kg/kWh]

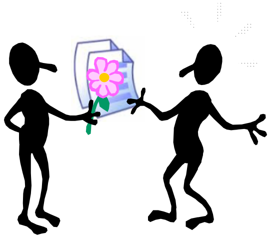
    Shaft power off-take better than (turbo-prop) shaft power?

- Possible explanation for unexpected high efficiency:

  Off-Take is only small amount of total engine power and does not change much the way the engine works



# Conclusion



- ✓ Fuel consumption due to shaft power off-take calculation:

$$\dot{m}_{F,P} = k_P \cdot SFC \cdot P$$

$$k_P = 0.0057 + 4.60 \cdot 10^{-8} \frac{1}{\mathrm{m}} h - 0.0106\, M - 4.44 \cdot 10^{-13} \frac{1}{\mathrm{m}^2} h^2 + 1.85 \cdot 10^{-7} \frac{1}{m} h \cdot M + 0.0049\, M^2$$

- ✓ Main result is the shaft power factor $k_P$ found to be in the order of 0.00225 N/W
- ✓ Simulation $k_P$ results matches well with average of literature values
- ✓ Linear SFC rise behavior within reasonable shaft power off-takes
- ➢ Unexpected high resulting efficiency value (*explanation still missing*)
- ➢ Future action:
  - Simulations with additional tools
  - Bleed air off-take investigation and comparison with shaft power off-takes
  - Comparison with more measured values (?)

# FUEL CONSUMPTION DUE TO SHAFT POWER OFF-TAKES FROM THE ENGINE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Linköping University
expanding reality

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