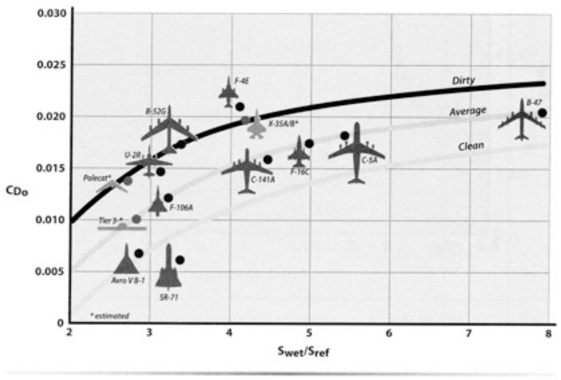
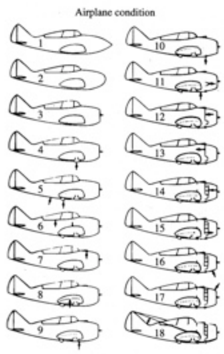


Figure G.7 Correlation of subsonic C_{D_0} with S_{wet}/S_{ref}.

Drag polar estimation

Recommended reading:

Schaufele: Chapter 12
Shevell: Chapter 11
Torenbeek: Appendix F
Nicolai & Carichner: Appendix G
Gur et al (2010). AIAA J Aircraft **47**(4): 1356–1367



Condition number	Description	C_D ($C_L = 0.15$)	ΔC_D	ΔC_D, %[a]
1	Completely faired condition, long nose fairing	0.0166		
2	Completely faired condition, blunt nose fairing	0.0169		
3	Original cowling added, no airflow through cowling	0.0186	0.0020	12.0
4	Landing-gear seals and fairing removed	0.0188	0.0002	1.2
5	Oil cooler installed	0.0205	0.0017	10.2
6	Canopy fairing removed	0.0203	−0.0002	−1.2
7	Carburetor air scoop added	0.0209	0.0006	3.6
8	Sanded walkway added	0.0216	0.0007	4.2
9	Ejector chute added	0.0219	0.0003	1.8
10	Exhaust stacks added	0.0225	0.0006	3.6
11	Intercooler added	0.0236	0.0011	6.6
12	Cowling exit opened	0.0247	0.0011	6.6
13	Accessory exit opened	0.0252	0.0005	3.0
14	Cowling fairing and seals removed	0.0261	0.0009	5.4
15	Cockpit ventilator opened	0.0262	0.0001	0.6
16	Cowling venturi installed	0.0264	0.0002	1.2
17	Blast tubes added	0.0267	0.0003	1.8
18	Antenna installed	0.0275	0.0008	4.8
	Total		0.0109	

[a]Percentages based on completely faired condition with long nose fairing.

Divide and conquer (drag)

1. We already discussed representative values for $C_{D,0}$ estimates of the complete aircraft. These are OK for first-pass estimates, but once we have a better idea of the configuration, or we need to know the effect lowering undercarriage or adding external stores, we have to be able to tackle the build-up approach to drag estimation.
2. The basic idea: total drag is the sum of various components, potentially each with different causes and different objects on which the component drags are exerted.

$$D_{\text{total}} = \tfrac{1}{2}\rho V^2 C_{D1} S_1 + \tfrac{1}{2}\rho V^2 C_{D2} S_2 + \cdots = \tfrac{1}{2}\rho V^2 \sum_{j=1}^{J} C_{Dj} S_j = q \sum_{j=1}^{J} C_{Dj} S_j$$

Now say $D_{\text{total}} \equiv q C_D S_{\text{ref}}$ then $$C_D = \frac{1}{S_{\text{ref}}} \sum_{j=1}^{J} C_{Dj} S_j$$

3. Slightly better would be to allow 'interference factors' K that account for the influence of flow around one object on flow around a nearby object.

$$C_D = \frac{1}{S_{\text{ref}}} \sum_{j=1}^{J} K_j C_{Dj} S_j$$

K_j values are often close to unity (and sometimes ignored).

4. Since each item $C_{Dj} S_j$ has units of area, another commonly used approach is to just quote an 'equivalent flat plate area' f_j for each object in the collection, each with an equivalent assumed $C_{Dj} = 1$.

$f_j \equiv C_{Dj} S_j$ then $$C_D = \frac{1}{S_{\text{ref}}} \sum_{j=1}^{J} K_j f_j$$

or, in combinations: $$C_D = \frac{1}{S_{\text{ref}}} \left[\sum_{j=1}^{M} K_j f_j + \sum_{j=M+1}^{N} K_j C_{Dj} S_j \right]$$

The source-book 'bible' for many component drag C_D values is still Hoerner's classic text *Fluid-Dynamic Drag*, published in 1965.

Divide and conquer (drag)

5. This approach allows us to easily estimate the effect of adding an accessory or other object to an existing airframe, if we know the new object's drag coefficient and basis area.

Example: Estimate the effect on C_{Do} of extending the main landing-gear of our twin turboprop aircraft, which had

$C_{Do\,clean} \simeq 0.02$

$S_{REF} = 23.2\,m^2$

and two main gear struts, each with a wheel $D = 0.675\,m$, $W = 0.180\,m$.

From Hoerner (1965), Fig 36, an approximate

$C_{D\square} = 1.01$

This includes a contribution for the gear strut.

The related drag area $S_\square$, is the equivalent rectangular area

$S_\square = D \times W = 0.675 \times 0.18\,m^2 = 0.1215\,m^2$. (have to check the text to know/confirm the related area on a case-by-case basis).

Hoerner

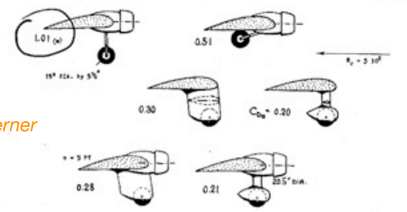


Figure 36. Drag coefficients (on wheel area $S_\square$) of a landing gear designed for a 16,000 lb. airplane (25,a); (*) this coefficient is believed to be subcritical with respect to the R'number of the circular strut.

Hence

$$C_{Do\,mains} \simeq \frac{C_{Do} S_{REF} + 2 \times C_{D\square} S_\square}{S_{REF}} = \frac{0.02 \times 23.2 + 2 \times 1.01 \times 0.1215}{23.2}$$

$= \underline{0.0306}$. (More than 50% increase. We should still allow for drag of nose landing gear, etc...).

In this example, interference factors were already included in the tabulated $C_{D\square}$ values and not required. Note that the outcome is still rather approximate and should be treated with caution.

Drag nomenclature

Aircraft drag has a number of different sources, which tends to add to the difficulty of its accurate prediction. It is useful to be aware of the dominant drag sources and their names.

1. **Skin friction drag** results from viscous shearing stresses integrated over wetted surface.
2. **Pressure drag (a.k.a. form drag)** results from integrated effect of static pressure over wetted surface, component resolved in drag direction.
3. **Profile drag** is the sum of skin friction and pressure drag, typically for a 2D airfoil *profile.*
4. **Viscous drag-due-to-lift** is pressure drag that is related to boundary layer growth produced by change in airfoil angle of attack: it is lift-dependent but is present in the absence of tip vortices.
5. **Inviscid drag-due-to-lift (a.k.a. induced drag)** results from the change in effective angle of attack produced by trailing wing-tip vortices. Can be computed via inviscid aerodynamic methods.
6. **Interference drag** is an increment in drag resulting from bringing two bodies into proximity.
7. **Trim drag** results from generation of aerodynamic forces required to bring aircraft into moment equilibrium about CG; typically dominated by drag-due-to-lift on horizontal tail.
8. **Base drag** is the specific contribution to pressure drag attributed to a blunt afterbody.
9. **Wave drag** results from non-cancelling static pressure rises across shock waves, resolved in the drag direction and integrated over wetted surface area. Flow must exceed M=1 at least locally.
10. **Excrescence drag** is drag associated with protruberances such as antennas, handles, external stores, poorly sealed gaps spoiling locally streamlined flow, etc.
11. **Cooling drag** is produced by momentum lost by air that passes through powerplant installation/ heat exchangers.
12. **Ram drag** is drag associated with momentum lost as air is slowed down to enter an inlet.

5

Skin friction drag

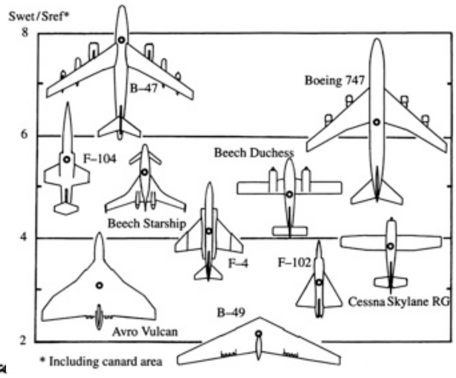
1. The largest aircraft drag component is typically produced by skin friction, which may be estimated on a surface-by-surface basis if we know the skin-drag friction coefficient C_f for each surface. A simplified approach for the clean-aircraft estimate of $C_{D,0}$ uses estimates of an overall **equivalent skin-friction coefficient C_{fe}** for the whole aircraft based on type-specific correlations. This is expected to be a rather better means of estimating $C_{D,0}$ than simple tabulated values based on aircraft type. Includes lift-independent profile drag.

$$C_{D,0} \approx C_{fe}\frac{S_{\text{wet}}}{S_{\text{ref}}}$$
$$\equiv C_{D\text{wet}}\frac{S_{\text{wet}}}{S_{\text{ref}}}$$

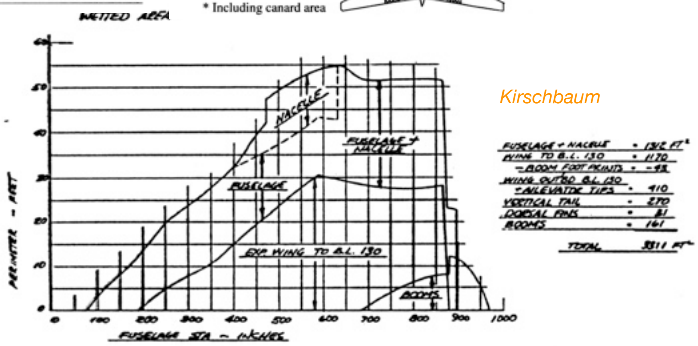
Table 12.3 Equivalent skin friction coefficients

$C_{D_0} = C_{f_e}\frac{S_{\text{wet}}}{S_{\text{ref}}}$	C_{f_e}-subsonic
Bomber and civil transport	0.0030
Military cargo (high upsweep fuselage)	0.0035
Air Force fighter	0.0035
Navy fighter	0.0040
Clean supersonic cruise aircraft	0.0025
Light aircraft–single engine	0.0055
Light aircraft–twin engine	0.0045
Prop seaplane	0.0065
Jet seaplane	0.0040

Raymer



2. Note that we still have the task of estimating S_{wet} or $S_{\text{wet}}/S_{\text{ref}}$. Again we have to address that task on a divide-and-conquer basis, but by now we should have estimates of the sizes and shapes of all the aircraft's aerodynamic components, so this is quite possible. The easiest approach now is to use the Comp Geom tool in OpenVSP.



Kirschbaum

6

Drag polar estimation

The aircraft drag polar relationship, i.e. $C_D = f(C_L)$ changes with aircraft configuration and speed.

In the context of design, the drag polars of fundamental interest are

1. Cruise (clean) configuration at appropriate speed and altitude – for payload/range calculations.
2. Takeoff configuration – for calculation of take-off field length, initial climb rate or gradient.
3. Landing configuration – for calculation of runway length required for landing.

Typically the cruise polar is the first focus, and drag increments are added for the remaining two.

(If the aircraft carries external stores, these also need to be considered in polar estimation.)

$$D = D_{\text{parasitic}} + D_{\text{airfoil profile}} + D_{\text{induced}} + \Delta D_{\text{compressibility}}$$

all non-lifting related drag — 2D sectional drag (viscous) — 3D tip-vortex induced (inviscid) — Shock-wave related

$$= q\left[S_{\text{wet, non-wing}}C_f + S_{\text{ref}}C_d(C_L) + S_{\text{ref}}K'C_L^2 + S_{\text{ref}}\Delta C_{D,c}(M,\Lambda,C_L)\right]$$

all non-lifting related drag — 2D sectional drag – can be related to a single airfoil profile, if profile is spanwise invariant/untwisted — 3D tip-vortex induced (inviscid) — Shock-wave related

$$= qS_{\text{ref}}\left[\frac{S_{\text{wet, non-wing}}}{S_{\text{ref}}}C_f + C_d(C_L) + K'C_L^2 + \Delta C_{D,c}(M,\Lambda,C_L)\right]$$

To start with we will ignore compressibility effects and deal with strictly subsonic polar models.

$$\approx qS_{\text{ref}}\left[\frac{S_{\text{wet, non-wing}}}{S_{\text{ref}}}C_f + C_d(C_L) + K'C_L^2\right]$$

This is what we need to model: $C_D = fn(C_L)$.

Drag polar estimation

We note that various different texts have subtly different ways of defining the whole-aircraft drag polar, even to the extent of using the same terms for slightly different quantities.

A common theme is that the subsonic drag polar may often be well modelled by a simple quadratic relationship over the useful ranges of C_L.

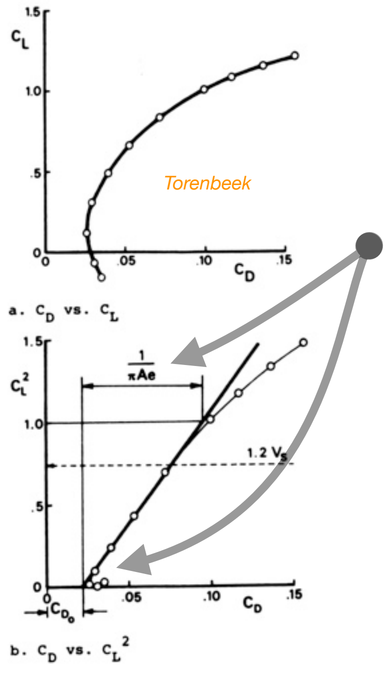


Fig. 5-4. Typical low-speed polar curve

The approximation we have used so far is

$$C_D \approx C_{D,0} + KC_L^2$$
$$\equiv C_{D,0} + \frac{C_L^2}{\pi Ae}$$

where $C_{D,0}$ and e are parameters in a 2-term quadratic fit to the real drag polar.

This simple 2-term model is quite reasonable provided the fit is carried out over the expected range of C_L for which the polar will be used. However we still face the need to actually estimate $C_{D,0}$ and e.

For aircraft with higher aspect ratios or higher design lift coefficients, a more complex (3-term) drag polar model may be used. Typically 3-term polar models incorporate airfoil drag polar information. (Though a 2-term polar is fine if appropriately constructed.)

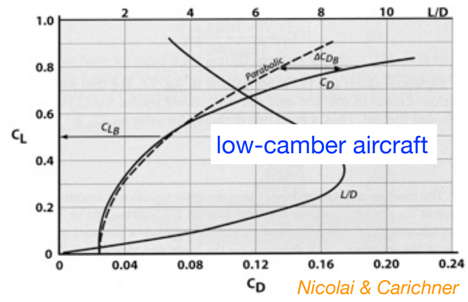


Figure 2.17 F-4C Aerodynamics at Mach 0.8 AR = 2.82, λ = 0.236, t/c = 5%, Series 64A, Λ = 45 deg.

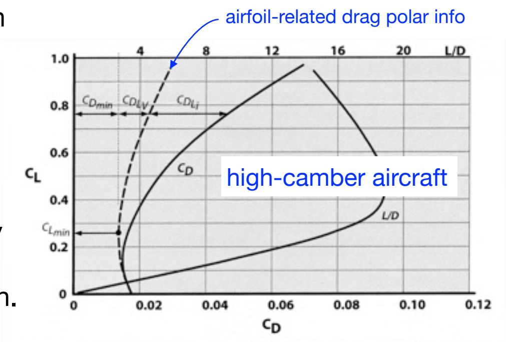


Figure 2.16 Low-speed drag polar (M ≤ 0.4) for C-141, clean configuration.

2-term drag polar estimation

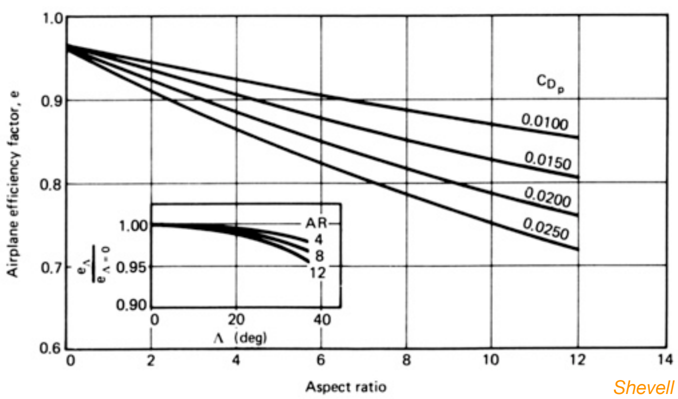
$$C_D \approx C_{D,0} + KC_L^2$$
$$\equiv C_{D,0} + \frac{C_L^2}{\pi Ae}$$

$C_{D,0}$ is estimated via drag-build-up methods on a component-by-component basis.

e is estimated from correlations already introduced or by inviscid computation (e.g VSPaero) and airfoil lift-dependent drag.

Shevell/Douglas correlation for e.

Note that it includes A as a parameter!



Here $C_{Dp} \equiv C_{D,0}$ is needed in advance.

A rationale for the effect of $C_{D,0}$ on e is that e must in reality reflect combined wing-body aerodynamics.

This correlation for e was established for a comparatively limited range of aircraft and should be treated with some caution (though it is OK for transport aircraft): also, it is specific to the 2-term polar model.

We next turn to methods for the estimation of $C_{D,0}$, including allowances for

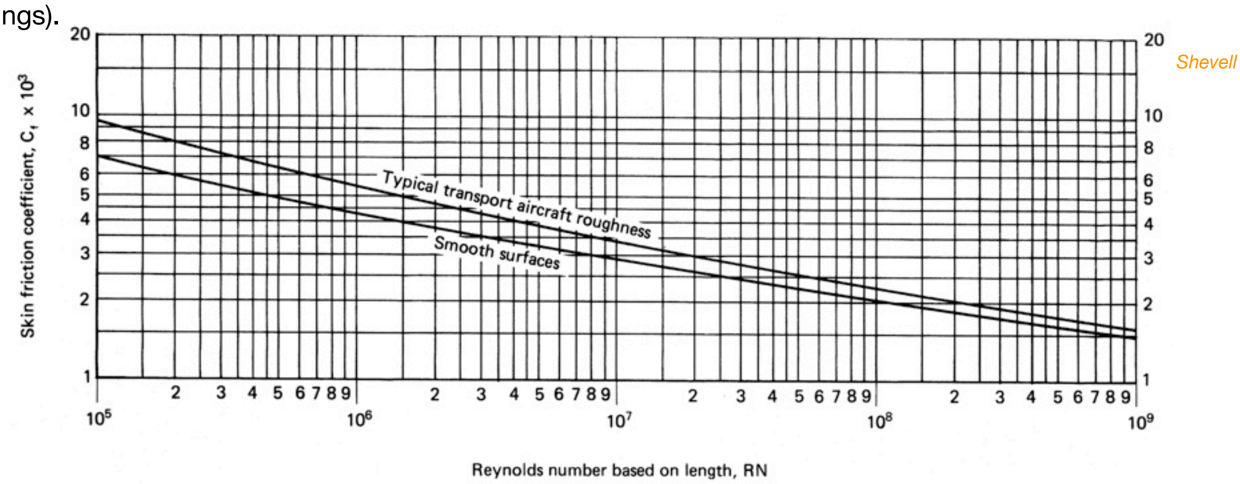
1. Skin friction and pressure drag of all wetted surfaces, lifting and non-lifting, at zero-lift condition;
2. External stores (and any other individual drag-producing components we can account for);
3. Excrescence drag associated with cooling and unsealed gaps.

Recall, however, that $C_{D,0}$ is not truly the zero-lift drag coefficient: rather, it is a parameter in a curve fit.

Data for drag estimation — 1

The dominant parasitic drag component for streamlined aircraft is boundary layer skin friction drag and for large/most aircraft the BL can be assumed turbulent over the majority of the wetted area.

For the purposes of drag estimation before application of correction factors all wetted surface areas are assumed to be flat plates (note: drag associated with engine ductwork is lumped into engine de-ratings).



BL drag depends on surface roughness/waviness as well as plate length Reynolds number.

Transport aircraft surfaces have an 'equivalent sand grain roughness' size of about 0.04mm.

The length to be used in the assessment is either the component length for non-lifting streamlined surfaces or the MAC in the case of lifting surfaces.

Broadly equivalent methods are used for $C_{D,0}$ estimates given by VSPaero Parasite Drag tool.

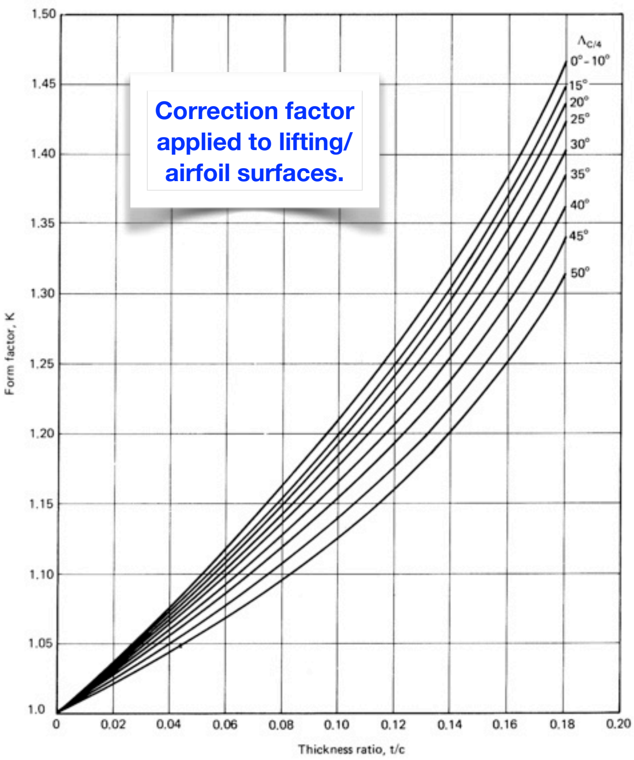
Data for drag estimation — 2

$M_0 = 0.5$

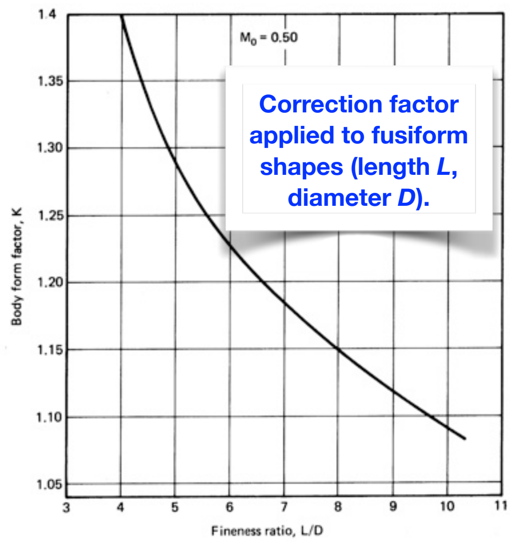
$K = [1 + Z(t/c) + 100(t/c)^4]$

where

$$Z = \frac{(2 - M_0^2)\cos\Lambda_{c/4}}{\sqrt{1 - M_0^2 \cos^2\Lambda_{c/4}}}$$



Correction factor applied to lifting/airfoil surfaces.



Correction factor applied to fusiform shapes (length *L*, diameter *D*).

Data for drag estimation — 3

Equivalent flat plate area $f \equiv D/q$ for various external components.

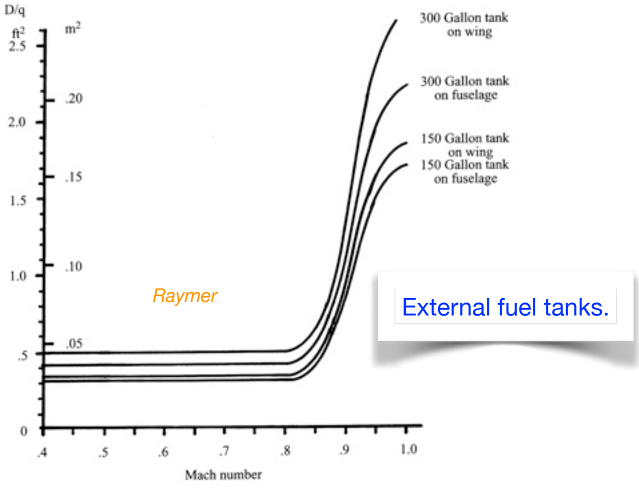


Fig. 12.23 External stores (fuel tanks) drag.

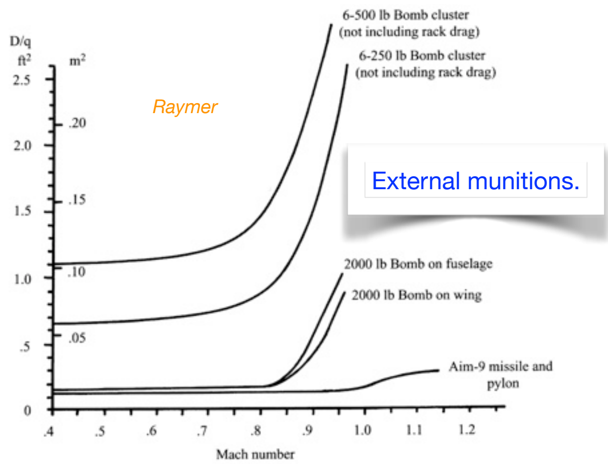


Fig. 12.24 Bomb and missile drag.

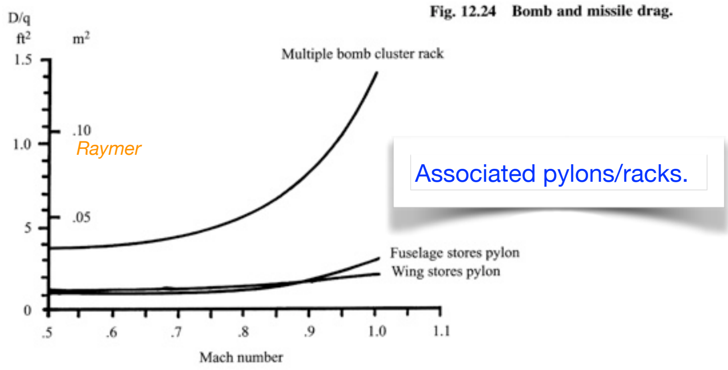


Fig. 12.25 Pylon and bomb rack drag.

Example

Estimate C_{D0} for a jet transport aircraft designed to cruise at $M = 0.78$, $h = 9$ km.

Two configurations (i) clean
(ii) carrying 4 external sensor pods each equivalent to a 300 gal fuel tank, wing mounted.

Assume aerodynamically balanced, sealed controls.

Wing: span 25m
reference area 90 m²
average t/c 0.11
sweep angle 25°
exposed root chord 5.5m
tip chord 1.1 m
wing area covered by fuselage 16%.

Fuselage: length 33m
diameter 3.5 m
wetted area 305 m²

H-tail: exposed planform area 25 m²
t/c 0.09
sweep angle 30°
taper ratio 0.35
root chord 3.5m.

V-tail: exposed planform area 15 m²
t/c 0.09
sweep angle 45°
taper ratio 0.80
root chord 4.7m

Engine pylons: wetted area 11 m²
t/c 0.06
sweep angle 0°
taper ratio 1
chord 5m

Engine nacelles: wetted area 42 m²
effective L/D 5
length 5m.

For Reynolds number need TAS and ν.

At 9km $T = -43.5\,°C = 229.7\,K$.

$\rho = 0.4664\ kg/m^3$

$a = 303.8\ m/s$.

$V = Ma = 0.78 \times 303.8\ m/s$

$= 237\ m/s$.

$$\mu = \frac{1.458 \times 10^{-6}\, T^{3/2}}{(T + 110.4)}\ Pa.s\ (T \text{ in Kelvin}).$$

$= 14.92 \times 10^{-6}\ Pa.s$

$$\nu = \frac{\mu}{\rho} = \frac{14.92 \times 10^{-6}}{0.4664}\ \frac{m^2}{s} = 32.0 \times 10^{-6}\ \frac{m^2}{s}.$$

JOB TITLE

13

Example

Wing

$$MAC = \frac{2C_r}{3}\left(\frac{1+\lambda+\lambda^2}{1+\lambda}\right) = \frac{2}{3}\left(C_r + C_t - \frac{C_r C_t}{C_r + C_t}\right)$$

$$= \frac{2}{3}\left(5.5+1.1 - \frac{5.5\times1.1}{5.5+1.1}\right) m = 3.80m.$$

$$Re = \frac{VL}{\nu} = \frac{237\times3.80}{32\times10^{-6}} = 28.1\times10^6$$

$C_{fe} = 0.00275$; $K = 1.21$.

Wetted area $S_j = 2\times90\times(1-0.16)m^2 = 151.2m^2$

$f = C_{fe}KS = 0.00275\times1.21\times151.2\ m^2 = \underline{0.503m^2}$

Fuselage

$$L/D = \frac{33}{3.5} = 9.43$$

$$Re = \frac{237\times33}{32\times10^{-6}} = 244\times10^6$$

$C_{fe} = 0.00195$; $K = 1.11$

$f = C_{fe}KS = 0.00195\times1.11\times305\ m^2 = \underline{0.660\ m^2}$

HTAIL

$$MAC = \frac{2}{3}\times3.5\times\left(\frac{1+0.35+0.35^2}{1.35}\right)m = 2.54m.$$

$$Re = \frac{237\times2.54}{32\times10^{-6}} = 18.8\times10^6$$

$C_{fe} = 0.003$; $K = 1.16$

$f = C_{fe}KS = 0.003\times1.16\times25\times2\ m^2 = \underline{0.174m^2}$

VTAIL

$$MAC = \frac{2}{3}\times4.7\times\left(\frac{1+0.8+0.64}{1.8}\right)m = 4.25m.$$

$$Re = \frac{237\times4.25}{32\times10^{-6}} = 31.5\times10^6$$

$C_{fe} = 0.0027$; $K = 1.12$

$f = C_{fe}KS = 0.0027\times1.12\times2\times15\ m^2 = \underline{0.091m^2}$

Pylons

$Re = \frac{237\times5}{32\times10^{-6}} = 37\times10^6$, $C_{fe} = 0.0026$

$K = 1.12$ $f = 0.0026\times1.12\times11\ m^2 = \underline{0.032m^2}$

Nacelles

$Re = \frac{237\times5}{32\times10^{-6}} = 37\times10^6$; $C_{fe} = 0.0026$

$K = 1.29$, $f = 0.0026\times1.29\times42\ m^2 = \underline{0.141m^2}$

JOB TITLE

14

Example

Total equivalent flat plate area

$f = 0.503+0.660+0.174+0.091+0.032+0.141\ m^2$

$= 1.601\ m^2$

Allow another 6% for control surface gaps (sealed)

$\underline{f} = 1.06\times1.601\ m^2 = \underline{1.697\ m^2}$

$$C_{D0,clean} = \frac{f}{S_{ref}} = \frac{1.697}{90} = \underline{0.0189}$$

For comparison; Total wetted area, S_{wet}

$= 151.2+305+50+30+11+42m^2 = 547.2\ m^2$

Overall $C_{fe} = \frac{f}{S_{wet}} = 0.0031$

cf. Raymers tabulated value of $C_{fe} = 0.0030$

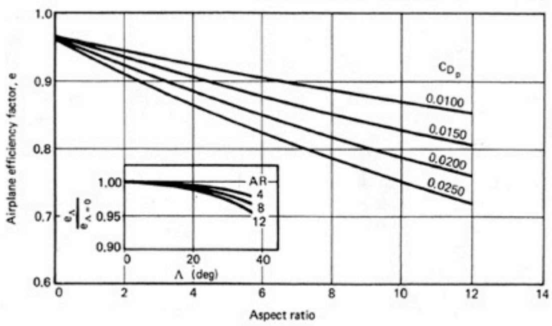
Effect of adding 4 external 300 gal tanks each with $f = 0.0465\ m^2$

$f = f_{clean} + f_{stores} = 1.697 + 4\times0.0465m^2 = \underline{1.883m^2}$

$$C_{D0,stores} = \frac{1.883}{90} = \underline{0.0209}$$

(10% increase)

Also estimate e and K.



$$A = \frac{b^2}{S_{ref}} = \frac{25^2}{90} = 6.94$$

$C_{Dp} \equiv C_{D0} = 0.0189$

$\Rightarrow e_{\Lambda=0} = 0.84$

$\frac{e_\Lambda}{e_{\Lambda=0}} = 0.98$ $\therefore e = 0.84\times0.98 = \underline{0.823}$

$$K = \frac{1}{\pi Ae} = \frac{1}{\pi\times6.94\times0.823} = 0.0557$$

$$(L/D)^* = \frac{1}{\sqrt{4C_{D0}K}} = 15.4$$

JOB TITLE

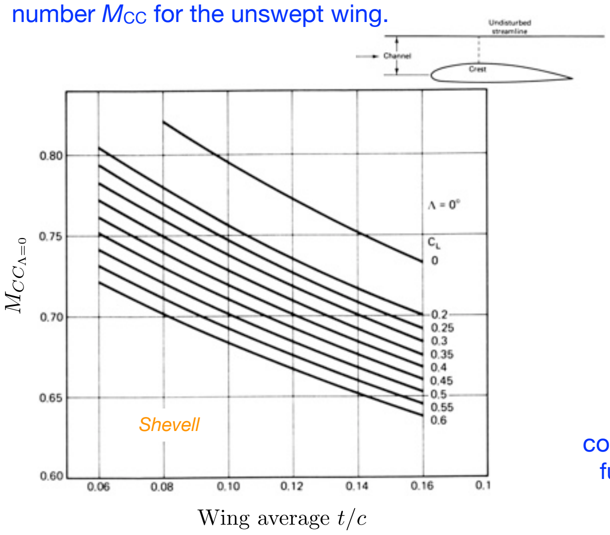
Estimating transonic drag rise

Most jet transport aircraft cruise at Mach number M_{DD} near the onset of substantial rise in C_D produced by compressibility effects in order to maximise *ML/D.*

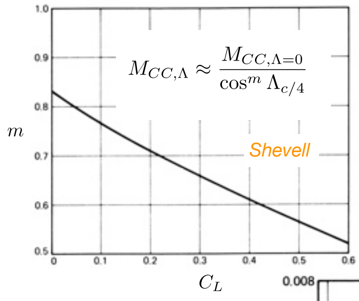
So estimation of M_{DD} (a.k.a. M_{Div}) and/or variation of C_D with M as summarised by $\Delta C_{D,c}(M, \Lambda, C_L)$ is important. Unfortunately also difficult in general. We concentrate on methods found to work reasonably well for typical jet transport aircraft.

At this stage the wing sweep $\Lambda_{c/4}$ should have already been chosen to make $M_{DD} = M_{\mathrm{cruise}}$, but that technique is (a) somewhat approximate and (b) valid only for the chosen value of C_L.

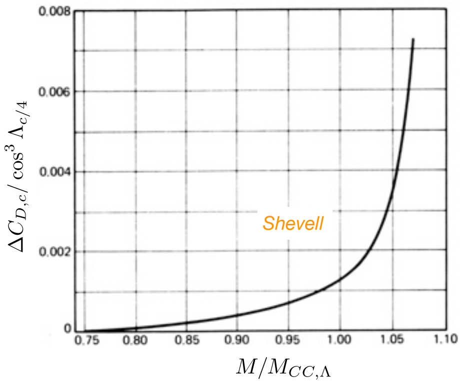
1. At a chosen value of C_L and with wing *t/c* ratio already known, estimate the 'crest critical' Mach number M_{CC} for the unswept wing.



2. Find the exponent m for the chosen C_L and compute the 'crest critical' Mach number for the swept wing, $M_{CC,\Lambda}$.



3. Estimate the compressibility contribution to C_D as a function of freestream Mach number *M.*



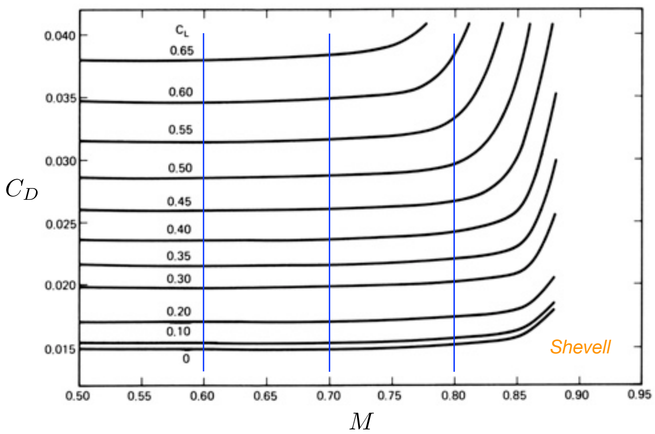
Estimating transonic drag rise

$$C_D = [C_{D,\min} + C_D(C_L)]_{M=0} + \Delta C_{D,c}(M, C_L) = C_D(C_L, M)$$

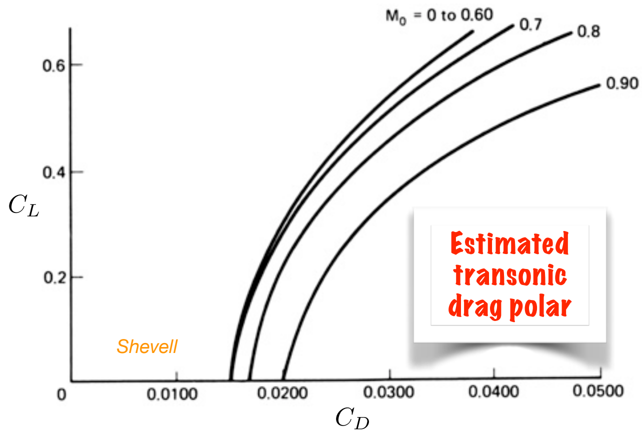
Previously computed

Just found this at one value of C_L

4. That enables us to plot one C_L= const. contour line on the map of C_D (C_L, *M*). Repeat for other C_L values.



5. By cross-plotting we can turn that into a map of C_D (C_L) (i.e. the drag polar) with M as an **independent** parameter.



For supersonic aircraft, or those which are not 'typical jet transports', use methods discussed by Nicolai & Carichner (or compressible-flow CFD).

Modifications to the drag polar for takeoff and landing

Take-off and landing drag polars can differ substantially from cruise, resulting from deployment of high-lift devices and landing gear (but compressibility effects can be ignored).

The take-off polar is significant for computing take-off climb performance ('second-segment climb'). The configuration is

1. Leading edge devices extended.
2. Trailing edge flaps set for take-off (less than maximum deflection).
3. Gear retracted (can add increment for extended gear if needed).
4. Speed = $k_{to}\, V_{stall}$ = 1.2 V_{stall}.

$$C_D = C_{D,0_{\text{cruise}}} + \Delta C_{D_{\text{slat}}} + \Delta C_{D_{\text{flap}}} + \frac{C_L^2}{\pi A e_{\text{low speed}}}$$

The 'low speed' aircraft efficiency $e_{\text{low speed}}$ is typically lower than the value used for cruise, largely because the span efficiency factor for the wing is lower as a result of non-optimal spanwise lift distribution with high-lift systems deployed.

$$e_{\text{low speed}} \approx 0.9\, e_{\text{cruise}}$$

Leading edge devices (e.g. slats) typically run the whole of the exposed wing span and a reasonable approximation for both take-off and landing configurations is

$$\Delta C_{D_{\text{slat}}} \approx 0.006$$

This leaves the flap contribution.

Modifications to the drag polar for takeoff and landing

Drag contribution from trailing edge devices depends on type and deflection angle (i.e. lift increment).

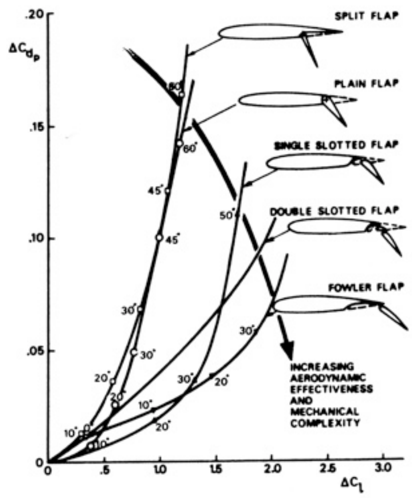
The take-off TE deflection is typically 30% – 50% of maximum (landing) deflection.

HIGH-LIFT DEVICE		TYPICAL FLAP ANGLE		$C_{L_{max}}/\cos\Lambda_{.25}$	
TRAILING EDGE	LEADING EDGE	TAKEOFF	LANDING	TAKEOFF	LANDING
PLAIN	-	20°	60°	1.40-1.60	1.70-2.00
SINGLE SLOTTED	-	20°	40°	1.50-1.70	1.80-2.20
FOWLER*	-	15°	40°	2.00-2.20	2.50-2.90
DOUBLE SLOTTED**	-	20°	50°	1.70-1.95	2.30-2.70
	SLAT			2.30-2.60	2.80-3.20
TRIPLE SLOTTED**	SLAT	20°	40°	2.40-2.70	3.20-3.50

* SINGLE SLOTTED
** WITH VARYING AMOUNTS OF CHORD EXTENSION (FOWLER MOTION)

Torenbeek

Table 7-2. Typical maximum lift coefficients for wings with high lift devices.



Torenbeek

For a given flap type and deflection angle, take $\Delta C_{D\text{flap}}$ from the supplied figures:

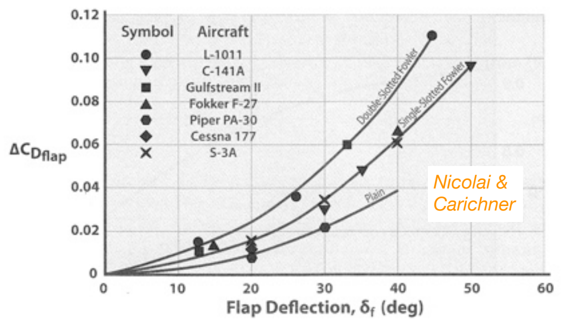


Figure 9.25 Trailing edge flap drag coefficient increment (referenced to wing area).

Note that the increments are typically comparable to or larger than the clean-aircraft $C_{D,0}$ value.

A typical additional drag allowance for an inoperative jet engine is

$$\Delta C_{D_{\text{locked rotor}}} \approx 0.002$$

Modifications to the drag polar for takeoff and landing

The landing approach drag polar is computed similarly to the take-off polar except that the trailing edge devices are given greater deflection and landing gear is extended. The configuration is

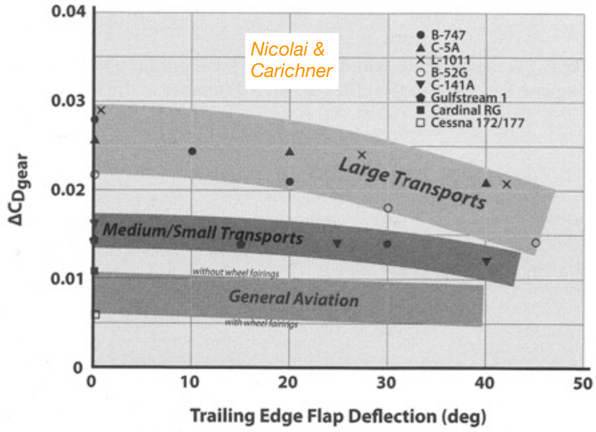
1. Leading edge devices extended.
2. Trailing edge flaps set for landing (maximum deflection).
3. Gear extended.
4. Speed = k_{app} V_{stall} =1.3 V_{stall}.

$$C_D = C_{D,0_{\text{cruise}}} + \Delta C_{D_{\text{slat}}} + \Delta C_{D_{\text{flap}}} + \Delta C_{D_{\text{gear}}} + \frac{C_L^2}{\pi A e_{\text{low speed}}}$$

These were all discussed above with the exception of $\Delta C_{D\text{gear}}$.

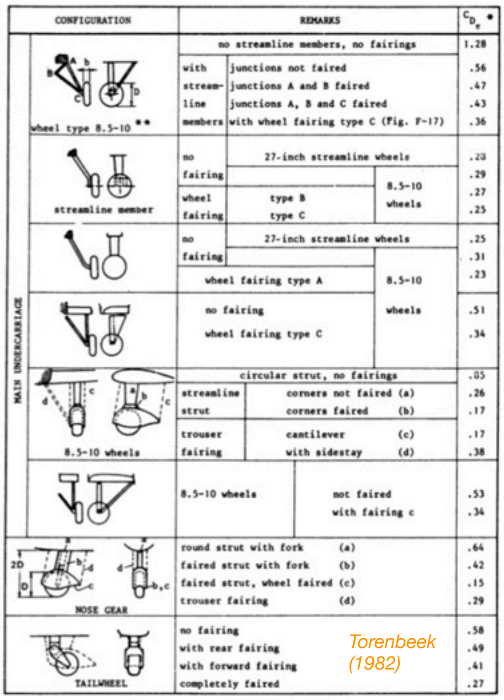
$\Delta C_{D\text{gear}}$ can be estimated in detail using drag build-up methods (or experiment, CFD) or approximately, using the figure to right:

Note again the large incremental values and the fact that the increment typically declines slowly with increasing flap deflection (which occurs because the additional circulation brought about by flap deployment slows the air passing below the wing, i.e. the location of the landing gear).



Modifications to the drag polar for takeoff and landing

If taking the drag-build-up approach to estimating landing gear excrescence drag, one may use the following table from Torenbeek (based largely on Hoerner's earlier compilation):



CONFIGURATION	REMARKS		C_{D_π} *
MAIN UNDERCARRIAGE: wheel type 8.5-10 **	no streamline members, no fairings		1.28
	with streamline members	junctions not faired	.56
		junctions A and B faired	.47
		junctions A, B and C faired	.43
		with wheel fairing type C (Fig. F-17)	.36
streamline member	no fairing	27-inch streamline wheels	.23
		8.5-10 wheels	.29
	wheel fairing type B	8.5-10 wheels	.27
	wheel fairing type C	8.5-10 wheels	.25
	no fairing	27-inch streamline wheels	.25
		8.5-10 wheels	.31
	wheel fairing type A	8.5-10 wheels	.23
	no fairing	8.5-10 wheels	.51
	wheel fairing type C	8.5-10 wheels	.34
8.5-10 wheels	circular strut, no fairings		.05
	streamline strut	corners not faired (a)	.26
		corners faired (b)	.17
	trouser fairing	cantilever (c)	.17
		with sidestay (d)	.38
	8.5-10 wheels	not faired	.53
		with fairing c	.34
NOSE GEAR	round strut with fork (a)		.64
	faired strut with fork (b)		.42
	faired strut, wheel faired (c)		.15
	trouser fairing (d)		.29
TAILWHEEL	no fairing		.58
	with rear fairing		.49
	with forward fairing		.41
	completely faired		.27

Torenbeek (1982)

*for main undercarriages C_{D_π} is referred to the circumscribed frontal area of two tires (2bD), for nose- and tail-gears to that of a single tire (bD)
**with other types the drag can be up to 15% above the values given

Fig. F-19. Fixed undercarriage drag (Refs. F-18, F-111 and F-112)

$C_{D_\square}$ is the item drag coefficient referred to frontal area, as noted, i.e.

$$f = \frac{C_{D_\square} \times \text{Area}}{q}$$

(Raymer provides the following table for landing gear component equivalent flat plate areas in ft², which presumably are irrational as no allowance for variation in item size is made:)

Table 12.5 Landing gear component drags

	D/q Frontal area
Regular wheel and tire	0.25
Second wheel and tire in tandem	0.15
Streamlined wheel and tire	0.18
Wheel and tire with fairing	0.13
Streamline strut ($1/6 < t/c < 1/3$)	0.05
Round strut or wire	0.30
Flat spring gear leg	1.40
Fork, bogey, irregular fitting	1.0–1.4

Raymer

Drag polar in takeoff and landing configurations

The low-speed polars for various low-speed configurations are typically assembled onto one summary plot for further use or comparison purposes.