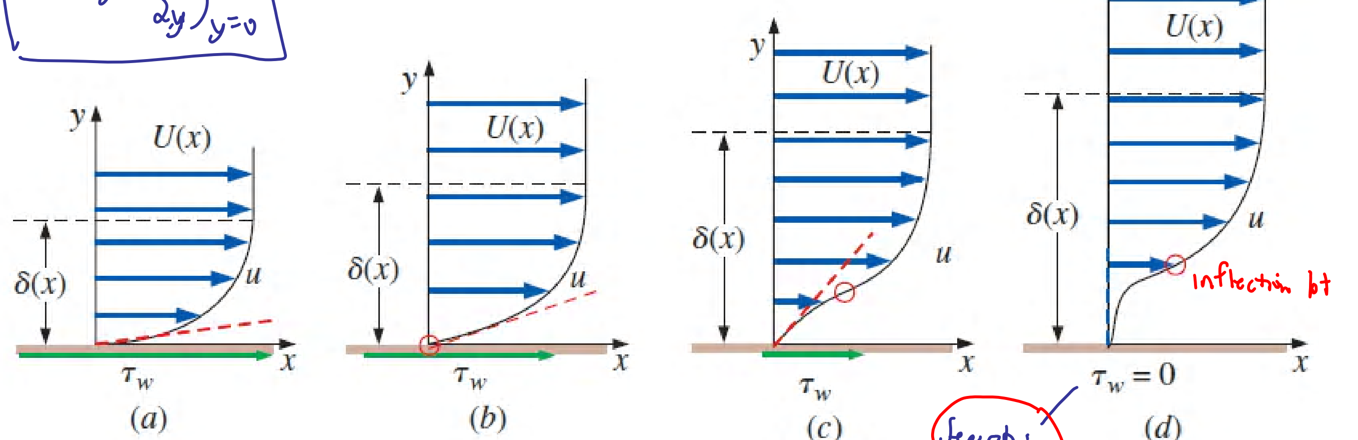
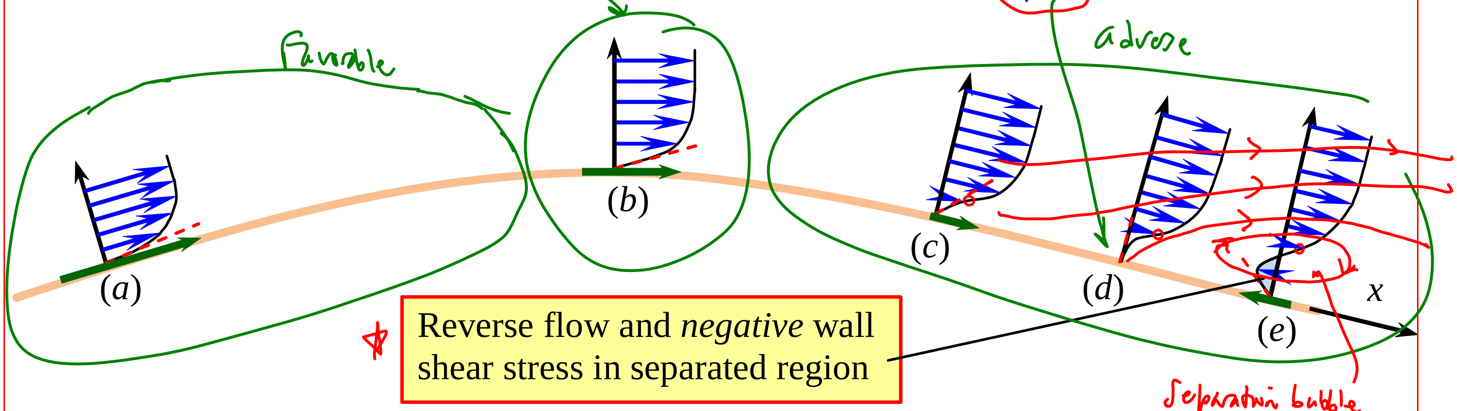
Today, we will:

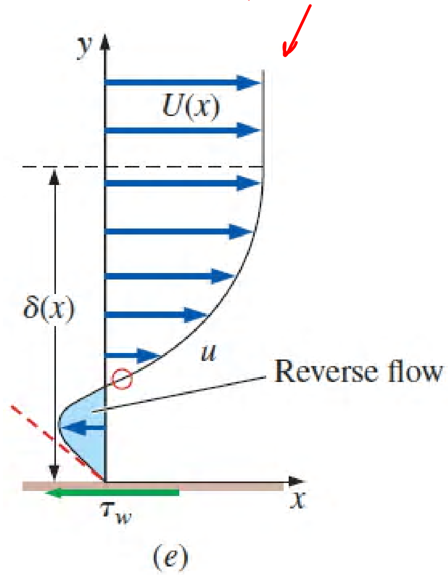
- Finish talking about boundary layers with pressure gradients (finish Chapter 10)
- Begin Chapter 11 – Flow over Bodies: Drag and Lift

The process of flow separation: → τ_w is decreasing as BL goes from favorable to adverse

$$\tau_w = \mu \left.\frac{\partial u}{\partial y}\right)_{y=0}$$







Since τ_w is decreasing, there is less skin friction

is separation good? No

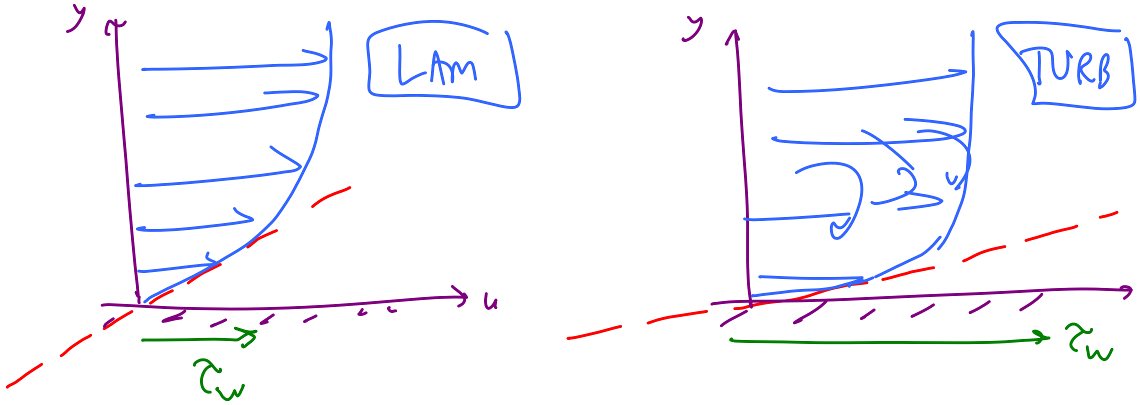
↓

But pressure drag increases significantly

friction drag ↓
pressure drag ↑ } when the flow separates

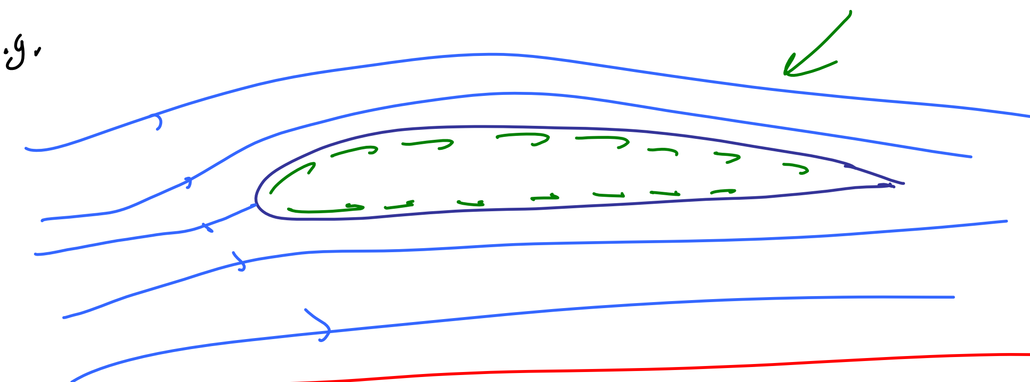
(pressure drag usually "wins")

C. Which is better, laminar BL or turbulent BL?



Turb. BL has more skin friction → laminar BL is "better"

E.g.

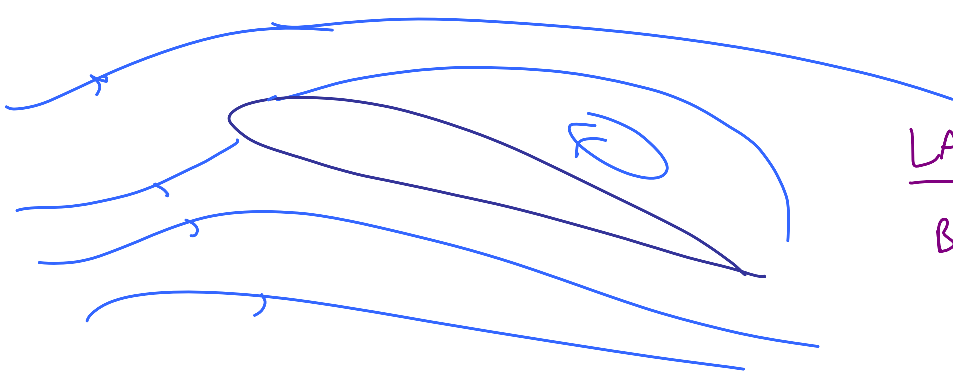


For a thin body w/o flow separation, laminar is better

BUT,

★ A turbulent BL is much more resistant to flow separation than is a laminar BL

Eg.

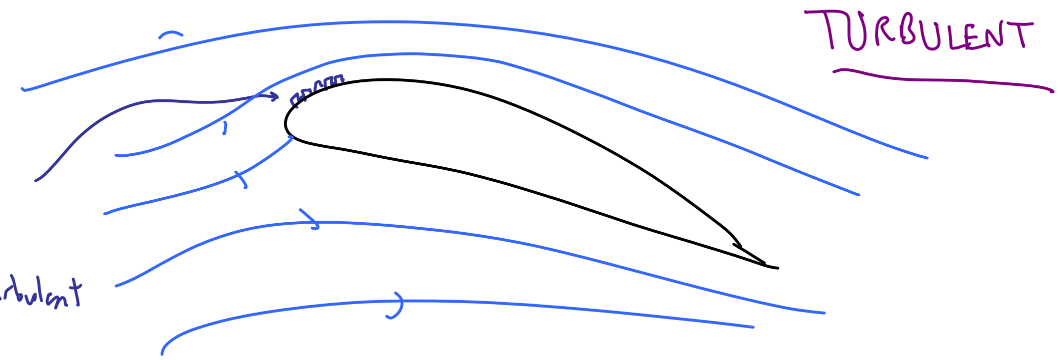


LAMINAR

BL separates

(stall)

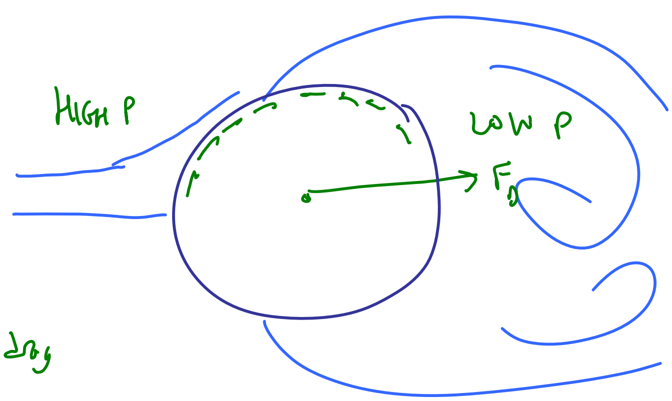
Turbulent is "better" when the laminar BL would separate



roughness helps BL to go turbulent

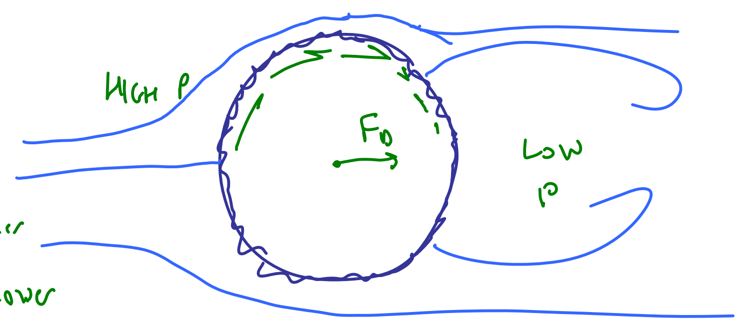
- Golf Balls

Smooth → laminar BL → high drag



W/ dimples → Turbulent BL

Skin friction drag is higher
But pressure drag is lower

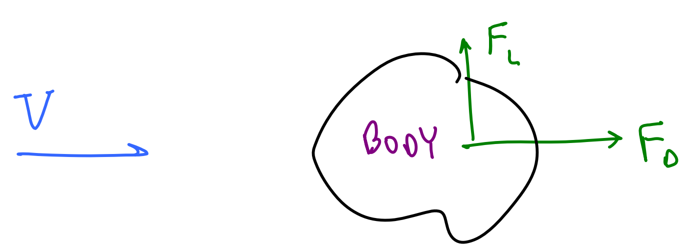


Smaller drag

IX FLOW OVER BODIES : LIFT & DRAG (CH. 11)

A. Introduction

1. Definitions



$F_D \parallel V$ — aerodynamic drag

$F_L \perp V$ — aerodynamic lift

from Ch. 7 →

$$C_D = \frac{F_D}{\frac{1}{2}\rho V^2 A} = \text{drag coeff.}$$

$$C_L = \frac{F_L}{\frac{1}{2}\rho V^2 A} = \text{lift coeff.}$$

A = an appropriate area

Most bodies, A = frontal area ← looking at the front

For thin bodies (flat plate, airfoils) → A = planform area
↓
looking at the top

2. Power required to overcome aero. drag

$$\dot{W}_{aero} = \underline{F_{D_{aero}}} \cdot \bar{V}$$

$$\{Power\} = \left\{\frac{work}{time}\right\} = \left\{\frac{force \cdot distance}{time}\right\} = \{force \cdot vel.\}$$

3. Drag on automobiles

$$\text{Total } F_D = F_{D_{\text{rolling resistance}}} + F_{D_{aero}}$$

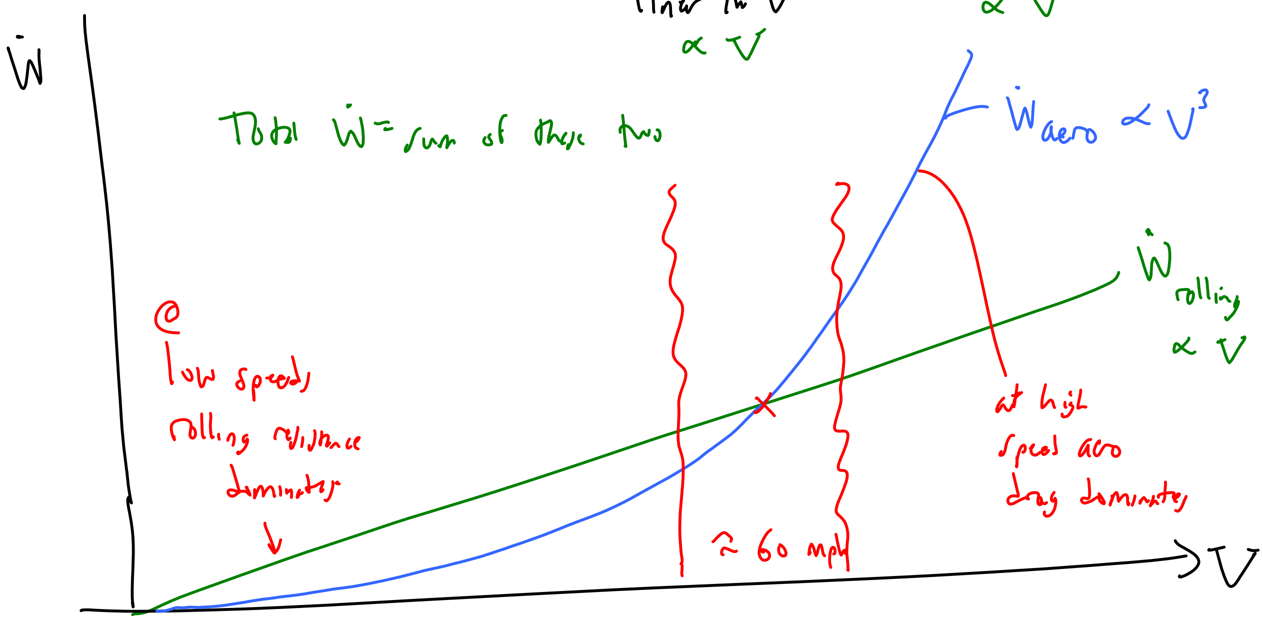
$$F_D = \mu_{rolling} \cdot W + C_D \tfrac{1}{2} \rho V^2 A$$

(W ↑ weight of the car)

Total power (to the wheels)

$$\dot{W} = F_D V = \underbrace{\mu_{rolling} W}_{\text{constant}} \cdot V + C_D \tfrac{1}{2} \rho V^3 A$$

linear in V — $\propto V$ $\qquad \propto V^3$



See website link → C_D for cars $\qquad$ C_D is dimensionless

$$\boxed{C_D A} \equiv \text{drag area} \rightarrow \{L^2\} \rightarrow ft^2 \text{ or } m^2$$

At highway speeds (≈ 60 mph), the power is half due to rolling resistance & half due to aerodynamic drag

↓

So → 20% decrease in C_D results in ≈ 10% increase in gas mileage at highway speeds

Comparison of two cars with identical engines, transmissions, frontal area, etc., but different aerodynamics

2005 Scion XA

$C_D = 0.31$

$C_D A = 7.0\ ft^2$

EPA Mileage estimate with manual transmission: **32 City, 37 Highway**.

2005 Scion XB

$C_D = 0.35$

$C_D A = 8.5\ ft^2$

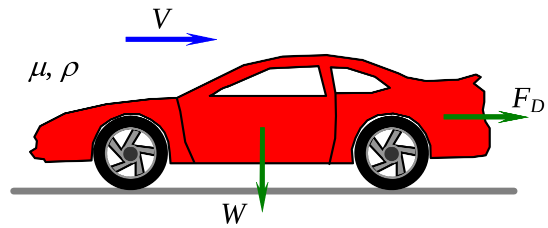
EPA Mileage estimate with manual transmission: **30 City, 33 Highway**.

Conclusions:

- Mileage estimates in the city do not differ very much, since aerodynamic drag is a small percentage of total drag at low speeds.
- Mileage estimates on the highway differ more significantly, since aerodynamic drag is much more significant at highway speeds.

Example: Engine power required to drive a car

Given: A 1999 Honda Prelude weighs 3000 lbf (m = 1361 kg). Its drag area is $C_D A$ = 0.5971 m^2, and its rolling resistance coefficient is μ_{rolling} = 0.0155. It is driven at 70.0 mph (31.29 m/s). The air density and kinematic viscosity are ρ = 1.204 kg/m^3 and ν = 1.516×10^{-5} m^2/s, respectively.



To do: Estimate the power requirement of the engine (in kW) delivered to the wheels.

Solution:

Equation: $\dot{W} = \mu_{\text{rolling}} W V + \frac{1}{2}\rho V^3 C_D A$

mg

$$\dot{W} = (0.0155)(1361\text{ kg})\left(9.807\ \frac{\text{m}}{\text{s}^2}\right)\left(31.29\ \text{m/s}\right)$$

$$+ \frac{1}{2}\left(1.204\ \frac{\text{kg}}{\text{m}^3}\right)\left(31.29\ \text{m/s}\right)^3\left(0.5971\ \text{m}^2\right)\left[\frac{\text{N}\cdot\text{s}^2}{\text{kg}\cdot\text{m}}\right]\left[\frac{\text{kW}\cdot\text{s}}{1000\ \text{N}\cdot\text{m}}\right]$$

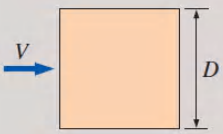
$$= \boxed{17.5\ \text{kW}} \approx 23.5\ \text{hp}$$

Drag Coefficients – See text, Table 11-1 (2-D bodies), Table 11-2 (3-D bodies)

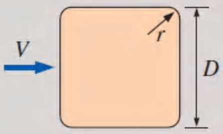
TABLE 11–1

Drag coefficients C_D of various two-dimensional bodies for Re > 10^4 based on the frontal area $A = bD$, where b is the length in direction normal to the page (for use in the drag force relation $F_D = C_D A \rho V^2/2$ where V is the upstream velocity)

Square rod

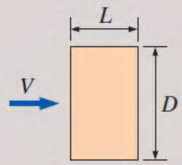


Sharp corners: $C_D = 2.2$



Round corners $(r/D = 0.2)$: $C_D = 1.2$

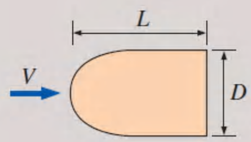
Rectangular rod



Sharp corners:

L/D	C_D
0.0*	1.9
0.1	1.9
0.5	2.5
1.0	2.2
2.0	1.7
3.0	1.3

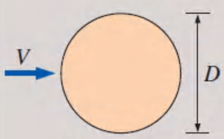
* Corresponds to thin plate



Round front edge:

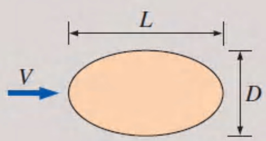
L/D	C_D
0.5	1.2
1.0	0.9
2.0	0.7
4.0	0.7

Circular rod (cylinder)



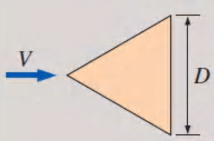
Laminar: $C_D = 1.2$
Turbulent: $C_D = 0.3$

Elliptical rod

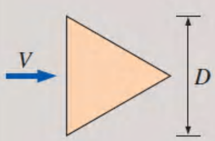


	C_D	
L/D	Laminar	Turbulent
2	0.60	0.20
4	0.35	0.15
8	0.25	0.10

Equilateral triangular rod

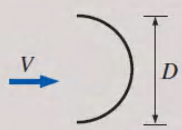


$C_D = 1.5$

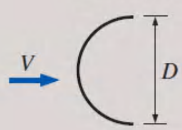


$C_D = 2.0$

Semicircular shell

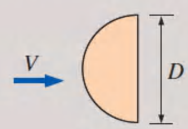


$C_D = 2.3$

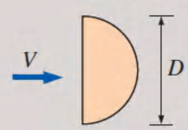


$C_D = 1.2$

Semicircular rod



$C_D = 1.2$

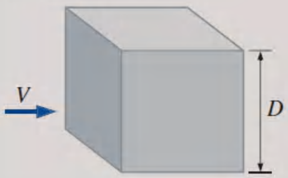


$C_D = 1.7$

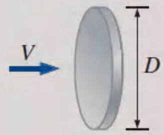
TABLE 11–2

Representative drag coefficients C_D for various three-dimensional bodies based on the frontal area for Re > 10^4 unless stated otherwise (for use in the drag force relation $F_D = C_D A \rho V^2/2$ where V is the upstream velocity)

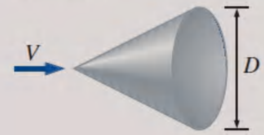
Cube, $A = D^2$



Thin circular disk, $A = \pi D^2/4$



Cone (for $\theta = 30°$), $A = \pi D^2/4$

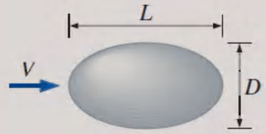


Sphere, $A = \pi D^2/4$

Laminar:
Re $\lesssim 2 \times 10^5$
$C_D = 0.5$
Turbulent:
Re $\gtrsim 2 \times 10^6$
$C_D = 0.2$

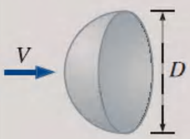
See Fig. 11–36 for C_D vs. Re for smooth and rough spheres.

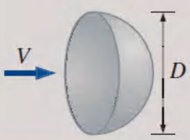
Ellipsoid, $A = \pi D^2/4$



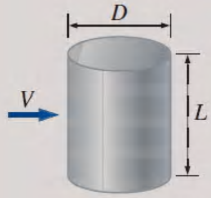
L/D	C_D Laminar Re $\lesssim 2 \times 10^5$	C_D Turbulent Re $\gtrsim 2 \times 10^6$
0.75	0.5	0.2
1	0.5	0.2
2	0.3	0.1
4	0.3	0.1
8	0.2	0.1

Hemisphere, $A = \pi D^2/4$





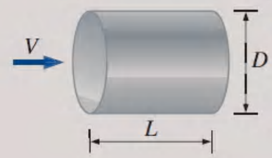
Finite cylinder, vertical, $A = LD$



L/D	C_D
1	0.6
2	0.7
5	0.8
10	0.9
40	1.0
∞	1.2

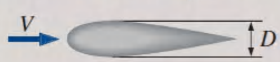
Values are for laminar flow (Re $\lesssim 2 \times 10^5$)

Finite cylinder, horizontal, $A = \pi D^2/4$

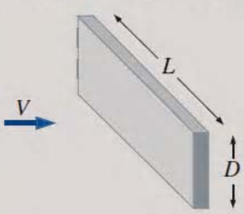


L/D	C_D
0.5	1.1
1	0.9
2	0.9
4	0.9
8	1.0

Streamlined body, $A = \pi D^2/4$



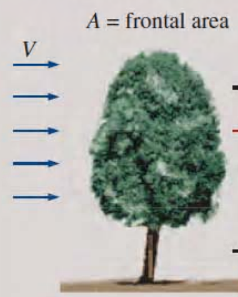
Rectangular plate, $A = LD$



$C_D = 1.10 + 0.02\,(L/D + D/L)$
for $1/30 < (L/D) < 30$

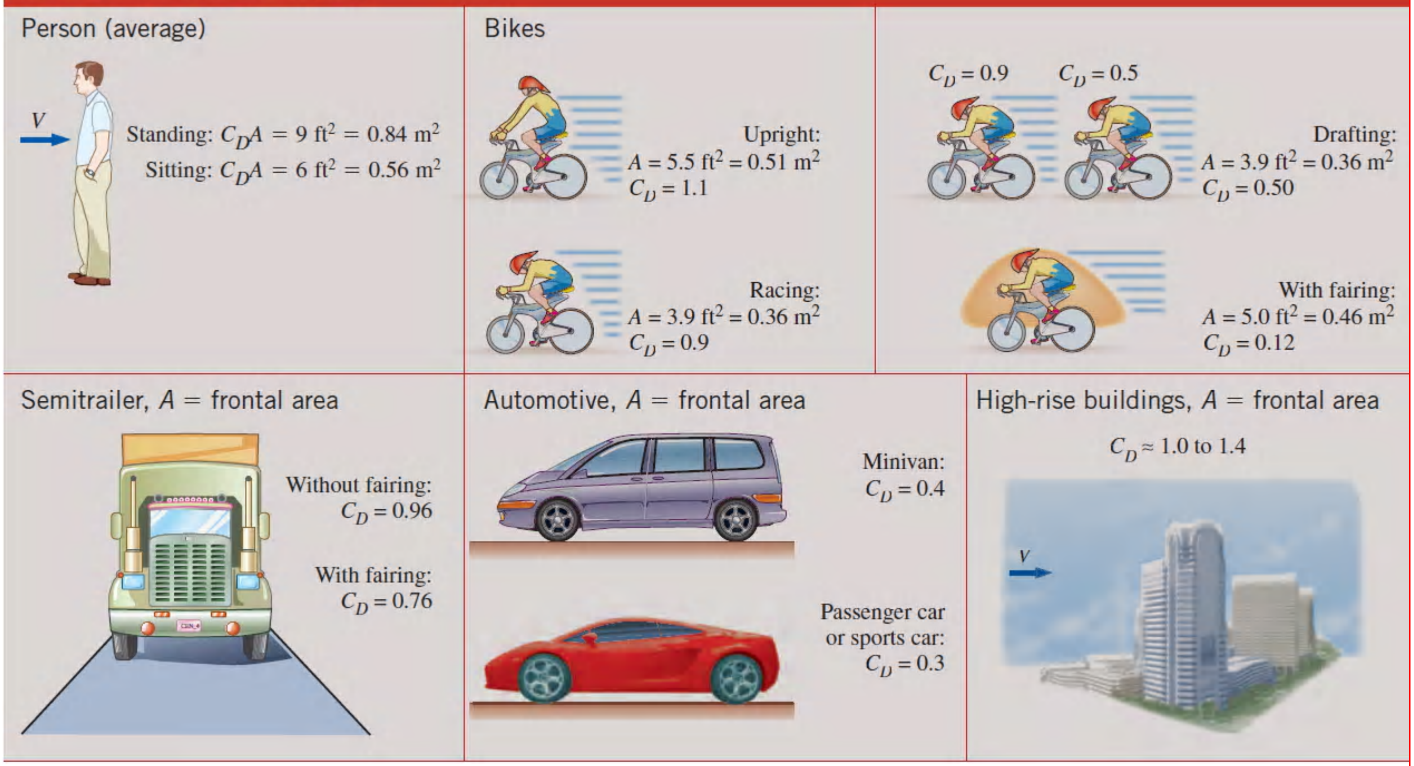
Parachute, $A = \pi D^2/4$

Tree, A = frontal area

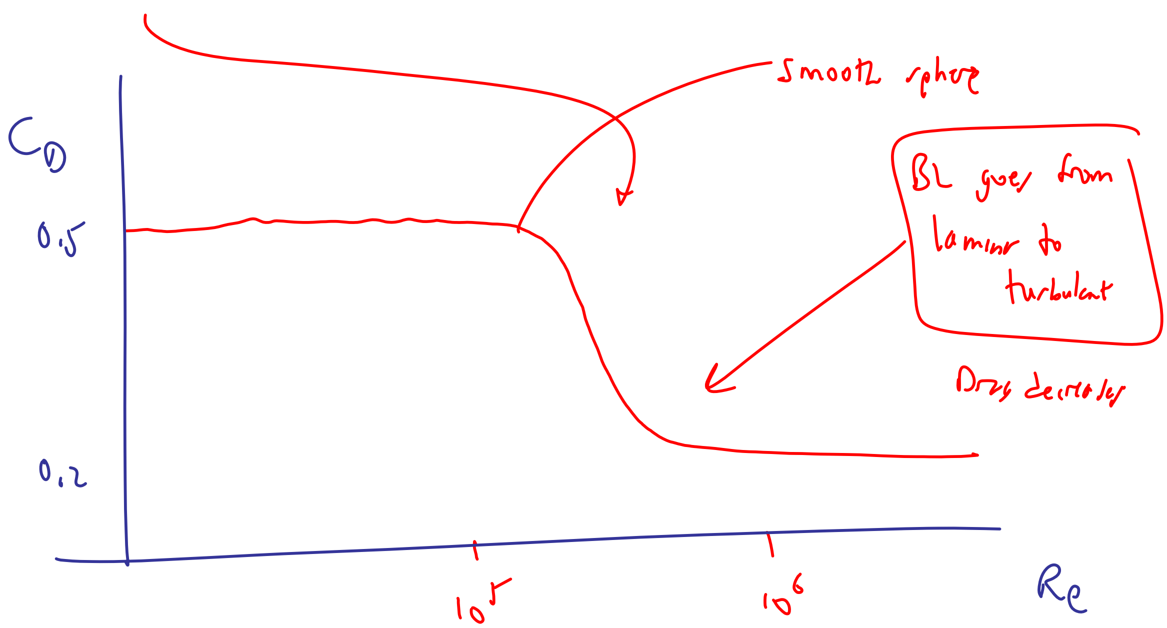


V, m/s	C_D
10	0.4–1.2
20	0.3–1.0
30	0.2–0.7

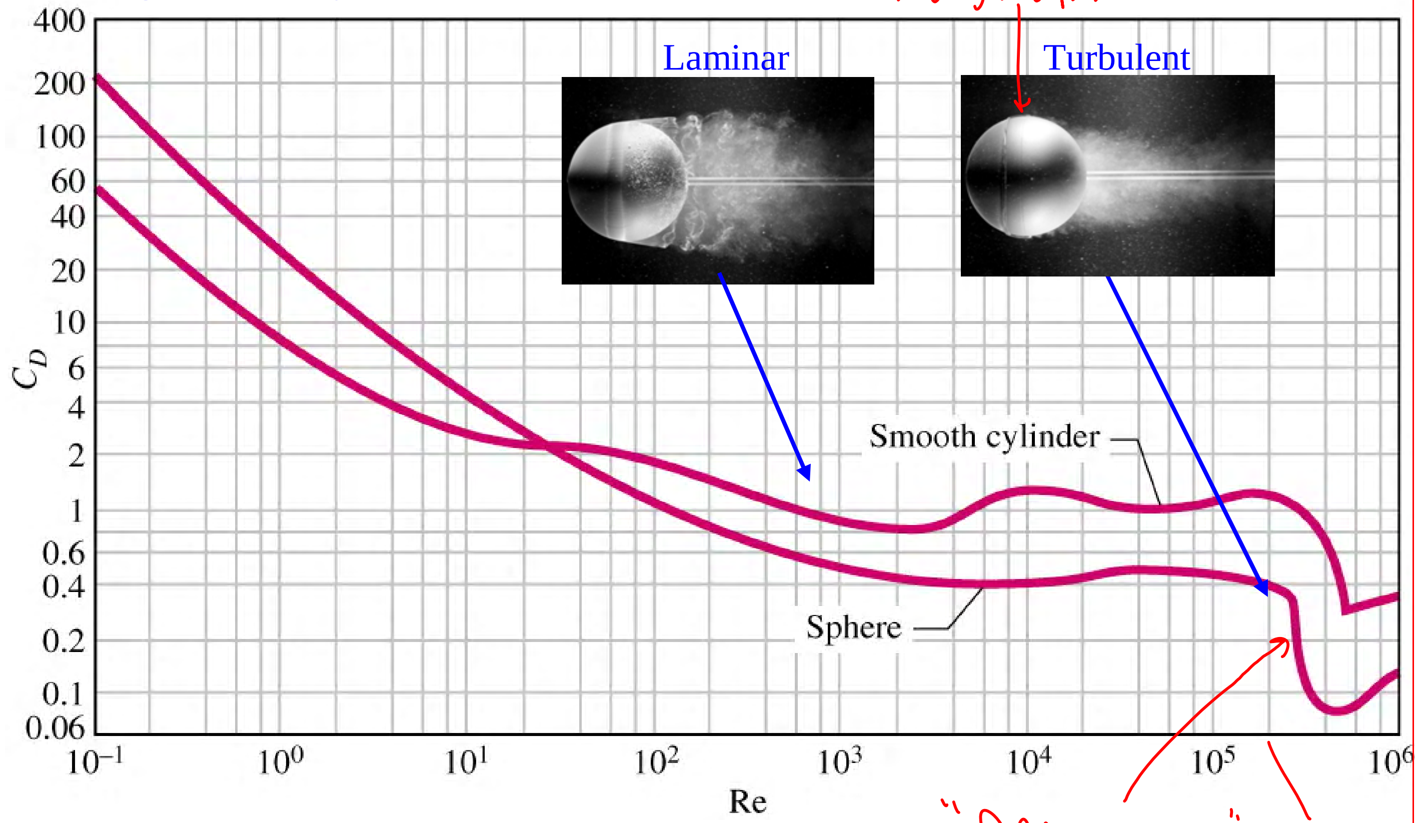
TABLE 11–2 (Continued)



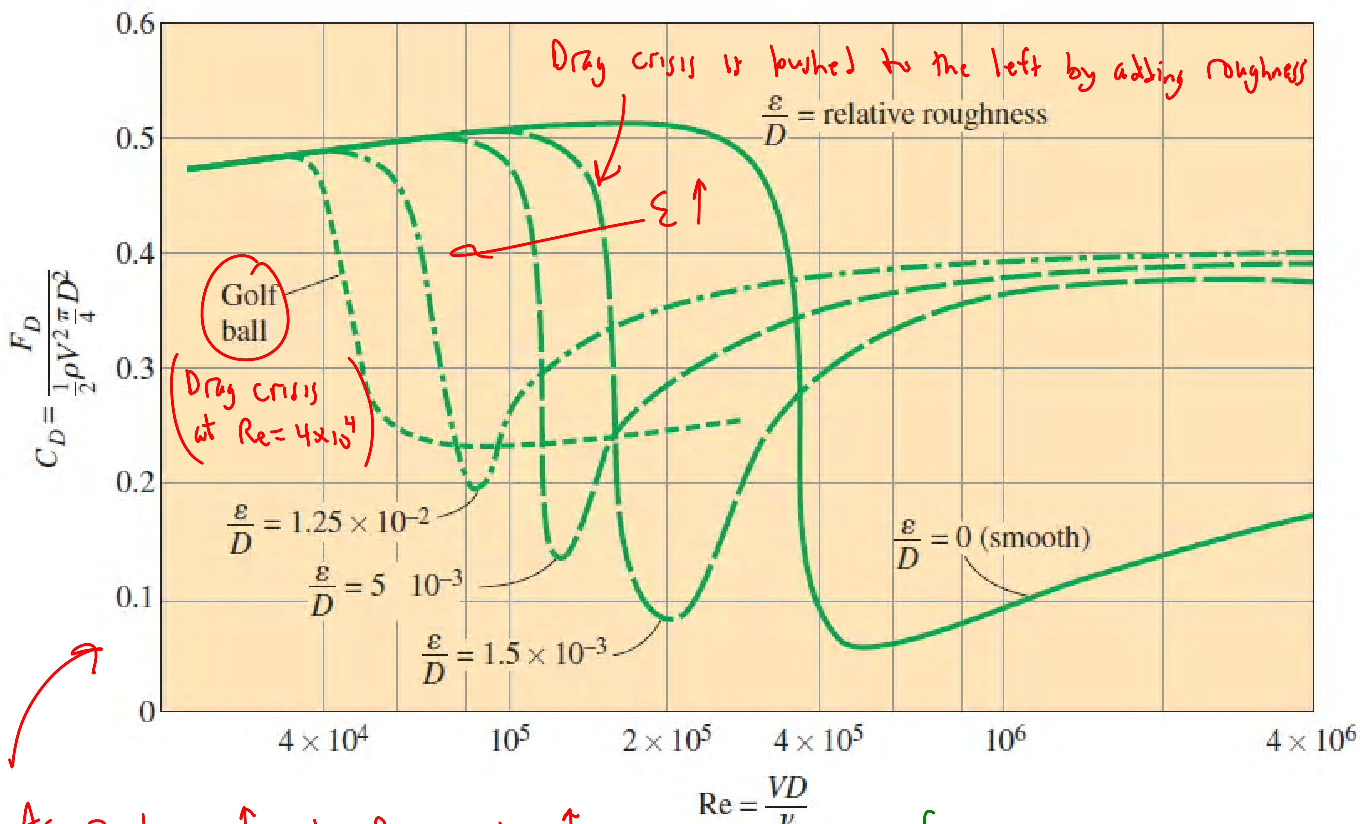
"Drag CRISIS" on spheres & cylinders



The "drag crisis" on cylinders and spheres



The effect of roughness on spheres



As roughness ↑, skin friction drag ↑, but pressure drag ↓ [BL is forced to go turbulent earlier & ∴ separates later] → Pressure drag wins & C_D ↓ until Re gets really big.