Today, we will:

- Finish external flow - lift and drag on cylinders and spheres (finish Chapter 11)
- Do some example problems – bicycle and truck drag
- Discuss lift on airplane wings

C_D drops suddenly when BL changes from laminar separation to turbulent separation

The "drag crisis" on cylinders and spheres

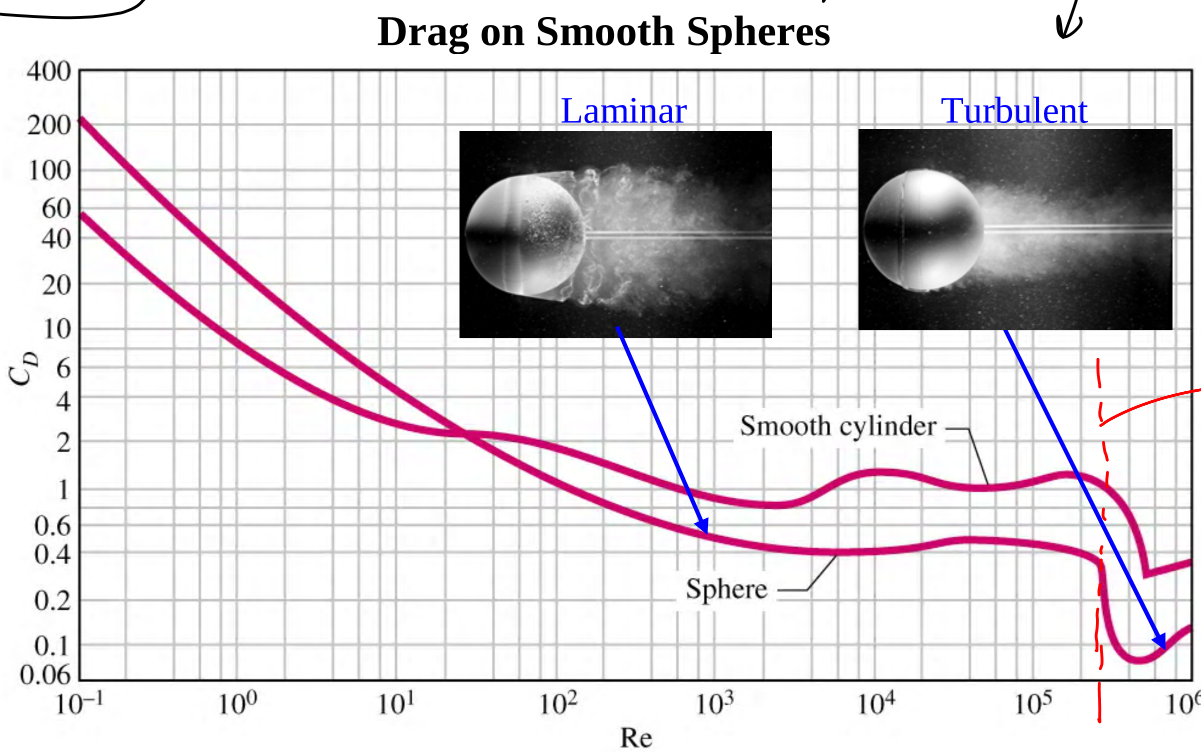


Figure 11-34 & 35. Average drag coefficient for cross-flow over a smooth circular cylinder and a smooth sphere.

Why? → Turbulent BL is more resistant to flow separation than a laminar BL is.

Roughness → ε/D on a cyl. or sphere

- Laminar BL → ε does not matter
- Turbulent BL → ε has a big effect

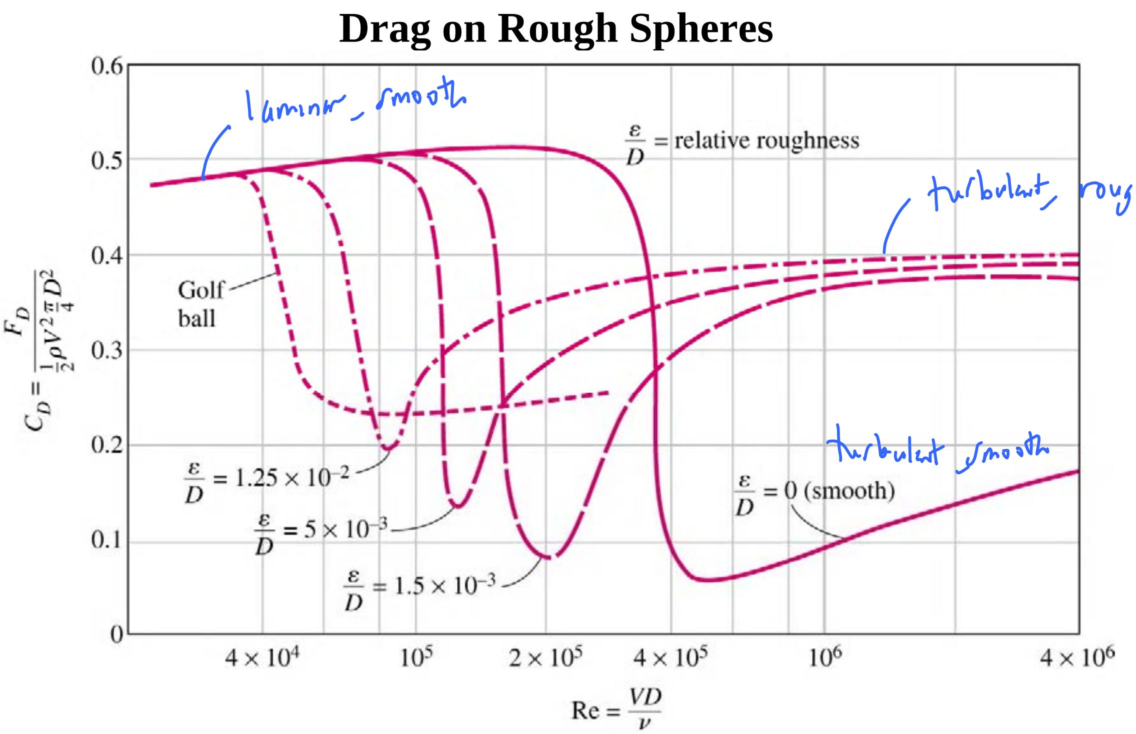
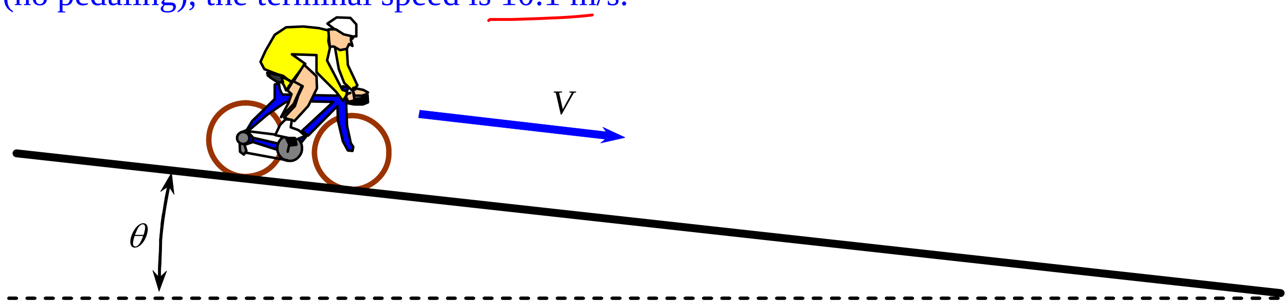


Figure 11-36. The effect of surface roughness on the drag coefficient of a sphere.

Example – Drag on a Bicycle Rolling Down a Hill

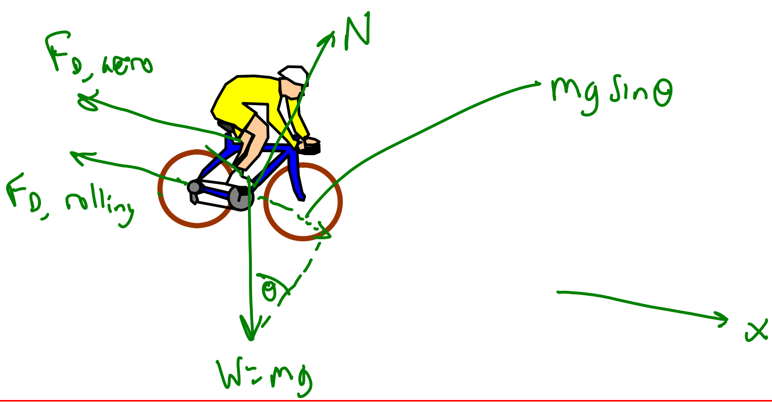
Given: A person coasts a bicycle down a long hill with a slope of 5° in order to measure the drag area of the bike and rider. The mass of the bike is 7.0 kg, the mass of the rider is 70.0 kg, and the rolling resistance of the bike is measured separately – it is 19.0 N. When the rider coasts down the hill (no pedaling), the terminal speed is 10.1 m/s.



(**a**) **To do**: Calculate the drag area $C_D A$ of the rider/bicycle combination.

Solution: (to be completed in class)

First draw a free-body diagram of the bicycle and rider, showing all forces acting.



$\sum F_x = 0$ (no accel.)

$F_{D_{aero}} + F_{D_{rolling}} = mg\sin\theta$

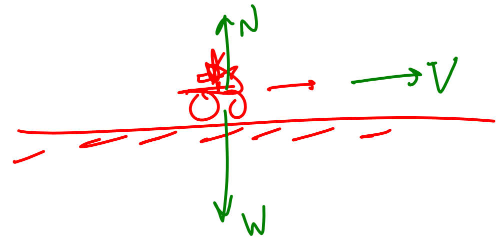
$\frac{1}{2}\rho V^2 C_D A + F_{D_{rolling}} = mg\sin\theta$

Solve for $C_D A$ → $\boxed{C_D A = \text{"drag area"} = \dfrac{mg\sin\theta - F_{D_{rolling}}}{\frac{1}{2}\rho V^2}}$

Numbers → $\boxed{C_D A = 0.763 \text{ m}^2}$

(b) To do: Calculate how much power it would take for the person to ride this bike on a level road at the same speed (10.1 m/s).

Solution: (to be completed in class)



Soln: $\dot{W} = \underbrace{F_D}_{\frac{1}{2}\rho V^2 C_D A + F_{D\_rolling}} V$

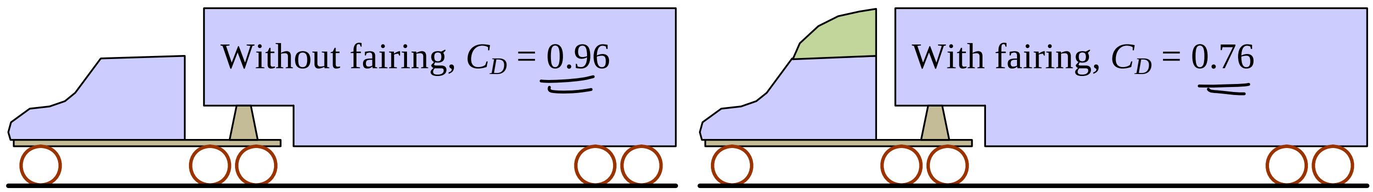
Numbers: $\boxed{\dot{W} = 665 \text{ W} \approx 0.892 \text{ hp}}$

Comment: N also increases slightly on level road compared to the hill, but this is a very small effect, especially at only 5° incline

$$\left[\sin(5^\circ) = 0.087, \quad \cos(5^\circ) = 0.996\right]$$

Example – Drag on an 18-Wheeler

Given: We compare the gas mileage and operating cost of an 18-wheeler driving at 60 mph (26.82 m/s) with and without an aerodynamic fairing. For both cases, the frontal area A = 8.5 m^2 and the rolling resistance is 2750 N. Take the density of the air to be 1.20 kg/m^3. The engine output is rated at E_o = 13.0 hp·hr/gal [for each gallon of diesel fuel used, the engine delivers 13 hp of useful shaft power to the wheels for one hour].



(**a**) **To do**: Calculate the power required to overcome the drag (rolling + aerodynamic) at a speed of 60 mph for both cases.

Solution: (to be completed in class)

$$\dot{W} = F_{D_{rolling}} V + \frac{1}{2}\rho V^3 C_D A$$

Numbers:

$$\dot{W}_{w/o} = 168.2 \text{ kW} \approx \boxed{168 \text{ kW}}$$

$$\dot{W}_{w/} = 148.56 \text{ kW} \approx \boxed{148 \text{ kW}}$$

With no fairing

With fairing

C_D improves by $\frac{0.96-0.76}{0.96} = 21\%$

$\dot{W}$ improves by $\frac{148-168}{168} = -12\%$

agrees with our "ballpark" estimate

(**b**) **To do**: Calculate the gas mileage (miles per gallon) for both cases at 60 mph, and the fuel cost savings provided by the fairing for a round trip cross-country trip (6000 miles). Assume fuel costs \$4.00 per gallon.

Solution: (to be completed in class)

$$\boxed{\text{mpg} = \frac{E_o V}{\dot{W}}} \rightarrow \# \text{s} \quad \text{mpg}_{w/o} = \frac{\left(13.\ \frac{\text{hp·hr}}{\text{gal}}\right)\left(60\ \frac{\text{mi}}{\text{hr}}\right)\left(\frac{0.7457 \text{ kW}}{\text{hp}}\right)}{168.2 \text{ kW}} = \boxed{3.46 \text{ mpg}}$$

$$\boxed{\text{mpg}_{w/} = 3.92 \text{ mpg}}$$

Improve ≈ 13%

For a 6000 mile trip,

$$\text{fuel cost}_{w/o} = (6000\ \cancel{mi})\left(\frac{1\ \cancel{gal}}{3.457\ \cancel{mi}}\right)\left(\frac{\$4.00}{\cancel{gal}}\right) = \$6942$$

$$\text{fuel cost w/} = \frac{}{3.915} = \$6130$$

$$\boxed{\text{Save} \simeq \$811 \text{ on one trip!}}$$

(c) Compare 60 mph to 70 mph (with fairing)

@ 60 mph → \$6130 for 6000 mi. trip

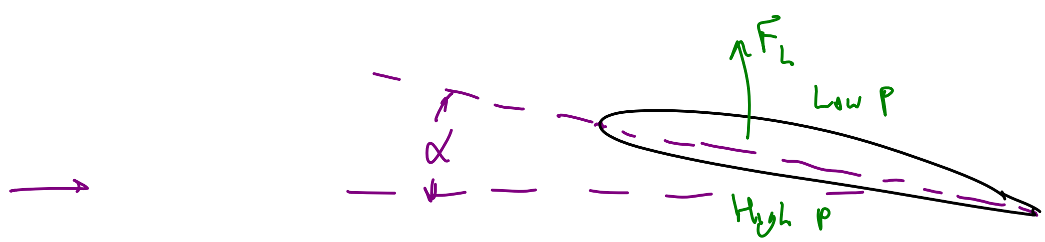
@ 70 mph → \$7250 " " " "

≃ \$1100 more!

B. Lift

1. 2-D airfoils

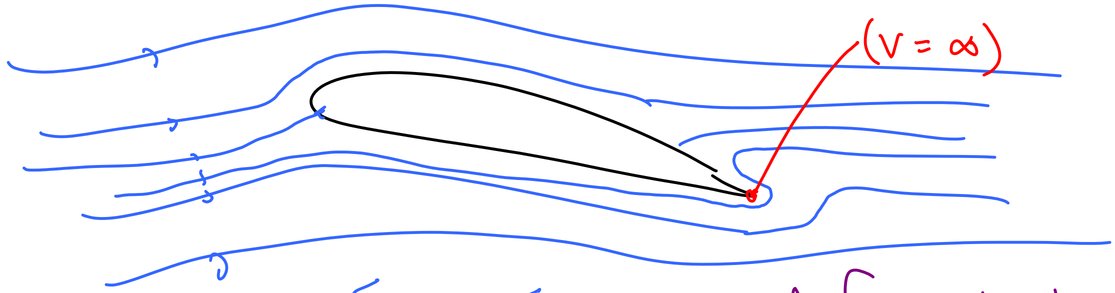
α = angle of attack



At low angles of attack (no stall), viscous effects are pretty small when calculating lift.

Pressure determines lift

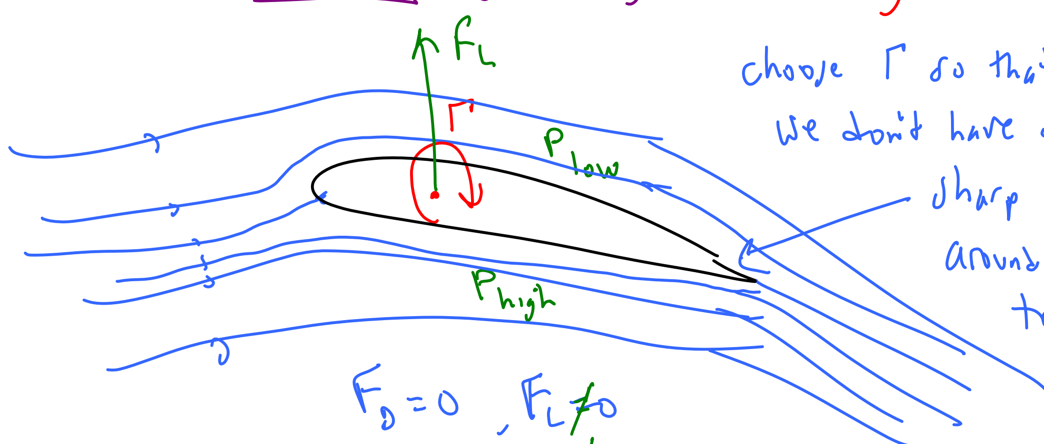
• What if we use potential flow (irrotational flow) to estimate F_L?



$F_D = 0$, $F_L = 0$

* [We simply add a line vortex to our solution]

If we add a line vortex (clockwise) (superposition)

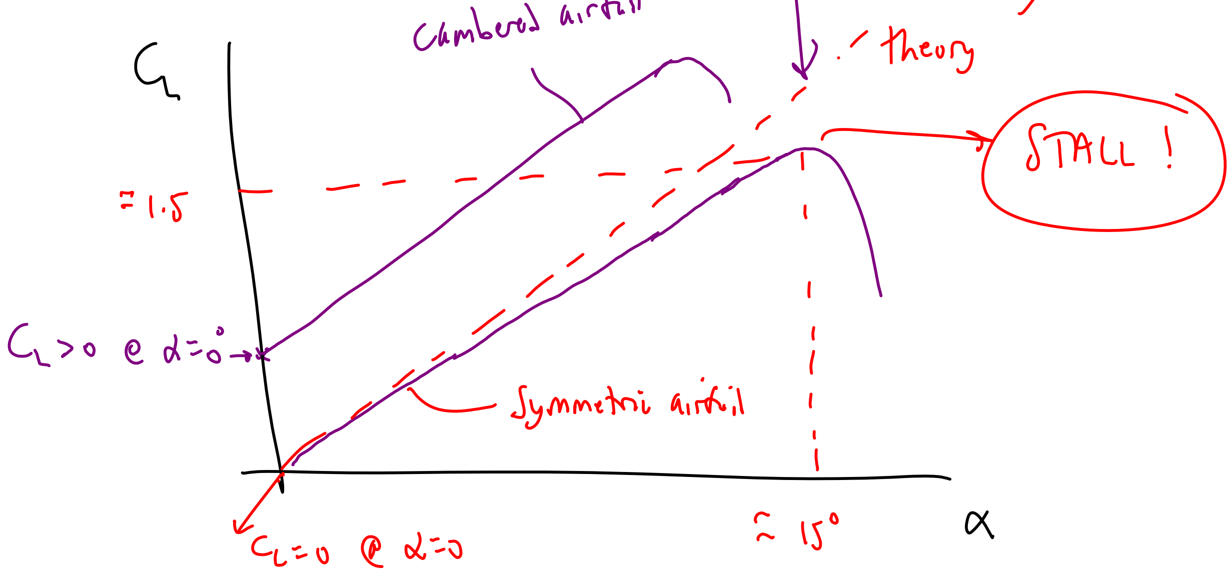


choose Γ so that we don't have such a sharp turn around the trailing edge

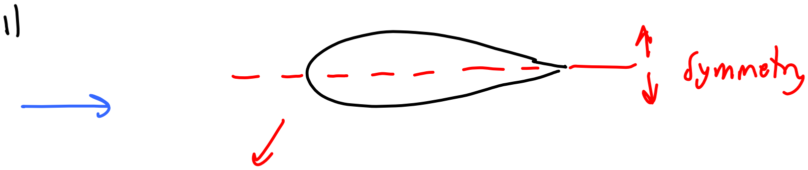
$F_D = 0$, $F_L \neq 0$

We can now predict the lift.

This is an excellent approximation for real flows (up to stall anyway)

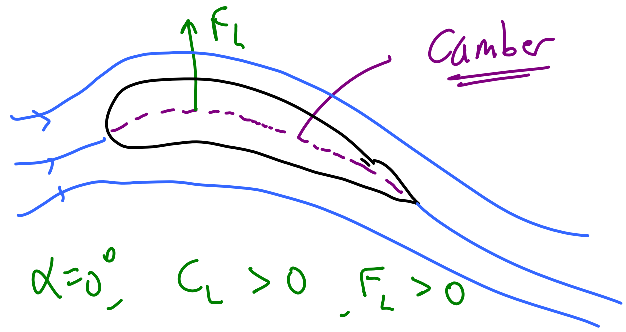


Symmetrical airfoil



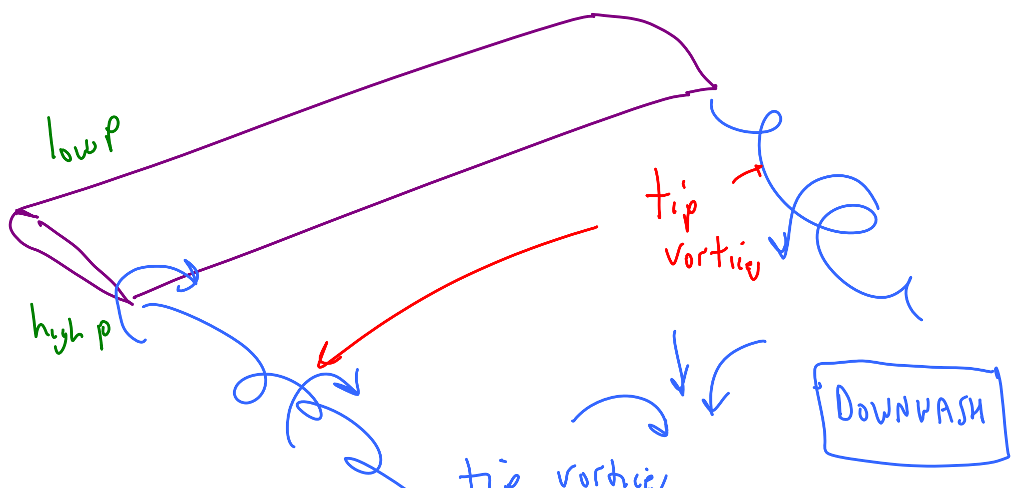
@ $\alpha = 0^\circ$, $C_L = 0$

Nonsymmetrical airfoil



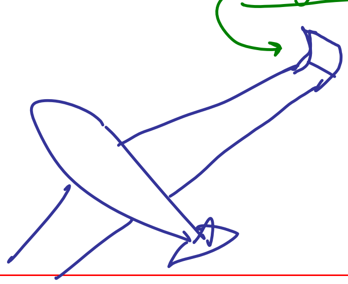
@ $\alpha = 0^\circ$, $C_L > 0$, $F_L > 0$

3-D airfoils (wings)



tip vortices
- waste energy (lots of k.e.)
- increase drag on wing → $\boxed{\text{Induced drag}}$ ☆

We can add winglets to lessen the strength of tip vortices



← You see these on modern airplanes

→ tip vortices still there, but weaker