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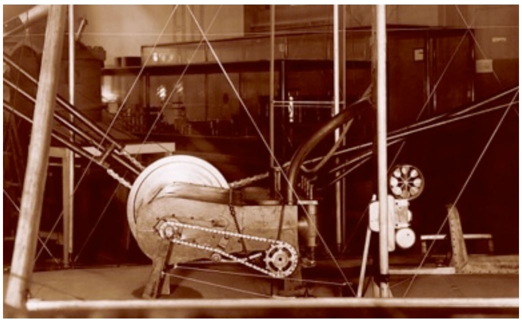
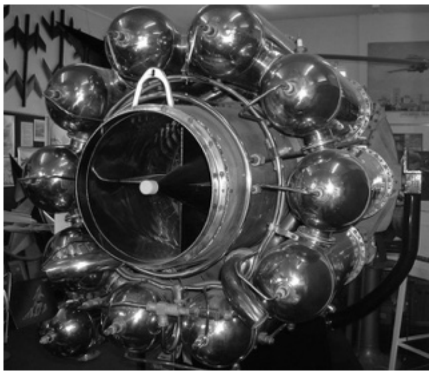
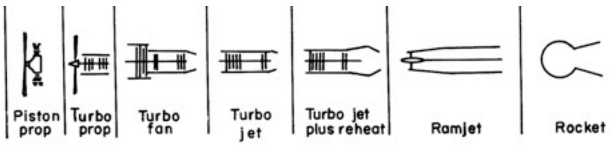


Characterisation of propulsion systems

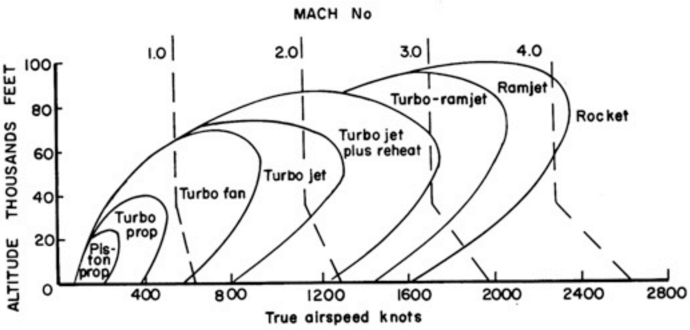


2

Powerplant selection



Nicolai

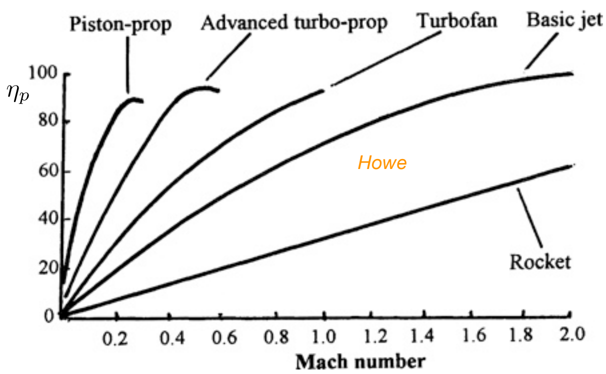


The choice of powerplant is primarily determined by the requirement for reasonable propulsive efficiency η_P at the Mach number regime of the dominant flight task (typically, cruise).

$$\eta_P = \frac{\text{available propulsive power}}{\text{total power transferred to air}} = \frac{2}{1 + V_j/V_\infty}$$

where V_j = average exhaust jet speed and V_∞ = flight speed. Mach number $M = V_\infty / a$.

For a constant propulsive efficiency (say 70% – 80%) it is evident that V_j must increase with flight speed, and it is this that determines the most appropriate type of powerplant.



Design Building Blocks

Rule-of-thumb guidelines for initial engine sizing

The key choice of basic type of propulsion for the class of aircraft has already been made based on target speed regime.

Ultimately, sizing the amount of installed propulsion capacity must be determined by balancing demands for performance and economy, which is attended to in developing the workable design.

But for the speculative design phase it is helpful to have guidelines in order to get an initial grasp of appropriate engine sizes/numbers. Use with caution.

Jet aircraft: T_0/W_0

Aircraft type	Typical installed T/W
Jet trainer	0.4
Jet fighter (dogfighter)	0.9
Jet fighter (other)	0.6
Military cargo/bomber	0.25
Jet transport (higher value for fewer engines)	0.25–0.4

Raymer

Dominant Mission Requirement	Range for $(T/W)_{TO}$ (uninstalled)
Long range	0.2–0.35
Short and intermediate range with moderate field length	0.3–0.45
STOL and utility transport	0.4–0.6
Fighter—close air support	0.4–0.6
Fighter—strike interdiction	0.45–0.7
Fighter—air-to-air	0.8–1.3
Fighter—interceptor	0.55–0.8

Nicolai & Carichner

Propeller aircraft: P_0/W_0

Aircraft type	Typical P/W hp/lb	{Watt/g}
Powered sailplane	0.04	{0.07}
Homebuilt	0.08	{0.13}
General aviation—single engine	0.07	{0.12}
General aviation—twin engine	0.17	{0.3}
Agricultural	0.09	{0.15}
Twin turboprop	0.20	{0.33}
Flying boat	0.10	{0.16}

Raymer

Initial estimate of installed engine size

Basic engine sizing guesses typically come from cruise thrust (or power) requirements, with some allowance for increases in output required at takeoff. More complete analysis comes later.

e.g. recall: for steady, level flight $T = \dfrac{W}{C_L/C_D}$

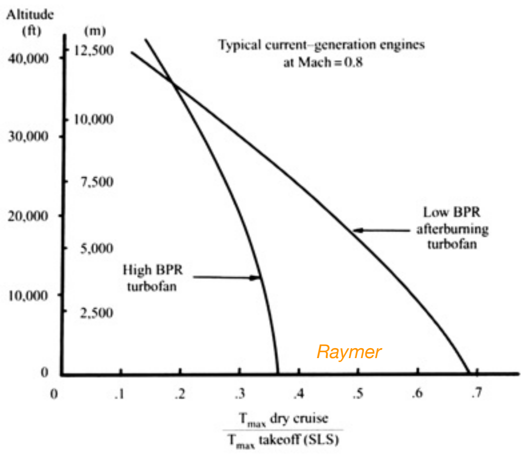
$$\left(\frac{T}{W}\right)_{\text{cruise}} = \frac{\alpha T_0}{\beta W_0} = \frac{1}{(L/D)_{\text{cruise}}}$$

Where T_0 and W_0 are respectively maximum rated sea-level thrust, and maximum take-off weight.

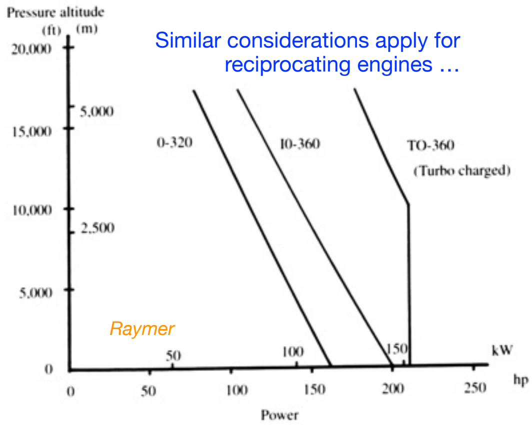
α is a thrust lapse ratio; depends on altitude and speed, bypass ratio…

β is aircraft weight fraction at (start of) cruise; accounts for fuel burned to reach cruise, O(0.95)

Indicative thrust lapse at cruise:



Similar considerations apply for reciprocating engines …



Example for civil transport aircraft

$$\left(\frac{L}{D}\right)_{\text{cruise}} \approx 0.866\left(\frac{L}{D}\right)_{\text{max}}$$

(Ignoring possible compressibility constraints…)

so for $\left(\frac{L}{D}\right)_{\text{max}} = 20,\quad \left(\frac{L}{D}\right)_{\text{cruise}} \approx 17.32$

$$\left(\frac{T}{W}\right)_{\text{cruise}} = \frac{1}{17.32} = 0.0577$$

From chart, $\alpha = \dfrac{T_{\text{cruise}}}{T_0} \approx 0.195$

$$\beta = \frac{W_{\text{initial cruise}}}{W_0} \approx 0.956$$

reflects fuel burned to reach cruise

Hence $\dfrac{T_0}{W_0} = 0.0577 \times 0.965 \times \dfrac{1}{0.195} = 0.283$

(NB: right in the middle of the ranges suggested by Raymer and Nicolai & Carichner.).

Still need to estimate W_0 (e.g. from mission analysis).

The two basic powerplant types

Soon we turn to describing the key characteristics of propulsion systems from the viewpoint of aircraft performance analysis and need to consider

1. The thrust or power produced as a function of aircraft altitude and speed.
2. The mass flow rate of fuel consumed per unit thrust or power.

Engine thrust, or power? Which is more appropriate? We note that by definition the available power delivered by a powerplant, P_A, is simply related to the available thrust, T_A.

$$P_A = V_\infty T_A$$

But we find that having two distinct categories is useful.

For propeller driven aircraft, the shaft power, while dependent on altitude, is almost independent of aircraft speed, and the total available power (= shaft power × η_p) at cruise is also almost independent of aircraft speed at cruise. So <u>we work with power-based descriptions</u> for prop aircraft.

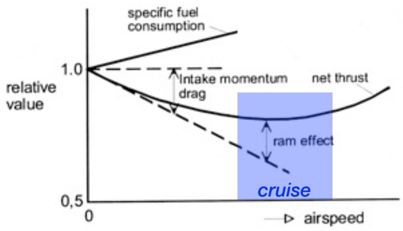
For jet driven aircraft, the available thrust initially falls linearly with airspeed, according to

$$\frac{T}{T_{V_\infty=0}} = \frac{V_j - V_\infty}{V_j} = 1 - \frac{V_\infty}{V_j} < 1$$

However there is a mitigating effect: inlet pressure (hence air density) rises with airspeed ('ram effect').

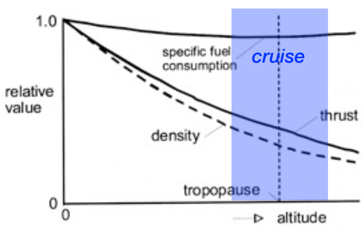
Overall, at cruise speeds, jet thrust is typically almost independent of airspeed, as is fuel consumption rate.

Effect of flight speed at constant altitude



Jet propulsion

Torenbeek & Wittenberg



Effect of altitude at constant flight speed

We <u>work with thrust-based descriptions</u> for jet aircraft.

7

Powerplant performance modelling

Approximation: jet engines at *cruise* speeds and altitudes provide *thrust* that is independent of airspeed, while piston engine/propeller combinations provide *power* that is independent of airspeed.

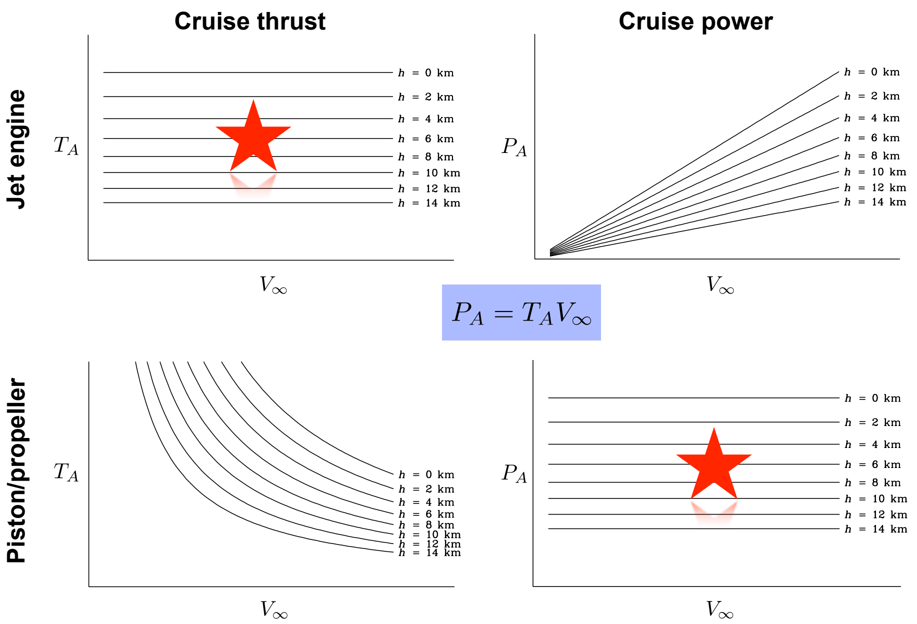
The logic for this is that the volume flow rate of air ingested (and fuel burnt) by a piston engine is nearly independent of airspeed, while for a jet engine it is nearly proportional to airspeed.

We will see that for jet engines, it will typically be simplest to deal with thrust characteristics while for piston/prop combinations, it will typically be simpler to deal with power (if the problem allows a choice).

The thrust and power production are also affected by altitude, mainly because the amount of oxygen available per unit volume of air falls with altitude.

Not shown here:

1. For jet engines, thrust falls with speed at low speeds (e.g. take-off).
2. For prop engines at low speeds, the maximum thrust is finite.
3. For prop engines at high speeds, compressibility effects limit thrust.
4. Effect of throttle variation.
5. Fuel consumption.



8

Total efficiency related to specific fuel consumption

One usually deals somewhat differently with powerplants rated on shaft power P_S (typically, propeller-powered aircraft), in which case propulsive (propeller) efficiency usually is broken out as a separate item, or on thrust T (typically, jet-powered aircraft), in which case it is not (propulsive efficiency is buried in specific fuel consumption). In either case, it is sometimes useful to consider the total efficiency.

For propeller-powered aircraft, $P_S \doteq \dfrac{\dot{m}_f}{c_p}$ (NB: different from specific excess power P_s.)

where c_p is the power-specific mass flow rate of fuel (dimensions: [mass/(power × time)])

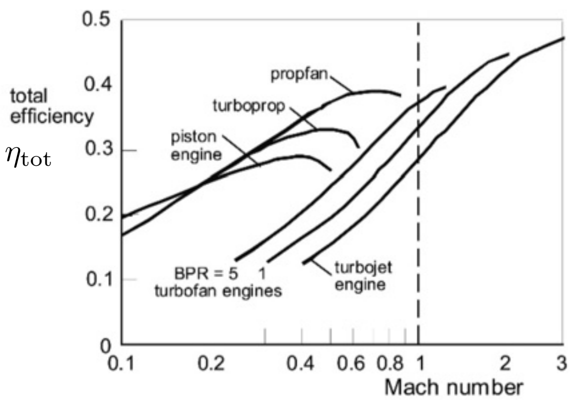
and the total efficiency is split up as $\eta_{\text{tot}} = \eta_{\text{pr}} \times \eta_{\text{th}}$ = propulsive efficiency × thermal efficiency

From $\eta_{\text{tot}} P_C = \eta_{\text{pr}} P_S \; (= TV)$ one finds $\eta_{\text{tot}} = \eta_{\text{pr}}/(c_p H)$

For jet-powered aircraft, $T \doteq \dfrac{\dot{m}_f}{c_t}$

where c_t is the thrust-specific mass flow rate of fuel (dimensions: [mass/(thrust × time)]).

From $\eta_{\text{tot}} P_C = TV$ one finds $\eta_{\text{tot}} = \eta_{\text{pr}} \times \eta_{\text{th}} = V/(c_t H)$



Torenbeek & Wittenberg

9

Powerplant performance modelling

For design purposes, we always need to relate the installed thrust or power, as described by the powerplant's maximum sea-level static thrust $\boldsymbol{T_0}$ or maximum sea-level static power, $\boldsymbol{P_0}$, to the amount the powerplant can deliver at any speed, altitude, throttle setting.

We will typically use the de-rating function α as a short-hand for this relationship.

$$T = \alpha T_0 \text{ (for jet engines)}$$

$$P = \alpha P_0 \text{ (for propeller engines)}$$

$$\alpha = \alpha(V, h, \text{throttle setting, engine design})$$

While the relationship may appear simple, it must be chosen with care as it buries a wealth of powerplant complexity and amounts to the designer's model for how the powerplant performs.

As such, it deserves detailed consideration and justification in design reporting.

It is typical to use different types of de-rating functions for different flight phases, often only takeoff, climb, and cruise (the primary cases).

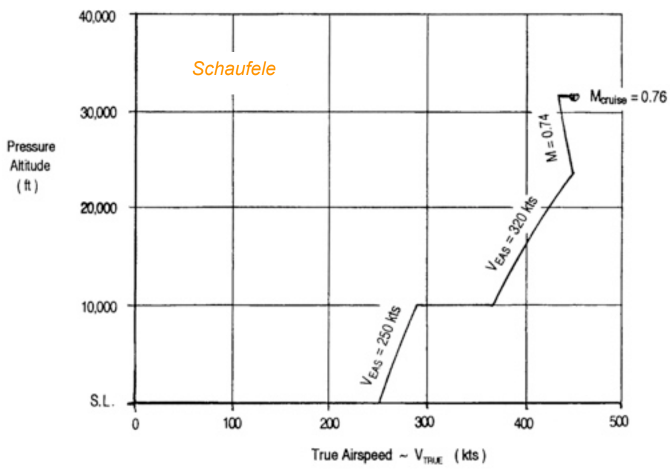


Fig. 8-7 Typical Jet Transport Climb Schedule

10

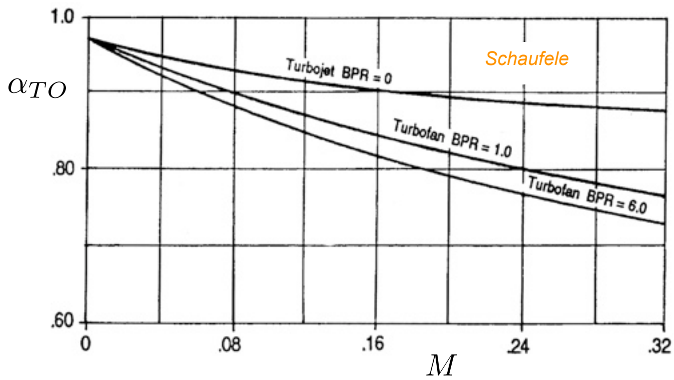
Characterisation of jet engines

For jet transport aircraft we are primarily concerned with finding α for **takeoff**, **climb**, and **cruise**.

For military/combat aircraft we may be also interested in short-term thrust for manoeuvres.

Take-off: engines are run at full rated thrust (full throttle) for short periods, usually near sea level (SL).

At low speed, jet thrust falls approximately linearly with speed, and the effect is stronger at higher bypass ratio (BPR), a.k.a. λ.



Note that the maximum value is approximately 0.97: this accounts for the fact that maximum installed thrust is typically less than the manufacturer's data, owing to losses incurred by inlet ductwork.

Torenbeek supplies a quasi-theoretical formula for these dependencies:

$$\alpha_{TO} = 1 - \frac{0.45(1+\lambda)}{\sqrt{(1+0.75\lambda)G}} M + (0.6 + 0.11\lambda/G)\, M^2$$

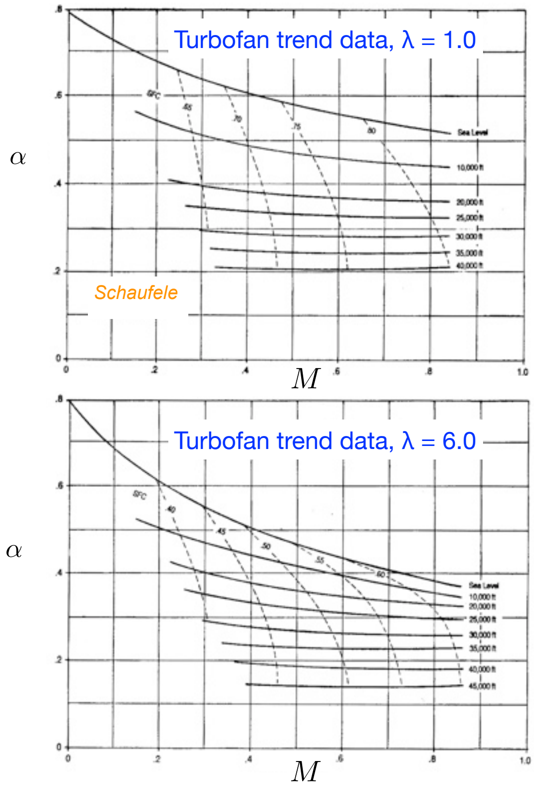
where 0.9< G <1.2.

To account for ducting/installation losses, derate this by a further factor of approximately 0.97.

Characterisation of jet engines

Cruise: engines are typically throttled back to achieve both longer life and better fuel efficiency.

Turbofan maximum cruise thrust is approximately independent of speed but falls with increasing altitude.

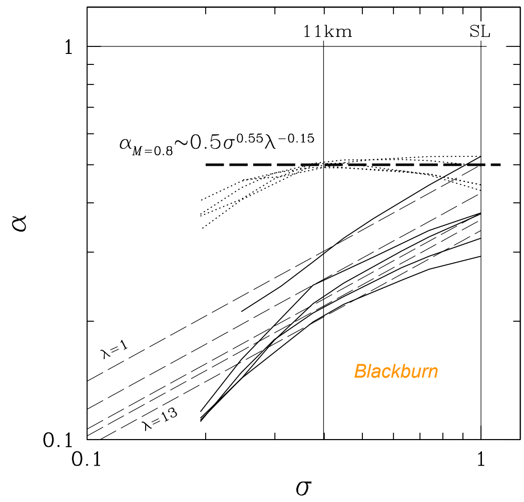


A correlation that does a reasonable job of fitting turbofan maximum cruise thrust near h = 11 km (typical jet cruise altitude) is

$$\alpha_{M=0.8} \simeq 0.5\sigma^{0.55}\lambda^{-0.15}$$

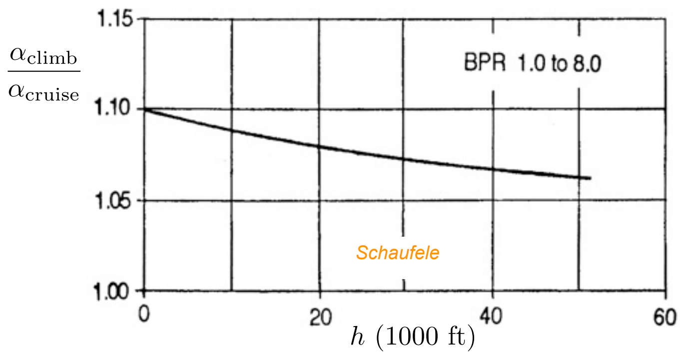
where $\sigma = \rho/\rho_0$ and $\lambda = \mathrm{BPR}$

Use this if no engine-specific data available.



Characterisation of jet engines

Climb: climb throttle setting is typically a little higher than for cruise. The correlation below also accounts for increased air density near sea level, compared to cruise heights.

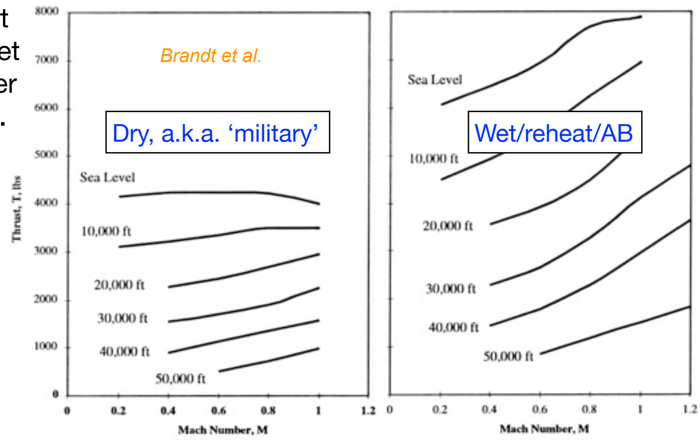


For combat aircraft, the maximum thrust for short periods is heavily dependent on engine design, inlet ductwork configuration, and whether an afterburner is to be used (which substantially increases TSFC).

Maximum thrust without afterburner is also called military thrust or 'dry' thrust.

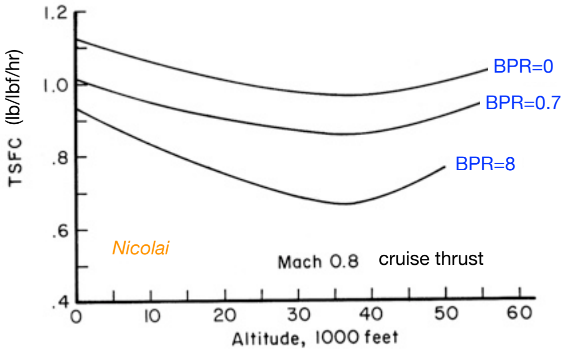
Maximum thrust with afterburner lit is also called thrust with reheat, afterburner, or 'wet' thrust.

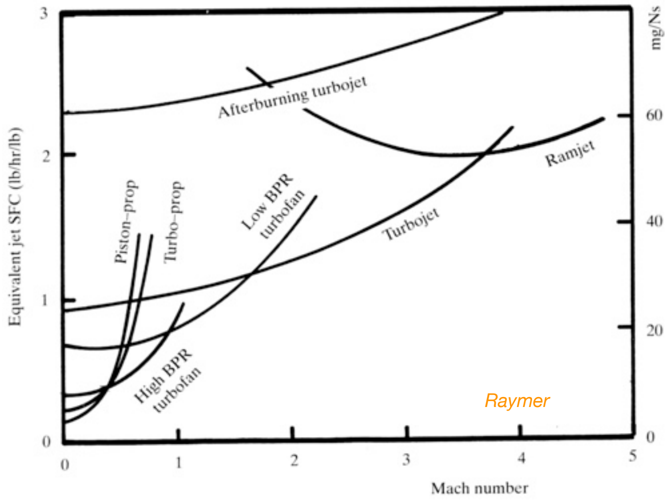
It's best to use appropriate performance curves rather than data correlations.



Characterisation of jet engines

We now turn to the issue of modelling thrust-specific fuel consumption, TSFC or c_t, for turbofan engines. Again this is a function of throttle setting, speed, altitude, BPR, etc.





Mattingly et al. supply correlations of form TSFC = $(C_1 + C_2 M^{1/2})\theta^{1/2}$. <u>Values have units of lb/lbf/hr, multiply by 28.33 to get mg/Ns.</u>
(mil power ⇒ dry, max power ⇒ wet)

$$\theta = T/T_0$$

High bypass ratio turbofan engine ($M < 0.9$):

$$TSFC = (0.45 + 0.54M_0)\sqrt{\theta}$$

Low bypass ratio mixed turbofan engine:

$$TSFC = (0.9 + 0.30M_0)\sqrt{\theta} \text{ mil power}$$

$$TSFC = (1.6 + 0.27M_0)\sqrt{\theta} \text{ max power}$$

Turbojet engine:

$$TSFC = (1.1 + 0.30M_0)\sqrt{\theta} \text{ mil power}$$

$$TSFC = (1.5 + 0.23M_0)\sqrt{\theta} \text{ max power}$$

For initial design purposes, we can alternatively take Raymer's values as sufficiently accurate:

Typical jet SFCs: 1/hr {mg/Ns}	Cruise	Loiter
Pure turbojet	0.9 {25.5}	0.8 {22.7}
Low-bypass turbofan	0.8 {22.7}	0.7 {19.8}
High-bypass turbofan	0.5 {14.1}	0.4 {11.3}

Indicative powerplant data — 1

Table A5.1 *Powerplant data – civil turbo-fan engines*

Manufacturer	Engine type	Sea level static thrust (ISA) kN	Sea level static thrust (ISA) lbf × (1000)	SLST specific fuel consumption (lb/lbf/h)	Bypass ratio	Dry mass consumption kg	Dry mass consumption lb	Maximum typical cruise thrust lbf(×100)/(Mach)/ALT 1000 ft	Typical cruise specific fuel consumption (lb/lbf/h)	Length m	Length in	Fan diameter m	Fan diameter in
Allied Signa Engines	TFE 731–5	19.1	4.3		3.34	409	900	0.98/0.8/40	0.8	1.66	65.4	0.75	29.7
BMW Rolls-Royce	BR 710	65	14.75		4.0	209	460	3.58/0.8/35	0.64	5.1*	200.8	1.11	43.7
BMW Rolls-Royce	BR 715	88.8	19.9		4.7			4.4/0.8/35	0.62	5.2*	205	1.34	52.8
CFE	738–1	25.5	5.72	0.39	5.3			1.3/0.8/40	0.645	2.52	99.2	0.9	35.5
CFM International	CFM 56–3B	89	20	0.38	5.0	1943	4280	4.86/0.8/35	0.67	2.36	93	1.52	59.8
CFM International	CFM 56–5C	139	31.2	0.32	6.6	2490	5494	6.9/0.8/35	0.57	2.62	103	1.84	72.4
General Electric	CF34–3A1	41	9.22	0.36						2.615	103	1.24	48.8
General Electric	CF6–80–C2	233	52.5	0.32	5.05	4250	9360	11.3/0.85/35		4.09	161	2.36	92.9
General Electric	GE90–85B	377	84.7		8.4	7080	15 600			4.88	192	3/35	132
International Aero. Eng.	V2500–A1	111.2	25		5.4	2304	5074	5.07/0.8/35	0.58	3.2	126	1.6	63
Pratt & Whitney	JT8D–200	77	17.4	0.51	1.77	2070	4524	4.95/0.8/30	0.724	3.92	154	1.17	46
Pratt & Whitney	PW4052–4460	231	52	0.34	5.8	4268	9400	–/0.8/35	0.537	3.37	133	2.38	94
Pratt & Whitney	PW 4084	376	84		6.41	6606	14 550			3.37	133	2.84	112
Pratt & Whitney Canada	PW 305B	23.6	5.23	0.39	4.5	427	940	1.15/0.8/40	0.68	2.07	81.5	0.8	31.5
Rolls-Royce	TAY 611	61.6	13.85		3.04	1340	2951	2.55/0.8/35	0.69	2.4	94.5	1.1	43.7
Rolls-Royce	RB211–535E4	178	40.1		4.3	3300	7264	8.5/0.8/35	0.60	2.99	117.7	1.88	74
Rolls-Royce	RB211–524G	258	58		4.3	4390	9670	11.8/0.85/35	0.57	3.18	125	2.19	86.2
Rolls-Royce	Trent 768	300	67.5		5.0	4785	10 550	11.5/0.82/35	0.565	3.9	153.5	2.47	97.2
Rolls-Royce	Trent 890	406	91.3		5.74	6000	13 100	13/0.83/35	0.557	4.3	169	2.79	110
Textron Lycoming	LF507–1F	31.1	7	0.406	5.6	629	1385			1.48	58.3	1.2	47.2
Williams Rolls-Royce	FJ44	8.2	1.9	0.48	3.28	202	445	0.6/0.7/30	0.75	1.18	46.5	0.6	24

Fielding

Indicative powerplant data — 2

Table A5.3 *Powerplant data – military turbo-jet and turbo-fan engines*

Manufacturer	Engine type	Sea level static thrust reheat kN	Sea level static thrust reheat lbf ×1000	(SLST) Sea level static thrust – dry kN	(SLST) Sea level static thrust – dry lbf ×1000	SLST dry specific fuel consumption lb/lbf/h	Bypass ratio	Basic engine mass kg	Basic engine mass lb	Length m	Length in	Diameter m	Diameter in
Allied Signal Engines	TFE 1042–70	42.1	9.5	27	6.06	0.8 (dry)	0.3	617	1360	2.88	113	0.6*	24
Eurojet	EJ 200	90	20				0.4	Approx. 1000	Approx. 2000	4.0	158	0.74	29
General Electric	F404–402	79	17.7	53	11.9			1035	2280	4.04	159	0.89	35
General Electric	F110–129	131.3	29.5	78.3	17.6		0.76			4.62	182	1.18	47
Klimov	RD–33	81	18.3	50	11.24	0.76 (dry)		1055	2324	4.17	164	1.0	39
Pratt & Whitney	F100–229	129.5	29.1	79.2	17.8	2.05 (wet)	0.36	3705	8160	4.8	189	1.1	43
Pratt & Whitney	F119–100	157.5	35										
Rolls-Royce	Viper 680–43	–	–	19.4	4.36	0.98	0	380	836	1.96	77	0.73	29
Rolls-Royce	Pegasus 11–61	–	–	106	23.8		1.2	1934	4260	3.48**	137	1.22	48
Rolls-Royce/ Turbomeca	Adour 871	–	–	26.6	5.99	0.74	0.8	590	1300	1.95	77	0.56*	22
Snecma	M53–P2	95	21.4	65	14.6	0.9 (dry)		1500	3307	5.0	197	1.0	39
Snecma	M88–2	72.9	16.4	48.7	10.95	0.78 (dry)				3.54	140		
Turbo-Union	RB199–104	73	16.4	40.5	9.1	1.76 (wet)	1.1 (approx.)	976	2150***	3.6	142	0.72	28

* Comp. face diameter; ** inc. nozzles; *** inc. afterburner.

Fielding

Characterising reciprocating engines

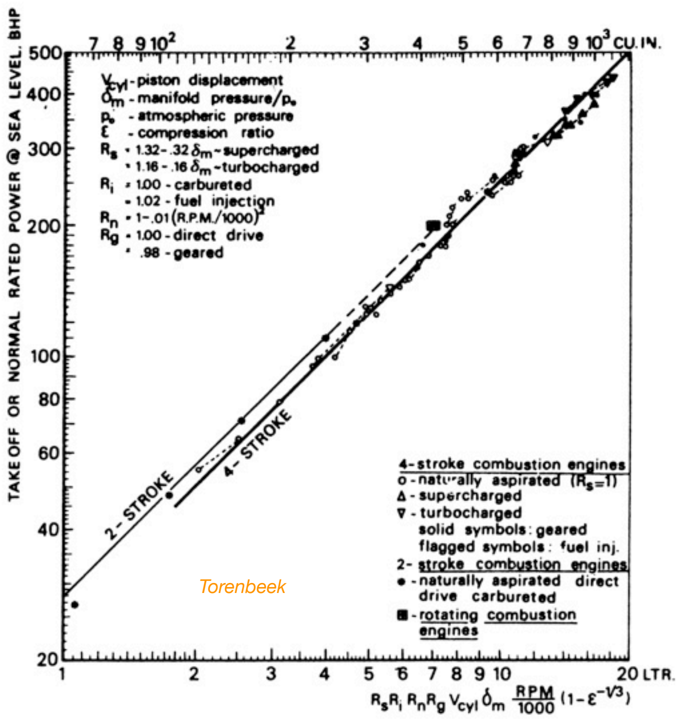
1. Reciprocating engine+prop typically has the lowest fuel consumption at low airspeeds.
2. Unlike jet engines, characterisation of propeller-type propulsion is separated between the engine shaft power P_s and propeller (propulsive) efficiency η_{pr}. (For jet engines, the propulsive efficiency is 'built into' the powerplant description.)

Reciprocating engine + propeller:

$$P = \eta_{\rm pr} P_s$$

$$P = \eta_{\rm pr}\, \alpha P_{s,0}$$

3. Maximum shaft power P_s developed by reciprocating engines is approximately independent of airspeed. They are rated by power at sea level P_{s0}, which is quite well correlated using a variety of factors (see plot).
4. The power-specific fuel consumption PSFC c_p is used to characterise fuel burn rate. Like shaft power it is approximately independent of airspeed. [c]=kg/Ws.



Torenbeek

Typical C_{bhp}: lb/hr/bhp {mg/W-s}	Cruise	Loiter
Piston-prop (fixed pitch)	0.4 {.068}	0.5 {.085}
Piston-prop (variable pitch)	0.4 {.068}	0.5 {.085}
Turboprop	0.5 {.085}	0.6 {.101}

Raymer

Reciprocating engine + propeller combination — 2

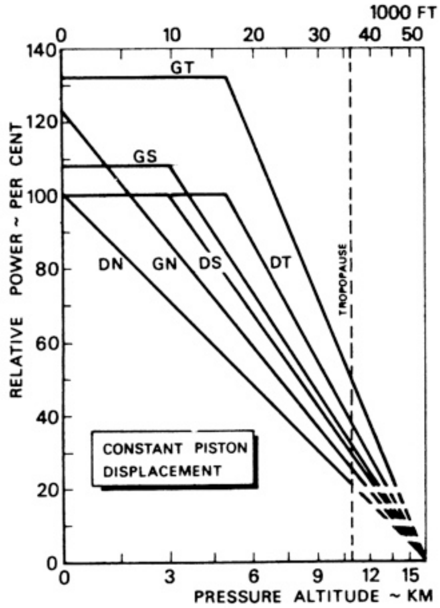
4. Reciprocating engine shaft power depends linearly on air density. With a supercharger or turbocharger — now rare — maximum power has to be limited at low altitude to avoid over-stressing the engine.

5. For all types shown, power falls linearly with air density to zero at an altitude of approx. 16km, where σ=0.132. For the standard type, direct drive, normally aspirated (DN):

$$\alpha = \frac{P_s}{P_{s0}} \approx f\left(\frac{\rho}{\rho_0}\right) = \frac{\sigma - c}{1 - c}, \quad c \approx 0.132$$

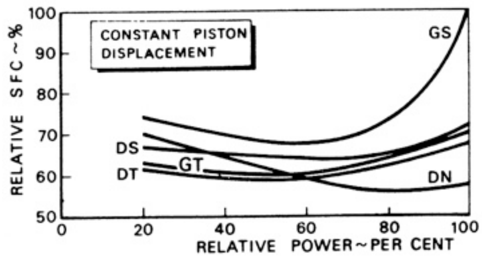
6. Power-specific fuel consumption, PSFC, c_p, is approximately independent of altitude, but does vary somewhat with throttle setting. For initial design purposes, Raymer's figures (previous slide) are adequate.

7. The turboprop engine + propeller combination is typically assumed to have similar characteristics as reciprocating engine + propeller for initial design purposes, i.e. it is assumed to have power independent of speed. An allowance may be made for contribution of jet efflux to propulsive effort.



- D direct drive
- G geared
- N normally aspirated
- S supercharged
- T turbocharged
- C carbureted
- I fuel injection

Torenbeek

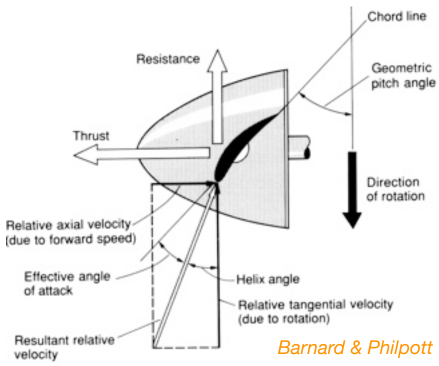


Torenbeek

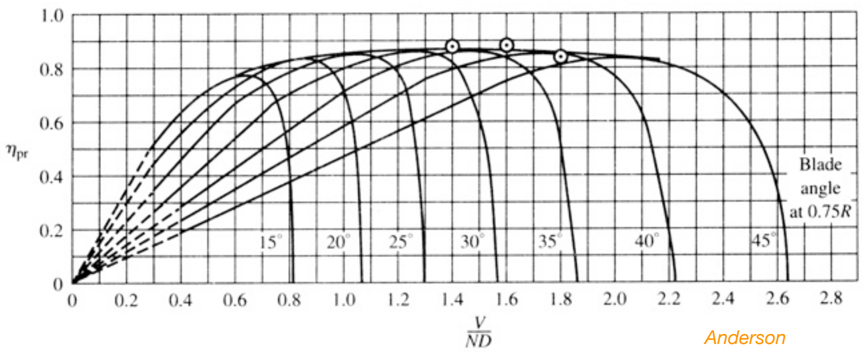
Reciprocating engine + propeller combination — 3

1. Available power P_A depends on propeller efficiency. A propeller is basically a rotating wing and needs to run at the correct angle of attack for maximum efficiency (i.e. maximum *L*/*D*). This is characterised by the propeller advance (gear!) ratio *J*.

$$P_A = \eta_{\rm pr} P_S, \quad \eta_{\rm pr} = f(J), \quad J = \frac{V_\infty}{ND} = \pi \frac{V_\infty}{r_{\rm tip}\,\omega}$$



Barnard & Philpott



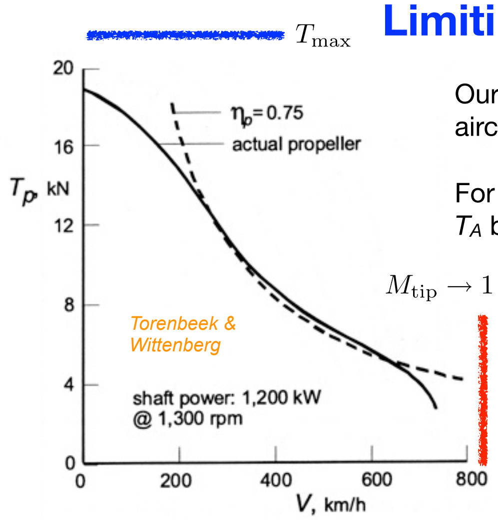
Anderson

2. Typical maximum values of $\eta_{\rm pr}$ are in the range 0.8-0.9.
3. For a fixed-pitch propeller, the pitch is chosen to maximise $\eta_{\rm pr}$ for the most important design task (e.g. cruise speed, rate of climb). Torenbeek, Nicolai have details of propellor choice/design.
4. If the aircraft cost justifies it, we can use a variable-pitch propeller, or better yet, a constant-speed propeller wherein an automatic governer allows the engine to run at a constant optimal speed (i.e. the governer keeps P_A constant). <u>This assumption allows considerable simplification in design.</u>
5. We can alternatively characterise the combination by thrust instead of power, and use thrust-specific fuel consumption TSFC c_t in place of PSFC, c_p. This is helpful if we want to compare to a turbojet.

$$T_A = \frac{\eta_{\rm pr} P_s}{V_\infty}, \quad c_t = \frac{c_p V_\infty}{\eta_{\rm pr}}$$

19

Limiting effects for propellers



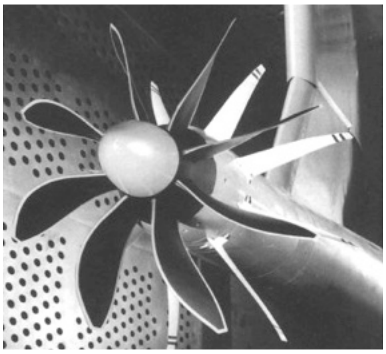
Our simple models for propeller performance are adequate for many aircraft performance problems, but are weak at very low or high speeds.

For low speeds, the simple approximation that $T_A V_\infty \equiv \eta_p P_s$ suggests T_A becomes infinite as $V_\infty \to 0$ (cannot be correct!).

Other simplified models suggest an upper limit to thrust at $V_\infty = 0$

$$T_{\max} \approx \left(2P_s^2 \rho A_p\right)^{1/3}$$

where $A_p = \pi R_p^2 = \pi D_p^2/4$ is the swept area of the propeller disc.



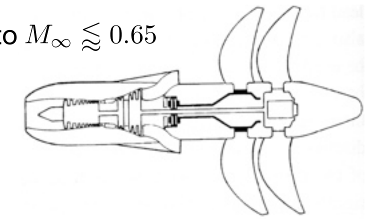
If the tip speeds approach the speed of sound, shock wave drag will act to limit the available thrust, too (and produce unacceptable noise levels).

$$v_{\text{tip}} = \sqrt{V_\infty^2 + (\pi n D_p)^2} \quad \text{or} \quad M_{\text{tip}} = M_\infty \sqrt{1 + (\pi/J)^2}$$

E.g. $J = 2$ and $M_\infty > 0.54$ gives $M_{\text{tip}} > 1$.

This has limited propeller applications to $M_\infty \lesssim 0.65$

More advanced designs with swept blades and thin sections have been proposed and tested, but so far not used in practice.



20

Propeller sizing

Detail of propeller sizing and design is quite complex; all we need to know for now is an approximate propeller diameter for a given power requirement.

$$D \approx K_p P_{s,0}^{1/4}$$

P in kW, *D* in m. Raymer

	British units	Metric units
No. blades	K_p	K_p
2	1.7	0.56
3	1.6	0.52
4 +	1.5	0.49
Power units	hp	kW
Diameter units	ft	m

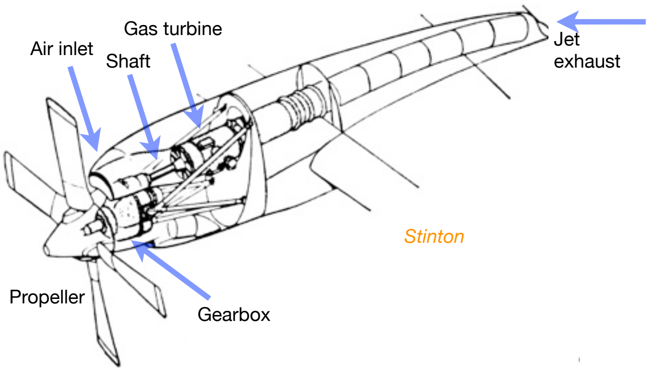
In addition the propeller tip speed needs to be kept below approximately *M* = 0.85

$$V_{\text{helical}}/a = \sqrt{(\pi n D)^2 + V^2} \lesssim 0.85$$

where *n* is revs/sec.

Turboprop — 1

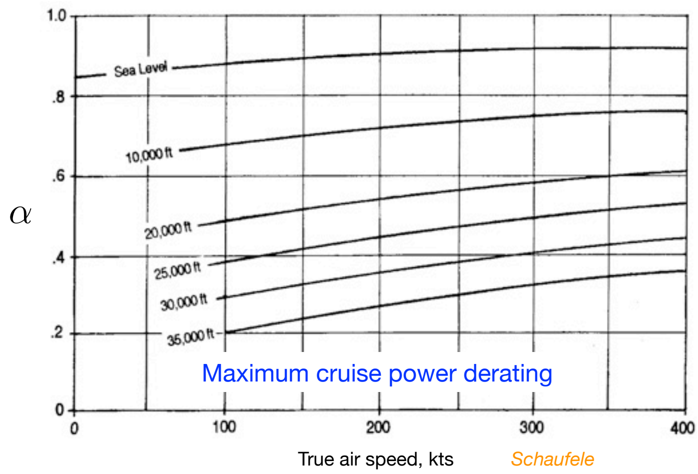
1. A turboprop is much like a propeller driven by a non-integrated gas turbine. Its performance characteristics are quite similar overall to those of the reciprocating engine + propeller combination, though jet exhaust may contribute at most 5% to thrust. For this reason, they are typically rated by <u>equivalent shaft power</u> P_{es}, rather than thrust.



$$P_A = \eta_{\mathrm{pr}} \alpha P_{\mathrm{es}}$$

2. Equivalent shaft power is approximately independent of airspeed, so α is mostly a function of σ, as well as throttle setting. $\alpha \approx \sigma^n$, where $0.7 < n < 1.0$, can use $n = 1$ in initial work but something smaller is a better approximation. Again, an additional derating should be used for throttle setting.

$$\alpha \simeq \sigma^n$$



Turboprop — 2

3. A turboprop is also like a very high bypass ratio turbofan, but without an external duct. Its efficiency is higher than a turbofan at moderate Mach numbers (M<0.4-0.6) and the upper limits are set by the need to keep prop-tip Mach numbers subsonic to avoid shock-related power loss.
4. (Power) Specific fuel consumption PSFC (or c) is relatively independent of altitude and airspeed. We can use the indicative values given by Raymer in initial design work:

Typical C_{bhp}: lb/hr/bhp {mg/W-s}	Cruise	Loiter
Piston-prop (fixed pitch)	0.4 {.068}	0.5 {.085}
Piston-prop (variable pitch)	0.4 {.068}	0.5 {.085}
Turboprop	0.5 {.085}	0.6 {.101}

Raymer

5. Just as for the reciprocating engine/propeller combination, we can alternatively characterise turboprop performance by thrust instead of power, and also use thrust-specific fuel consumption TSFC c_t instead of PSFC c.

$$T_A = \frac{\eta_{\mathrm{pr}} P_{\mathrm{es}}}{V_\infty}, \qquad c_t = \frac{c V_\infty}{\eta_{\mathrm{pr}}}$$

6. Propfans or unducted fans i.e. 'modern generation' turboprops with propellers designed for Mach numbers closer to unity than conventional versions, (e.g. up to M=0.8 or more) have been proposed and tested but not widely used (yet).

Indicative powerplant data — 3

Table A5.2 *Powerplant data – turbo-prop engines*

Manufacturer	Engine type	Take off shaft horsepower	SFC Take-off lb/h/ESHP	Dry mass (inc. gearbox)		Length		Maximum width	
				kg	lb	m	in	m	in
Allied Signal Engines	TPE 331–12	1100	0.52			1.1	43.3	0.53	21
Allied Signal Engines	TPE 331–14GR	1650	0.51			1.35	53	0.58	23
Allison	AE 2100 A	3690	0.415			1.96	77	0.67	264
Allison	T56	4920	0.50			3.71	146	0.99	39
General Electric	CT7–9	1740	0.48	295	650	2.44	96	0.74	29
Pratt & Whitney Canada	PT6A–25C	550	0.63			1.57	62	0.48	19
Pratt & Whitney Canada	PW124B	2950	0.454			2.06	81	0.84	33
Pratt & Whitney Canada	PW127	3300	0.449			2.06	81	0.84	33
Rolls-Royce/Snecma	Tyne MK21	6100				2.76	109	0.84	43

Fielding

Scaling laws for sizing propulsion systems

Supposing we have reference performance characteristics for an example powerplant and we want to estimate the mass, size etc of a comparable powerplant of larger thrust (or power) capacity.

Commonly called 'rubberising' an engine.

If we say *SF*=scale *factor*=$T_{0scaled}/T_{0ref}$ (for a jet) or SF=$P_{0scaled}/P_{0ref}$ (reciprocating engine or turboprop) then the following approximate relationships apply:

Jet

Raymer/Nicolai

Weight $W \approx W_{\text{ref}} SF^{1.1}$

Length $l \approx l_{\text{ref}} SF^{0.4}$

Diameter $d \approx d_{\text{ref}} SF^{0.5}$

Thrust-specific fuel consumption values remain fixed.

Prop

Raymer

Table 10.3 Scaling laws for piston and turboprop engines

$X_{\text{scaled}} = X_{\text{actual}} SF^{b}$; b from table values
$SF = \text{power}_{\text{scaled}}/\text{power}_{\text{actual}}$

	Piston engines			
X	Opposed	In-line	Radial	Turboprop
Weight	0.78	0.78	0.809	0.803
Length	0.424	4.24	0.310	3.730
Diameter	—[a]	—[a]	0.130	0.120

[a]Width and height vary insignificantly within ±50% horsepower.

Power-specific fuel consumption values remain fixed.