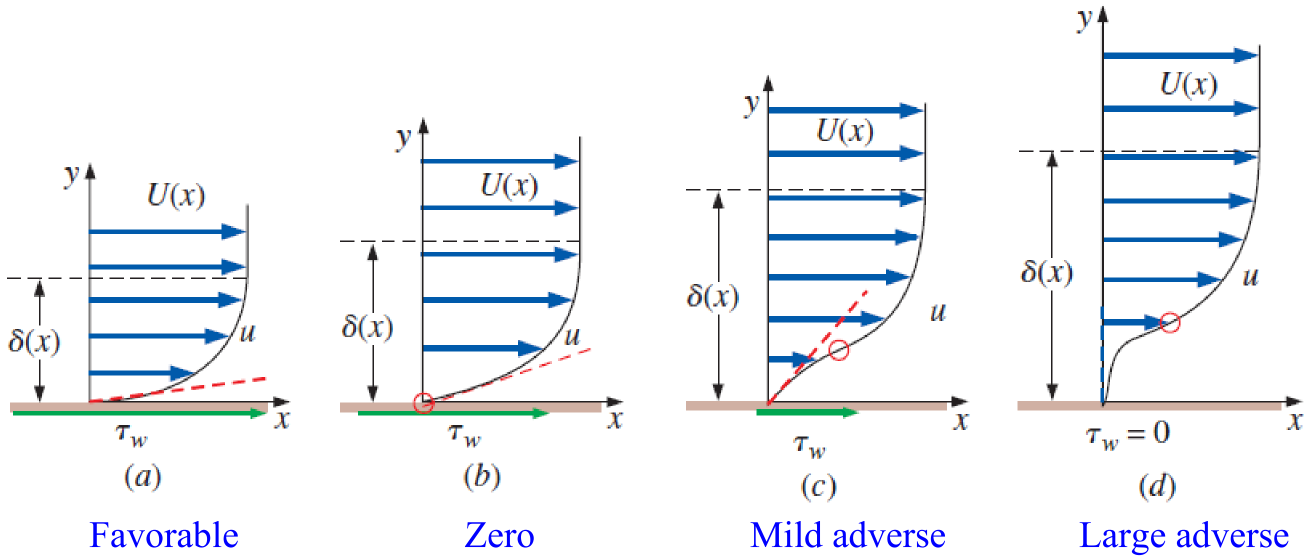
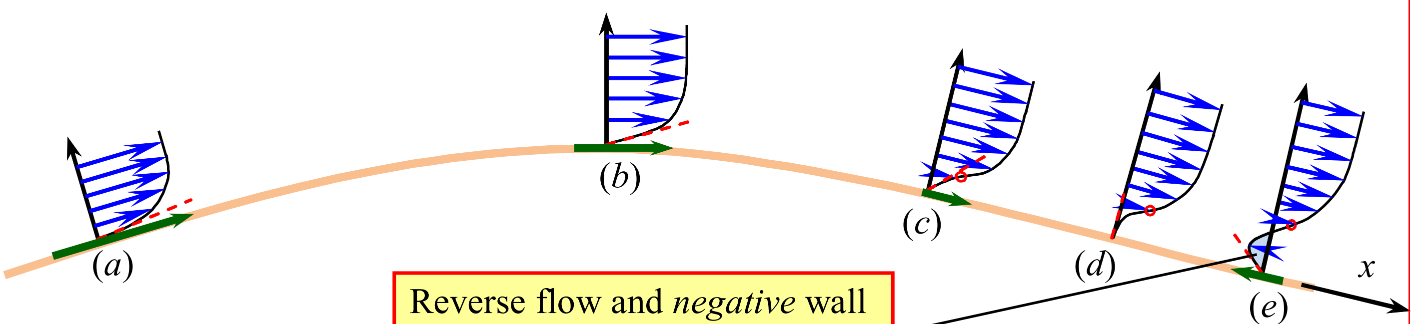
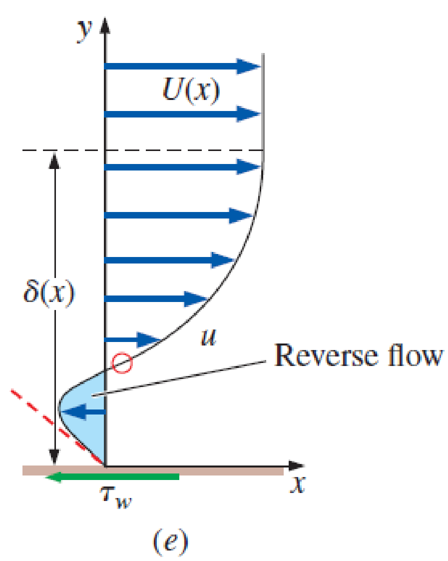
Today, we will:

- 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:







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

2005 Scion XA

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

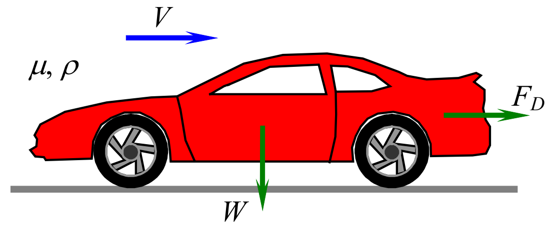
2005 Scion XB

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 $C_D A = 0.5971\ \text{m}^2$, and its rolling resistance coefficient is $\mu_{\text{rolling}} = 0.0155$. It is driven at 70.0 mph (31.29 m/s). The air density and kinematic viscosity are $\rho = 1.204\ \text{kg/m}^3$ and $\nu = 1.516\times10^{-5}\ \text{m}^2/\text{s}$, respectively.

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

Solution:

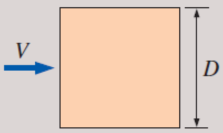
Equation: $\dot{W} = \mu_{\text{rolling}} W V + \frac{1}{2}\rho V^3 C_D A$

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

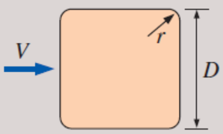
TABLE 11–1

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

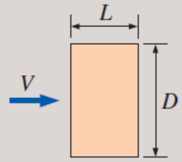


Sharp corners: $C_D = 2.2$



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

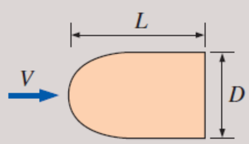
Rectangular rod



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

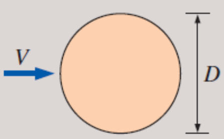
* Corresponds to thin plate



Round front edge:

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

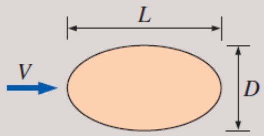
Circular rod (cylinder)



Laminar: $C_D = 1.2$

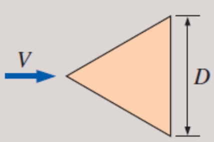
Turbulent: $C_D = 0.3$

Elliptical rod

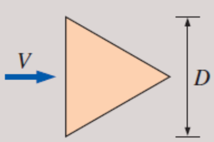


	C_D	
L/D	Laminar	Turbulent
2	0.60	0.20
4	0.35	0.15
8	0.25	0.10

Equilateral triangular rod

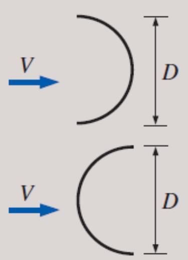


$C_D = 1.5$



$C_D = 2.0$

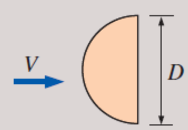
Semicircular shell



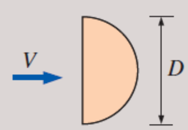
$C_D = 2.3$

$C_D = 1.2$

Semicircular rod



$C_D = 1.2$

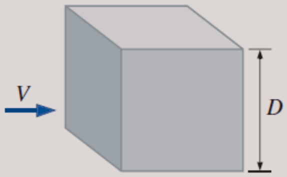


$C_D = 1.7$

TABLE 11–2

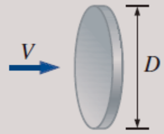
Representative drag coefficients C_D for various three-dimensional bodies based on the frontal area for Re $> 10^4$ unless stated otherwise (for use in the drag force relation $F_D = C_D A \rho V^2/2$ where V is the upstream velocity)

Cube, $A = D^2$



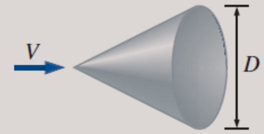
$C_D = 1.05$

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



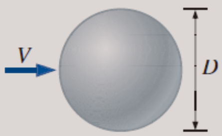
$C_D = 1.1$

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



$C_D = 0.5$

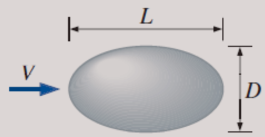
Sphere, $A = \pi D^2/4$



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

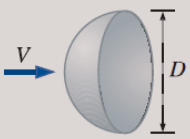
See Fig. 11–36 for C_D vs. Re for smooth and rough spheres.

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

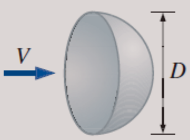


L/D	C_D Laminar Re $\lesssim 2 \times 10^5$	C_D Turbulent Re $\gtrsim 2 \times 10^6$
0.75	0.5	0.2
1	0.5	0.2
2	0.3	0.1
4	0.3	0.1
8	0.2	0.1

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

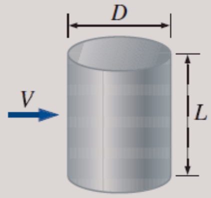


$C_D = 0.4$



$C_D = 1.2$

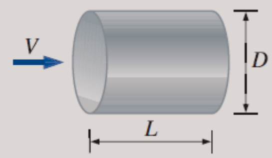
Finite cylinder, vertical, $A = LD$



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

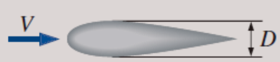
Values are for laminar flow (Re $\lesssim 2 \times 10^5$)

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



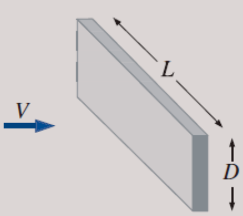
L/D	C_D
0.5	1.1
1	0.9
2	0.9
4	0.9
8	1.0

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



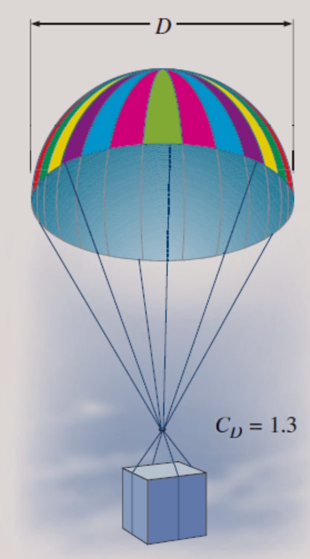
$C_D = 0.04$

Rectangular plate, $A = LD$

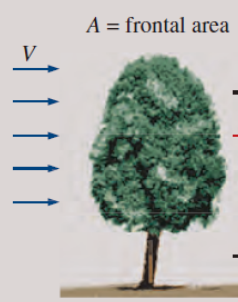


$C_D = 1.10 + 0.02\,(L/D + D/L)$ for $1/30 < (L/D) < 30$

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)

Person (average)

Standing: $C_D A = 9\ \text{ft}^2 = 0.84\ \text{m}^2$

Sitting: $C_D A = 6\ \text{ft}^2 = 0.56\ \text{m}^2$

Bikes

Upright:
$A = 5.5\ \text{ft}^2 = 0.51\ \text{m}^2$
$C_D = 1.1$

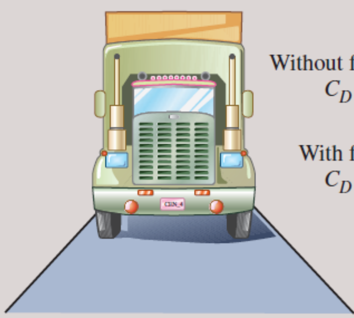
Racing:
$A = 3.9\ \text{ft}^2 = 0.36\ \text{m}^2$
$C_D = 0.9$

$C_D = 0.9$ $C_D = 0.5$

Drafting:
$A = 3.9\ \text{ft}^2 = 0.36\ \text{m}^2$
$C_D = 0.50$

With fairing:
$A = 5.0\ \text{ft}^2 = 0.46\ \text{m}^2$
$C_D = 0.12$

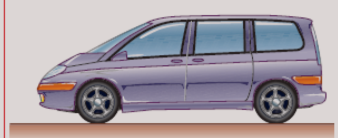
Semitrailer, A = frontal area



Without fairing:
$C_D = 0.96$

With fairing:
$C_D = 0.76$

Automotive, A = frontal area



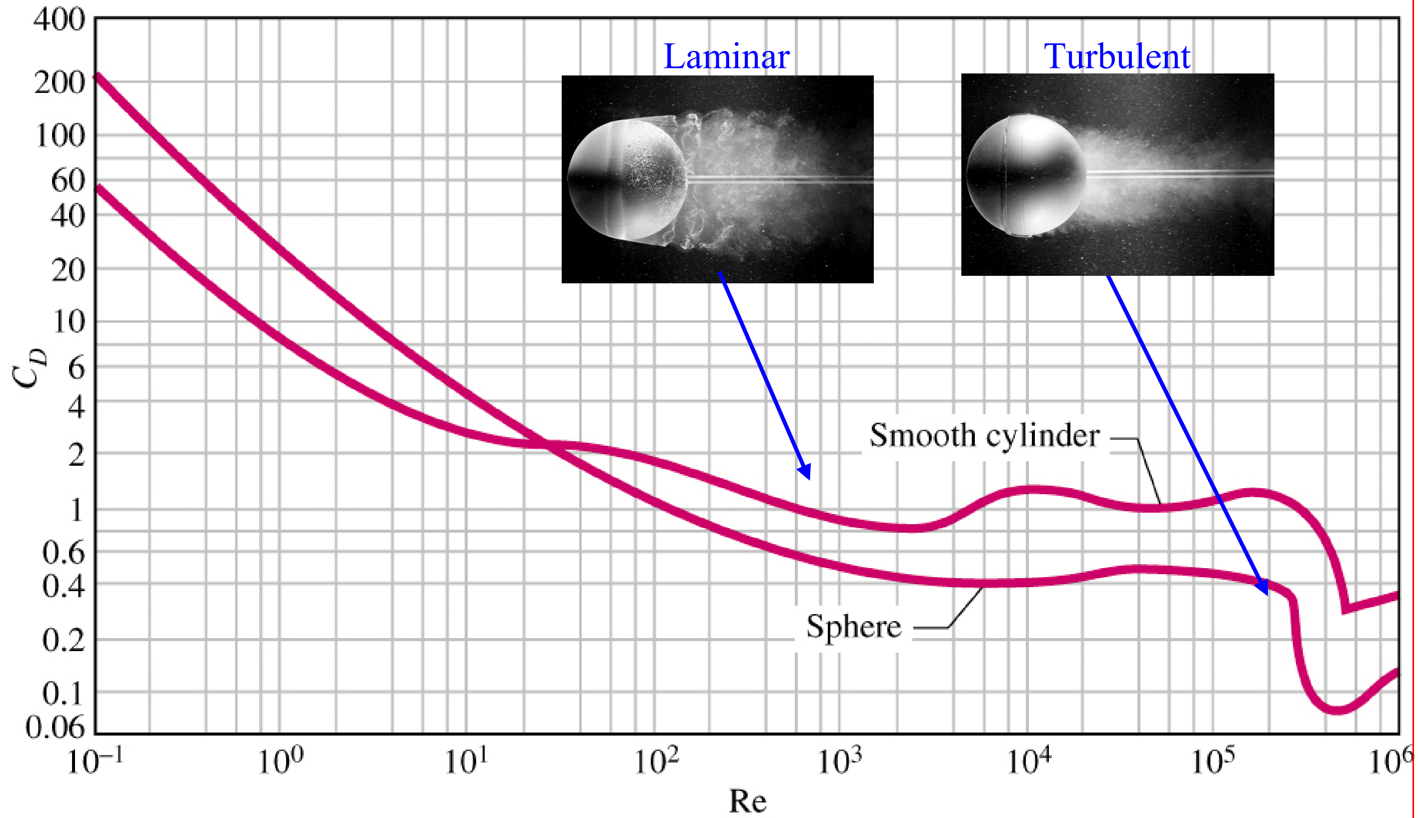
Minivan:
$C_D = 0.4$

Passenger car or sports car:
$C_D = 0.3$

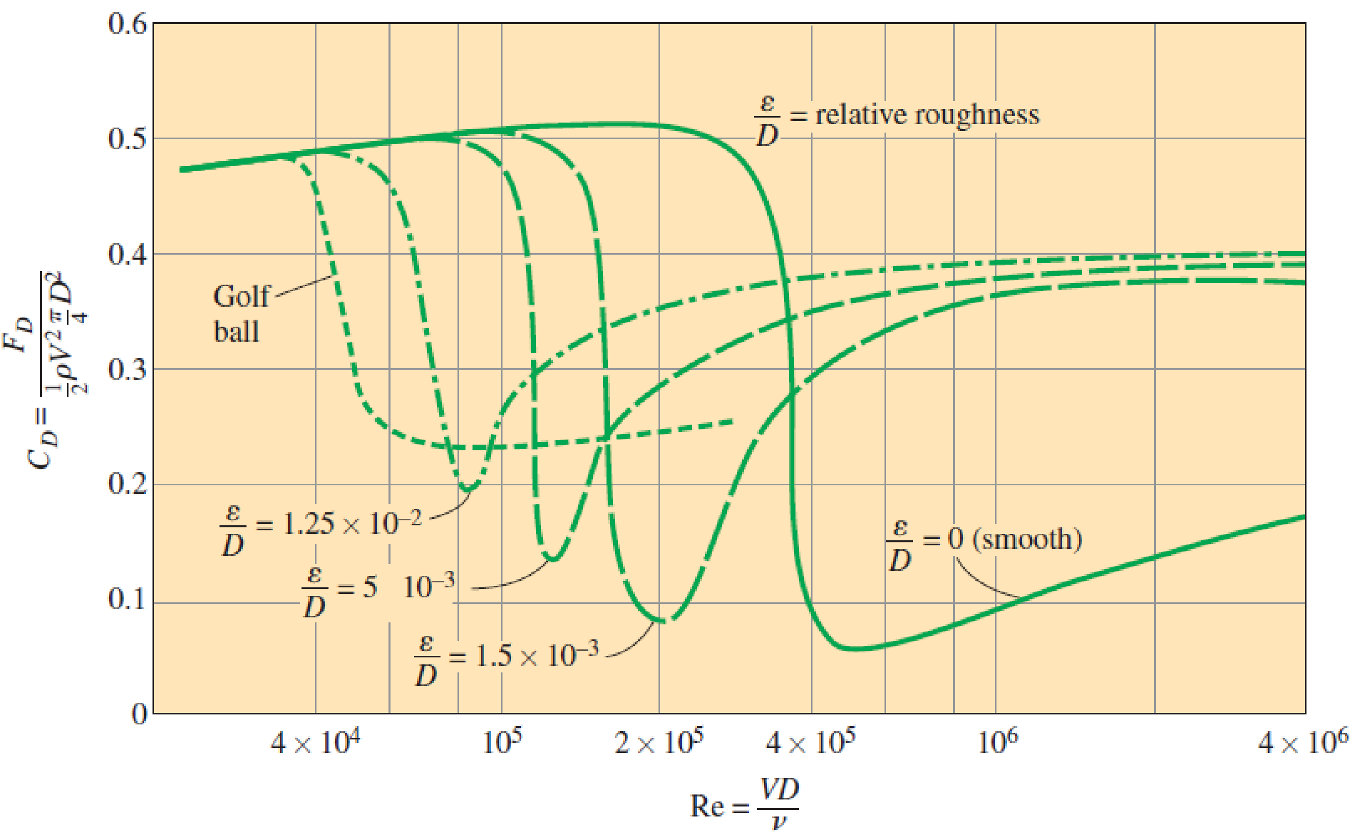
High-rise buildings, A = frontal area

$C_D \approx 1.0$ to 1.4

The "drag crisis" on cylinders and spheres

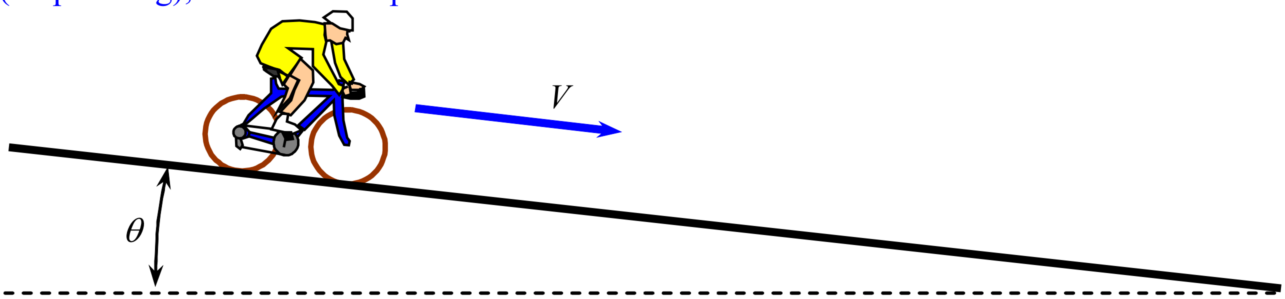


The effect of roughness on spheres



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.

(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)