Schaufele Annotations
Chapter 12 Drag Buildup

Parasite Drag

For a flat surface of area S_{wet} and skin friction coefficient C_f, which is parallel to a flow of velocity V and density ρ, the drag of the surface can be written as

$$D = C_f \frac{1}{2} \rho V^2 S_{wet} = C_f \, q \, S_{wet} \qquad \text{Eq. 12.1}$$

or

$$\frac{D}{q} = C_f \, S_{wet} \qquad \text{Eq. 12.2}$$

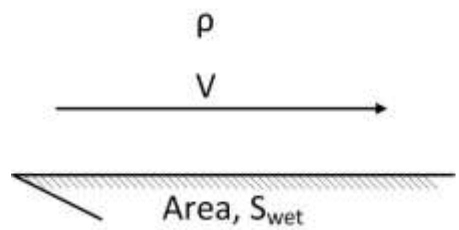


Figure 12.1 Flat Plate Skin Friction Drag

In practice most aircraft surfaces are not flat, so a correction factor K must be included to take account of pressure and separation drag. We can therefore write

$$\frac{D}{q} = K \, C_f \, S_{wet} \qquad \text{Eq. 12.3}$$

where K is an empirical form factor and is a function of the surface geometry.
The parasite drag of the whole airplane is the sum of the drags of each component or

$$D_{P_{airplane}} = \sum_i D_i \qquad \text{Eq. 12.4}$$

or in coefficient form

$$C_{D_P} = \frac{D_P}{q \, S_{ref}} = \sum_i \frac{D_i}{q \, S_{ref}} = \sum_i \left(\frac{D}{q}\right)_i \frac{1}{S_{ref}} = \sum_i \frac{K_i \, C_{f_i} \, S_{wet_i}}{S_{ref}} \qquad \text{Eq. 12.5}$$

This is Schaufele Eq. (12-2). It may be more convenient to calculate the drag of each component in the form D/q, sum all the values of D/q, and then divide by the wing reference area. D/q has the units of area, and may also be written as f, the equivalent flat plate area (or equivalent parasite drag area). This name is based on the fact that the value of f is roughly equal to the area of a flat plate held normal to the flow which has the same drag.

Most components (wing, tail, fuselage, etc.) are aerodynamically smooth, so the drag is mostly due to skin friction, and drag is calculated using skin friction coefficient. The value of f (or D/q) is then calculated using Equation 12.3. Some components, such as deployed landing gear and flaps, and flap hinges (in Schaufele's book), are bluff, so drag is mostly due to separation. For these cases, drag is often calculated based directly on the equivalent flat plate area f, and skin friction drag is not calculated. Drag of bluff components may be stated as f/(unit area), in which case this coefficient must be multiplied by the component frontal area (normal to the flow) to obtain the value of f. In Schaufele's book the flap hinge drag increment is stated directly as f.

Eq. 12.5 may therefore be written as:

$$C_{D_p} = \frac{\sum \frac{D}{q}}{S_{ref}} \qquad \text{Eq. 12.6}$$

It may be more convenient to think of drag buildup in this format. Either the values of ΔC_{D_p} may be summed for all components, or the values of D/q for all components may be summed, and then divided by S_{ref}.

In an industrial-grade mission sizing and design optimization computer program, the aircraft undergoes subtle changes of shape every time the computer loops through a weight iteration, or the design parameters of the airplane are changed. Typically the design parameters that are held constant, or modified under the control of the program are:

- Wing: AR_{wing}, Λ_{wing}, λ_{wing}, $(t/c)_{wingroot}$, $(t/c)_{wingtip}$
- Horizontal tail: AR_H, Λ_H, λ_H, $(t/c)_H$, V_H ,
- Vertical tail: AR_V, Λ_V, λ_V, $(t/c)_V$, V_V ,
- Nacelle: l_{pylon}/d_{nac}, d_{nac}/thrust, l_{nac}/thrust
- Fuselage: l_{fuse}, d_{fuse}, l_{taper}/l_{fuse}

The computer program then calculates the wetted area of the components, and excludes from each component the areas of the intersections, as illustrated in Fig 12.2. In this chapter of Schaufele the configuration is assumed to be fixed, so there is no requirement for iteration.

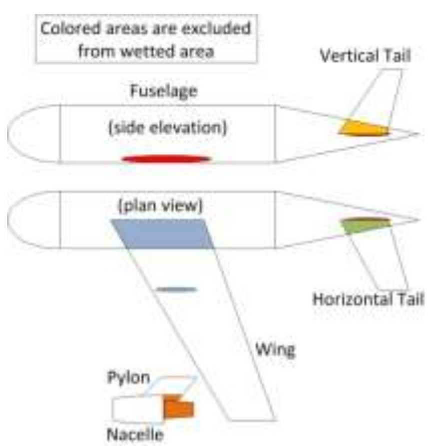


Figure 12.2 Wetted area buildup

Thrust and drag accounting for the nacelle and pylon is a matter for negotiation between the airframe manufacturer and the engine manufacturer. Usually drag due to the area of the nacelle and pylon that is scrubbed by the fan exhaust is subtracted from engine thrust. Sometimes the engine manufacturer will take responsibility for all nacelle drag. Parasite drag buildup can easily be calculated using a spreadsheet using a table with the format shown in Figure 12.3.

Component	S_{wet} (ft^2)	S_{xs} (ft^2)	l_{ref} (ft)	RN	K	C_f	$\frac{f}{S_{xs}}$	f (ft^2)	ΔC_{D_P}
Wing									
Fuselage									
Horiz. Tail									
Vert. Tail									
Pylons									
Nacelles									
Flap Hinges								0.15	
Slats									
Flaps									
LG									
Total									$\Sigma\ \Delta C_{D_P}$

Figure 12.3 Parasite Drag Buildup Table

In Figure 12.3

- S_{wet} is calculated (and remember to include both sides of a lifting surface).
- l_{ref} is the overall length of the fuselage, pylon, nacelles, or other streamlined, non-lifting surface. For a lifting surface it is the length of the m.a.c. (there is no need to calculate the m.a.c. of the exposed area; the reference area m.a.c. is close enough).
- RN is the Reynolds Number based on reference area.
- K is the form factor using Schaufele Figures 12-3 and 12-4. In a computer program this may also be a function of Mach number.
- C_f is the turbulent skin friction coefficient (Schaufele Fig. 12-2). In a computer model this is also expressed in an algebraic form, including a Mach term.
- $f = K\, C_f\, S_{wet}$
- f/S_{xs} is the flat plate drag per unit cross-sectional area.
- $\Delta C_D = f/S_{ref}$

The curve of Schaufele Fig. 11-2 can be expressed as

$$C_f = \frac{0.455}{\left(\log_{10} R_L\right)^{2.58}} \qquad \text{Eq. 12.8}$$

C_f is a function of surface finish, and this expression is only valid for a typical metal aircraft skin condition, as stated in the figure. C_f is also a function of Mach number (independently of Reynolds number), but the correction is small for subsonic Mach numbers (a doubling of Mach number from 0.4

to 0.8 results in a decrease in C_f of about 4%) and is omitted here (Ref 12.1). Fig. 12-2 (and the expression above) is valid for a Mach number of 0.5 (Ref. 12.2).

Boxes shaded in light grey are not required to be used in these exercises. However, in some cases component drag will be quoted as D/q per unit cross-section area, in which case these boxes will be used. In this example, the suggested value of f for flap hinge fairings (which are prominent on a DC-9 and DC-10, and slightly less prominent on the 787) as 0.15 ft^2. This value is valid for a DC-9 only. The cell values for hinge cross-section area and hinge D/q per unit area can therefore be left blank because the final value is given. Airplanes with plain flaps will not have exposed flap hinges. Airplanes with multiple slotted flaps will normally have fairings that have a form factor as for a fuselage shape. The drag calculation will therefore be performed as for a fuselage.

In the calculation of the nacelle form factor, Schaufele uses the external diameter of the nacelle. This is incorrect. Most of the air within the nacelle maximum diameter passes through the engine, and the form factor should be based on the fact that some air passes around the outside of the nacelle. The equivalent form factor is:

$$D_{equiv} = \sqrt{D_n^2 - D_h^2} \qquad \text{Eq. 12.7}$$

where D_n is the nacelle maximum diameter and D_h is the highlight diameter. The highlight is the line around the most forward surface of the nacelle. Typically $D_h = 0.8\ D_n$ so that $D_{equiv} = 0.6\ D_n$, and D_{equiv} should be used in calculating nacelle form factor.

Schaufele factors the sum of all values of D/q by 1.1 to account for miscellaneous drag items. Often these drag items will be broken down into more detail, and will include interference drag factors, which are a function of the two components in question.

In Schaufele Figure 12-11 the value of C_D at Mach numbers below the drag rise is shown as being constant with Mach number. This is not quite correct. Schaufele Figure 12-2 shows that the skin friction coefficient C_f (and thus C_D) decreases with increasing Reynolds number. This implies that when flying at a constant altitude, C_D decreases with increasing speed. The effect is fairly small (a doubling of speed results in less than 10% decrease in C_f) but not insignificant.

Airplane Parasite Drag

The equivalent skin friction coefficient for the whole airplane, C_F, is defined in Schaufele Eq. (12-4) as

$$C_F = \frac{f}{S_{wet}}$$

where f is the equivalent flat plate area for the whole airplane. Combining this with Schaufele Eq. (12-3)

$$f = C_{D_p} S_{ref}$$

we can write

$$C_{D_p} = \frac{f}{S_{ref}} = C_F \frac{S_{wet}}{S_{ref}}$$ Eq. 12.9

This provides us with a quick and easy way of calculating C_{D_p}. Schaufele Fig. 12-6 shows us that for most civil jets C_F = 0.003. From a knowledge of airplane wetted area and wing reference area, it is therefore possible to estimate C_{D_p} reasonably accurately for this class of airplane. For other classes of airplane, there is a larger variation in C_F so this short-cut method is much less accurate.

Drag due to Lift

Unfortunately engineers use the term "induced drag" when they mean "drag due to lift". To compound the issue, drag due to lift is usually written as C_{D_i}. Drag due to lift has two components, inviscid drag due to lift, and viscous drag due to lift. Inviscid drag due to lift is induced drag, and comprises about 2/3 of total drag due to lift at cruise. On a finite wing, the tip vortices induce a downwash in the area of the wing that rotates the local lift vector aft. The component of the local lift vector in the direction of the free stream flow is induced drag. The bound vortex on the wing, in combination with the free-stream flow, produces higher velocities on the upper surface of the wing, and lower velocities on the lower surface. These increased velocities produce increased skin friction drag and flow separation, which appear as viscous drag due to lift.

L/D vs C_L Plot

The value of lift to drag ratio L/D may be written as:

$$\frac{L}{D} = \frac{C_L}{C_D} = \frac{C_L}{C_{D_p} + \frac{C_L^2}{\pi AR\, e} + \Delta C_{D_c}}$$ Eq. 12.10

The calculation of parasite drag coefficient C_{D_p} is described above. Using Schaufele Fig. 12-9, the calculation of drag due to lift is straightforward, with a knowledge of the wing geometry and parasite drag coefficient.

The graph in the upper half of Fig. 12-9 reflects the fact an aircraft with a larger fuselage diameter as a percentage of wing span will most likely have a larger value of C_{D_p}. At the same time it will also have a larger reduction in spanwise lift distribution at the centerline. This change from the ideal elliptical distribution will result in a reduction in airplane efficiency factor.

When generating plots of L/D versus C_L for different Mach numbers, you must take account of the fact that C_{D_c} is a function of both C_L and Mach number. From Schaufele Fig. 4-8, for a given value of wing sweep angle and average thickness ratio, find the relationship between M_{DIV} and C_L. From Schaufele Fig.

12-10, for a given Mach number and C_L (from which you now know M_{DIV} and hence $(M-M_{DIV})$), you could calculate ΔC_{D_c} except that it would be somewhat tedious to do manually.

To generate a plot of L/D versus C_L using a spreadsheet, the relationship between ΔC_{D_c} and $(M-M_{DIV})$ must be expressed analytically. An example, which may be used for the design exercise, is:

$$\Delta C_{D_c} = \frac{1}{1163}\left[\frac{1}{\left(0.972 - \sqrt{0.945 + (M - M_{DIV})}\right)^2} - 1\right] - 0.0002 \qquad \text{Eq. 12.11}$$

This function will have negative values when $(M-M_{DIV}) < -0.4$, so the value of ΔC_{D_C} can be set to zero for that condition in a spreadsheet using an Excel conditional function:

IF(condition, value_if_true, value_if_false)

In reality, the value of ΔC_{D_C} reduces to zero when $(M-M_{DIV}) < -0.1$ or thereabouts, but the resulting error in the value of C_D is quite small, so the function is adequate for this exercise.

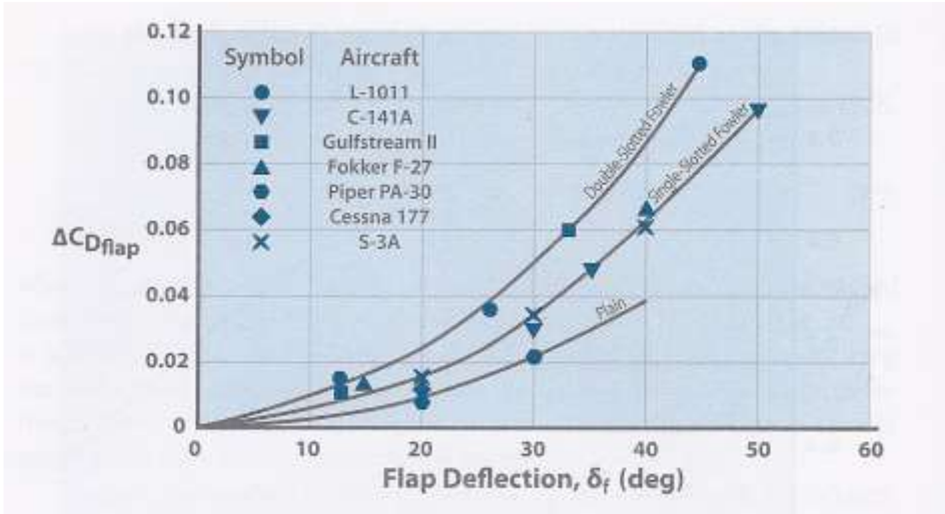
There is no consensus as to the definition of M_{DIV}. Common definitions are for the values of M when:

- $\Delta C_{D_c} = 0.0020$ (Boeing definition)
- $\frac{\Delta C_{D_c}}{\Delta M} = 0.1$ (Douglas definition)

The Douglas definition results in a higher value of M_{DIV} than the Boeing definition. As can be seen from Schaufele Fig. 12-10, a value of $\Delta C_{D_c} = 0.0016$ is used in this figure, and this produces a value of M_{DIV} that is lower than either the Boeing or Douglas definitions. Eq. 12.11, shown above, meets the Boeing definition.

Landing Configuration

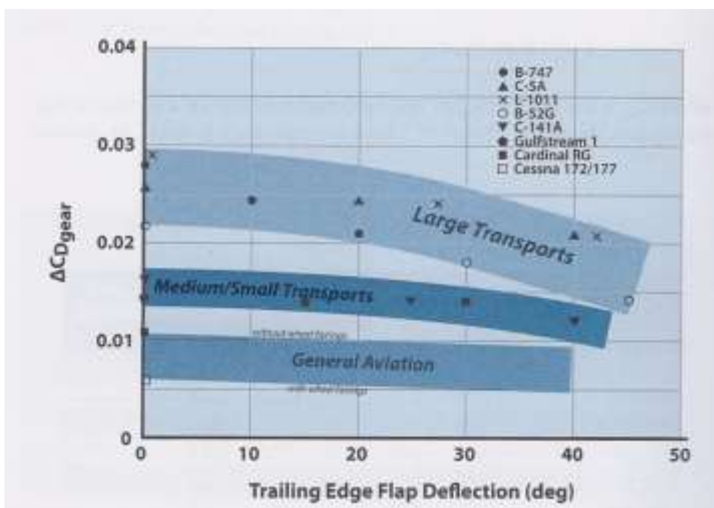
Schaufele Fig. 12-15 shows the increase in landing gear parasite drag for one aircraft configuration (probably for the DC-9). Figure 12.4 (from Reference 12.3) shows a more general set of data for different aircraft types.



Source: Nicolai/Carichner

Fig. 12-4 Flap Drag as Function of Deflection

Schaufele Fig. 12-17 shows the parasite drag increment due to landing gear extension for one aircraft configuration (probably also for the DC-9). However, the drag increment is also a function of aircraft type, and the relationship shown in Fig. 12-17 is valid for large transports only. It is better to express landing gear drag in the form D/q, rather than ΔC_D , so that the drag definition is independent of wing area.



Source: Nicolai/Carichner

Figure 12.5 Parasite Drag Increment due to Landing Gear Extension

Figure 12.5 shows additional relationships for medium/small transports, and general aviation.

References

12.1 Raymer, D.P., "Aircraft Design: A Conceptual Approach, 4th Edition", AIAA, 2006
12.2 Shevell, R.S., "Fundamentals of Flight, 2nd Edition", Prentice Hall, 1983

12.3 Nicolai, L.M., and Carichner, G.E., “Fundamentals of Aircraft and Airship Design, Volume 1 – Aicraft Design”, AIAA, 2012