*CP1 & honors (not AP®)*

# Drag

**Unit:** Forces in One Dimension

**NGSS Standards/MA Curriculum Frameworks (2016):** N/A

**AP® Physics 1 Learning Objectives/Essential Knowledge (2024):** N/A

**Mastery Objective(s):** (Students will be able to…)

- Calculate the drag force on an object.

**Success Criteria:**

- Correct drag coëfficient is chosen.
- Variables are correctly identified and substituted correctly into the equation.
- Algebra is correct and rounding to appropriate number of significant figures is reasonable.

**Language Objectives:**

- Explain why aerodynamic drag depends on each of the variables in the equation.

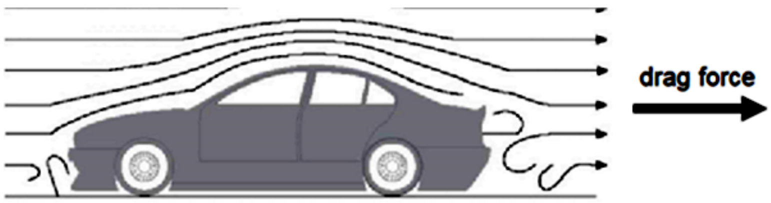
**Tier 2 Vocabulary:** drag

## Labs, Activities & Demonstrations:

- Crumpled piece of paper or tissue *vs.* golf ball (drag force doesn't depend on mass).
- Projectiles with same mass but different shapes.

## Notes:

Drag is the force exerted by particles of a fluid* resisting the motion of an object relative to a fluid. The drag force is essentially friction between the object and particles of the fluid.




Most of the problems that involve drag fall into three categories:

1. The drag force is small enough that we ignore it.
2. The drag force is equal to some other force that we can measure or calculate.
3. The question asks only for a qualitative comparison of forces with and without drag.

* A fluid is any substance whose particles can separate easily, allowing it to flow (does not have a definite shape) and allowing objects to pass through it. Fluids can be liquids or gases.

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Calculating drag is complicated, because the effects of drag change dramatically at different relative velocities.

The drag force can be estimated in simple situations, given the velocity, shape, and cross-sectional area of the object and the density of the fluid it is moving through.

For these situations, the drag force is given by the following equation:

$$\vec{\boldsymbol{F}}_D = -\frac{1}{2}\rho\vec{\boldsymbol{v}}^2 C_D A$$

where:

- $\vec{\boldsymbol{F}}_D$ = drag force
- $\rho$ = density of the fluid that the object is moving through
- $\vec{\boldsymbol{v}}$ = velocity of the object (relative to the fluid)
- $C_D$ = drag coëfficient of the object (based on its shape)
- $A$ = cross-sectional area of the object in the direction of motion

This equation can be applied when:

- the object has a blunt form factor
- the object's velocity relative to the properties of the fluid causes turbulence in the object's wake
- the fluid is in laminar (not turbulent) flow before it interacts with the object
- the fluid has a relatively low viscosity*

However, fluid flow is a lot more complicated than the above equation would suggest, and there are few situations in which the above equation gives a good result.

* Viscosity is a measure of how "gooey" a fluid is, meaning how much it resists flow and hinders the motion of objects through itself. Water has a low viscosity; honey and ketchup are more viscous.

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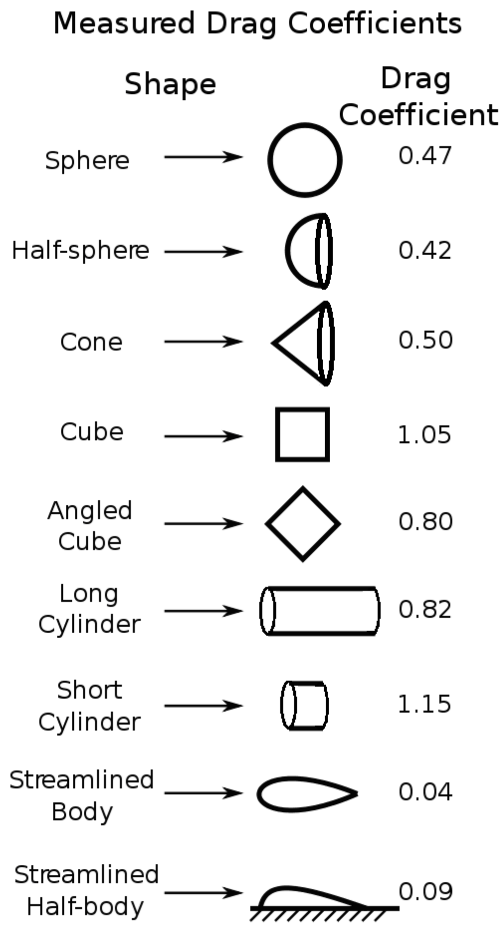
The drag coëfficient, $C_D$, is a dimensionless number (meaning that it has no units). The drag coëfficient encompasses all of the types of friction associated with drag, including form drag and skin drag. It serves the same purpose in drag problems that the coëfficient of friction ($\mu$) serves in problems involving friction between solid surfaces.




Approximate drag coëfficients for simple shapes are given in the table to the right, assuming that the fluid is moving (relative to the object) in the direction of the arrow.

The reason that raindrops have their characteristic shape ("streamlined body") is because the drag force changes their shape until they have the shape with the least amount of drag.

The reason that many cars have roofs that slope downward from the front of the car to the back is to reduce the drag force.

Drag coefficients of some vehicles and other objects:

| **Vehicle** | $C_D$ |
|---|---|
| Toyota Camry | 0.28 |
| Ford Focus | 0.32 |
| Honda Civic | 0.36 |
| Ferrari Testarossa | 0.37 |
| Dodge Ram truck | 0.43 |
| Hummer H2 | 0.64 |

| **Object** | $C_D$ |
|---|---|
| skydiver (vertical) | 0.70 |
| skydiver (horizontal) | 1.0 |
| parachute | 1.75 |
| bicycle & rider | 0.90 |

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To highlight some of the problems with the drag equation presented here, it is necessary to explain more about fluid flow.

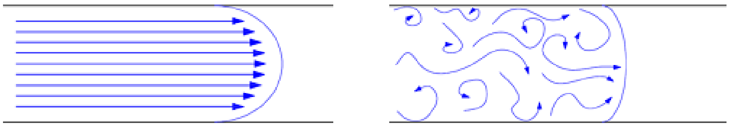
Fluid flow is often characterized by a dimensionless number (*i.e.,* one that has no units because all of the units cancel) called the Reynolds number.

Reynolds number (*Re*): the ratio of inertial forces (remember that inertia = resistance to movement) to the viscous forces in a fluid. Reynolds number is given by:

$$\text{Re} = \frac{\rho \vec{v} L}{\mu}$$

where $\rho$ is the density of the fluid, $\vec{v}$ is the relative velocity, $L$ is the "characteristic length" and $\mu$ is the viscosity (resistance to flow) of the fluid.

There are two basic types of fluid flow:



laminar flow turbulent flow

laminar flow: occurs when the velocity of the fluid (or the object moving through it) is relatively low, and the particles of fluid generally move in a straight line in an organized fashion. Generally, flow is laminar if $Re < 2300$.

Turbulent flow: occurs when the velocity of the fluid (or the object moving through it) is high, and the particles move in a more jumbled, random manner. In general, turbulent flow causes higher drag forces. Generally, flow is turbulent if $Re > 2900$.

The type of flow affects the drag coëfficient, $C_D$ :

- In laminar flow, the drag coëfficient is roughly proportional to $\frac{1}{Re}$. Because the Reynolds number is proportional to velocity, this means the drag coëfficient is roughly proportional to $\frac{1}{v}$. (This means that while the force is proportional to $\vec{v}^2$ for a constant $C_D$, the actual drag force in laminar flow is proportional to $\vec{v}$.)
- In turbulent flow, the drag coëfficient depends greatly on the characteristics of the system. In many systems with turbulent flow, the drag coefficient is proportional to $\frac{1}{Re^7}$.

Note also that the viscosity of a Newtonian fluid drops steeply with temperature, which means the temperature also affects the Reynolds number, and therefore the drag coëfficient.

This is all to say that a reasonable quantitative treatment of fluid flow and drag is well beyond the scope of this course.

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