










Drag coefficient

In fluid dynamics, the **drag coefficient** (commonly denoted as: C_d , C_x or C_w) is a dimensionless quantity that is used to quantify the drag or resistance of an object in a fluid environment, such as air or water. It is used in the drag equation in which a lower drag coefficient indicates the object will have less aerodynamic or hydrodynamic drag. The drag coefficient is always associated with a particular surface area.^[1]

The drag coefficient of any object comprises the effects of the two basic contributors to fluid dynamic drag: skin friction and form drag. The drag coefficient of a lifting airfoil or hydrofoil also includes the effects of lift-induced drag.^{[2][3]} The drag coefficient of a complete structure such as an aircraft also includes the effects of interference drag.^{[4][5]}

Shape	Drag Coefficient
Sphere → 	0.47
Half-sphere → 	0.42
Cone → 	0.50
Cube → 	1.05
Angled Cube → 	0.80
Long Cylinder → 	0.82
Short Cylinder → 	1.15
Streamlined Body → 	0.04
Streamlined Half-body → 	0.09

Measured Drag Coefficients
 Drag coefficients in fluids with Reynolds number approximately 10⁴

Contents

- Definition**
- Background**
- Drag coefficient c_d examples**
 - General
- Aircraft**
- Blunt and streamlined body flows**
 - Concept
 - Practical example
- See also**
- Notes**
- References**

Definition

The drag coefficient c_d is defined as

$$c_d = \frac{2F_d}{\rho u^2 A}$$

where:

F_d is the drag force, which is by definition the force component in the direction of the flow

velocity,^[6]

ρ is the mass density of the fluid,^[7]

u is the flow speed of the object relative to the fluid,

A is the reference area.

The reference area depends on what type of drag coefficient is being measured. For automobiles and many other objects, the reference area is the projected frontal area of the vehicle. This may not necessarily be the cross sectional area of the vehicle, depending on where the cross section is taken. For example, for a sphere $A = \pi r^2$ (note this is not the surface area = $4\pi r^2$).

For airfoils, the reference area is the nominal wing area. Since this tends to be large compared to the frontal area, the resulting drag coefficients tend to be low, much lower than for a car with the same drag, frontal area, and speed.

Airships and some bodies of revolution use the volumetric drag coefficient, in which the reference area is the square of the cube root of the airship volume (volume to the two-thirds power). Submerged streamlined bodies use the wetted surface area.

Two objects having the same reference area moving at the same speed through a fluid will experience a drag force proportional to their respective drag coefficients. Coefficients for unstreamlined objects can be 1 or more, for streamlined objects much less.

Background

The drag equation

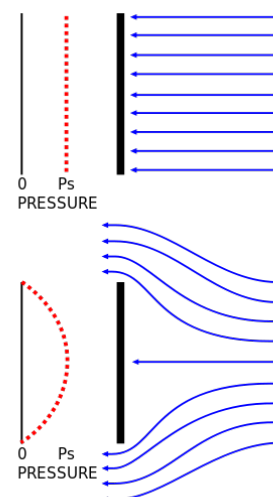
$$F_d = \frac{1}{2} \rho u^2 c_d A$$

is essentially a statement that the drag force on any object is proportional to the density of the fluid and proportional to the square of the relative flow speed between the object and the fluid.

C_d is not a constant but varies as a function of flow speed, flow direction, object position, object size, fluid density and fluid viscosity. Speed, kinematic viscosity and a characteristic length scale of the object are incorporated into a dimensionless quantity called the Reynolds number Re . C_d is thus a function of Re . In a compressible flow, the speed of sound is relevant, and C_d is also a function of Mach number Ma .

For certain body shapes, the drag coefficient C_d only depends on the Reynolds number Re , Mach number Ma and the direction of the flow. For low Mach number Ma , the drag coefficient is independent of Mach number. Also, the variation with Reynolds number Re within a practical range of interest is usually small, while for cars at highway speed and aircraft at cruising speed, the incoming flow direction is also more-or-less the same. Therefore, the drag coefficient C_d can often be treated as a constant.^[8]

For a streamlined body to achieve a low drag coefficient, the boundary layer around the body must remain attached to the surface of the body for as long as possible, causing the wake to be narrow. A high form drag results in a broad wake. The boundary layer will transition from laminar to turbulent if Reynolds number of the flow around the body is sufficiently great. Larger velocities, larger objects, and lower viscosities contribute to larger Reynolds numbers.^[9]



Flow around a plate, showing stagnation.

For other objects, such as small particles, one can no longer consider that the drag coefficient C_d is constant, but certainly is a function of Reynolds number.^{[10][11][12]} At a low Reynolds number, the flow around the object does not transition to turbulent but remains laminar, even up to the point at which it separates from the surface of the object. At very low Reynolds numbers, without flow separation, the drag force F_d is proportional to v instead of v^2 ; for a sphere this is known as Stokes law. The Reynolds number will be low for small objects, low velocities, and high viscosity fluids.^[9]

A C_d equal to 1 would be obtained in a case where all of the fluid approaching the object is brought to rest, building up stagnation pressure over the whole front surface. The top figure shows a flat plate with the fluid coming from the right and stopping at the plate. The graph to the left of it shows equal pressure across the surface. In a real flat plate, the fluid must turn around the sides, and full stagnation pressure is found only at the center, dropping off toward the edges as in the lower figure and graph. Only considering the front side, the C_d of a real flat plate would be less than 1; except that there will be suction on the back side: a negative pressure (relative to ambient). The overall C_d of a real square flat plate perpendicular to the flow is often given as 1.17. Flow patterns and therefore C_d for some shapes can change with the Reynolds number and the roughness of the surfaces.

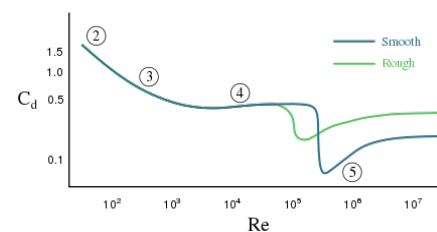
Drag coefficient c_d examples

General

In general, c_d is not an absolute constant for a given body shape. It varies with the speed of airflow (or more generally with Reynolds number Re). A smooth sphere, for example, has a c_d that varies from high values for laminar flow to 0.47 for turbulent flow. Although the drag coefficient decreases with increasing Re , the drag force increases.

Shapes (<https://web.archive.org/web/20070715171817/http://aerodyn.org/Dr ag/tables.html>)

C_d	Item
0.001	laminar flat plate parallel to the flow ($Re < 10^6$)
0.005	turbulent flat plate parallel to the flow ($Re > 10^6$)
0.075	<u>Pac-car</u>
0.076	Milan SL (one of the fastest practical <u>velomobiles</u>) [13]
0.1	smooth sphere ($Re = 10^6$)



Drag coefficient C_d for a sphere as a function of Reynolds number Re , as obtained from laboratory experiments. The dark line is for a sphere with a smooth surface, while the lighter line is for the case of a rough surface. The numbers along the line indicate several flow regimes and associated changes in the drag coefficient:

- 2: attached flow (Stokes flow) and steady separated flow,
- 3: separated unsteady flow, having a laminar flow boundary layer upstream of the separation, and producing a vortex street,
- 4: separated unsteady flow with a laminar boundary layer at the upstream side, before flow separation, with downstream of the sphere a chaotic turbulent wake,
- 5: post-critical separated flow, with a turbulent boundary layer.

0.47	smooth sphere ($Re = 10^5$)
0.14	<u>Fiat Turbina</u> 1954
0.15	<u>Schlörwagen</u> 1939 ^[14]
0.18	<u>Mercedes-Benz T80</u> 1939
0.186-0.189	<u>Volkswagen XL1</u> 2014
0.19	<u>General Motors EV1</u> 1996 ^[15]
0.212	<u>Tatra 77A</u> 1935
0.23	<u>Tesla Model 3</u> ^[16] , <u>Audi A4 B9</u> (2016) ^[17]
0.235	<u>Renault Eolab</u>
0.24	<u>Hyundai Ioniq</u>
0.24	<u>Tesla Model S</u> ^[18]
0.24	<u>Toyota Prius</u> (4th Generation) ^[19]
0.25	<u>Toyota Prius</u> (3rd Generation)
0.26	<u>BMW i8</u>
0.26	<u>Nissan GT-R</u> (2011-2014)
0.27	<u>BMW E39 5 Series</u> (1995-2003, Germany) ^[20]
0.27	<u>Nissan GT-R</u> (2007-2010)
0.27	<u>Chrysler 200</u> (2015-2017)
0.28	1969 <u>Dodge Charger Daytona</u> and 1970 <u>Plymouth Superbird</u>
0.28	1986 <u>Opel Omega saloon</u> . ^[21]
0.28	<u>Mercedes-Benz CLA-Class Type C 117</u> . ^[22]
0.29	<u>Mazda3</u> (2007) ^[23]
0.295	bullet (not ogive, at subsonic velocity)
0.3	<u>Saab 92</u> (1949), <u>Audi 100 C3</u> (1982)
0.31	<u>Maserati Ghibli Sedan</u> (2014) ^[24]
0.324	<u>Ford Focus Mk2/2.5</u> (2004-2011, Europe)
0.33	

	<u>BMW E30 3 Series</u> (1984-1993, Germany)
0.35	<u>Maserati Quattroporte V</u> (M139, 2003–2012)
0.36	<u>Citroen CX</u> (1974-1991, France), <u>Tesla Semi</u> (2017, United States of America)
0.37	<u>Ford Transit Custom Mk8</u> (2013, Turkey)
0.48	rough sphere ($Re = 10^6$), <u>Volkswagen Beetle</u> ^{[25][26]}
0.58	<u>Jeep Wrangler TJ</u> (1997-2005) ^[27]
0.75	a typical <u>model rocket</u> ^[28]
1.0	coffee filter, face-up ^[29]
1.0	<u>road bicycle plus cyclist</u> , touring position ^[30]
1.0–1.1	<u>skier</u>
1.0–1.3	wires and cables
1.0–1.3	man (upright position)
1.1-1.3	ski jumper ^[31]
1.2	<u>Usain Bolt</u> ^[32]
1.28	flat plate perpendicular to flow (3D) ^[33]
1.3–1.5	<u>Empire State Building</u>
1.4	<u>Formula 1</u>
1.8–2.0	<u>Eiffel Tower</u>
1.98–2.05	flat plate perpendicular to flow (2D)

Aircraft

As noted above, aircraft use their wing area as the reference area when computing c_d , while automobiles (and many other objects) use frontal cross sectional area; thus, coefficients are **not** directly comparable between these classes of vehicles. In the aerospace industry, the drag coefficient is sometimes expressed in drag counts where 1 drag count = 0.0001 of a C_d .^[34]

Aircraft^[35]

c_d	Aircraft type
0.021	<u>F-4 Phantom II (subsonic)</u>
0.022	<u>Learjet 24</u>
0.024	<u>Boeing 787</u> ^[36]
0.0265	<u>Airbus A380</u> ^[37]
0.027	<u>Cessna 172/182</u>
0.027	<u>Cessna 310</u>
0.031	<u>Boeing 747</u>
0.044	<u>F-4 Phantom II (supersonic)</u>
0.048	<u>F-104 Starfighter</u>
0.095	<u>X-15 (Not confirmed)</u>

Blunt and streamlined body flows

Concept

Drag, in the context of fluid dynamics, refers to forces that act on a solid object in the direction of the relative flow velocity (note that the diagram below shows the drag in the opposite direction to the flow). The aerodynamic forces on a body come primarily from differences in pressure and viscous shearing stresses. Thereby, the drag force on a body could be divided into two components, namely frictional drag (viscous drag) and pressure drag (form drag). The net drag force could be decomposed as follows:

$$\begin{aligned}
 c_d &= \frac{2F_d}{\rho v^2 A} \\
 &= c_p + c_f \\
 &= \underbrace{\frac{1}{\rho v^2 A} \int_S dA (p - p_o) (\hat{\mathbf{n}} \cdot \hat{\mathbf{i}})}_{c_p} + \underbrace{\frac{1}{\rho v^2 A} \int_S dA (\hat{\mathbf{t}} \cdot \hat{\mathbf{i}}) T_w}_{c_f}
 \end{aligned}$$

where:

- c_p is the pressure drag coefficient,
- c_f is the friction drag coefficient,
- \hat{t} = Tangential direction to the surface with area dA ,
- \hat{n} = Normal direction to the surface with area dA ,
- T_w is the shear Stress acting on the surface dA ,
- p_o is the pressure far away from the surface dA ,
- p is pressure at surface dA ,
- \hat{i} is the unit vector in direction normal to the surface dA , forming a unit vector $d\hat{A}$

Therefore, when the drag is dominated by a frictional component, the body is called a **streamlined body**; whereas in the case of dominant pressure drag, the body is called a **blunt body**. Thus, the shape of the body and the angle of attack determine the type of drag. For example, an airfoil is considered as a body with a small angle of attack by the fluid flowing across it. This means that it has attached boundary layers, which produce much less pressure drag.

The wake produced is very small and drag is dominated by the friction component. Therefore, such a body (here an airfoil) is described as streamlined, whereas for bodies with fluid flow at high angles of attack, boundary layer separation takes place. This mainly occurs due to adverse pressure gradients at the top and rear parts of an airfoil.

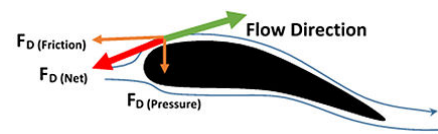
Due to this, wake formation takes place, which consequently leads to eddy formation and pressure loss due to pressure drag. In such situations, the airfoil is stalled and has higher pressure drag than friction drag. In this case, the body is described as a blunt body.

A streamlined body looks like a fish (Tuna, Oropesa, etc.) or an airfoil with small angle of attack, whereas a blunt body looks like a brick, a cylinder or an airfoil with high angle of attack. For a given frontal area and velocity, a streamlined body will have lower resistance than a blunt body. Cylinders and spheres are taken as blunt bodies because the drag is dominated by the pressure component in the wake region at high Reynolds number.

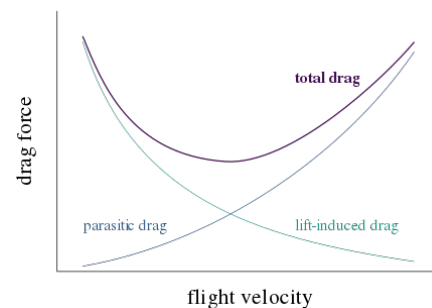
To reduce this drag, either the flow separation could be reduced or the surface area in contact with the fluid could be reduced (to reduce friction drag). This reduction is necessary in devices like cars, bicycle, etc. to avoid vibration and noise production.

Practical example

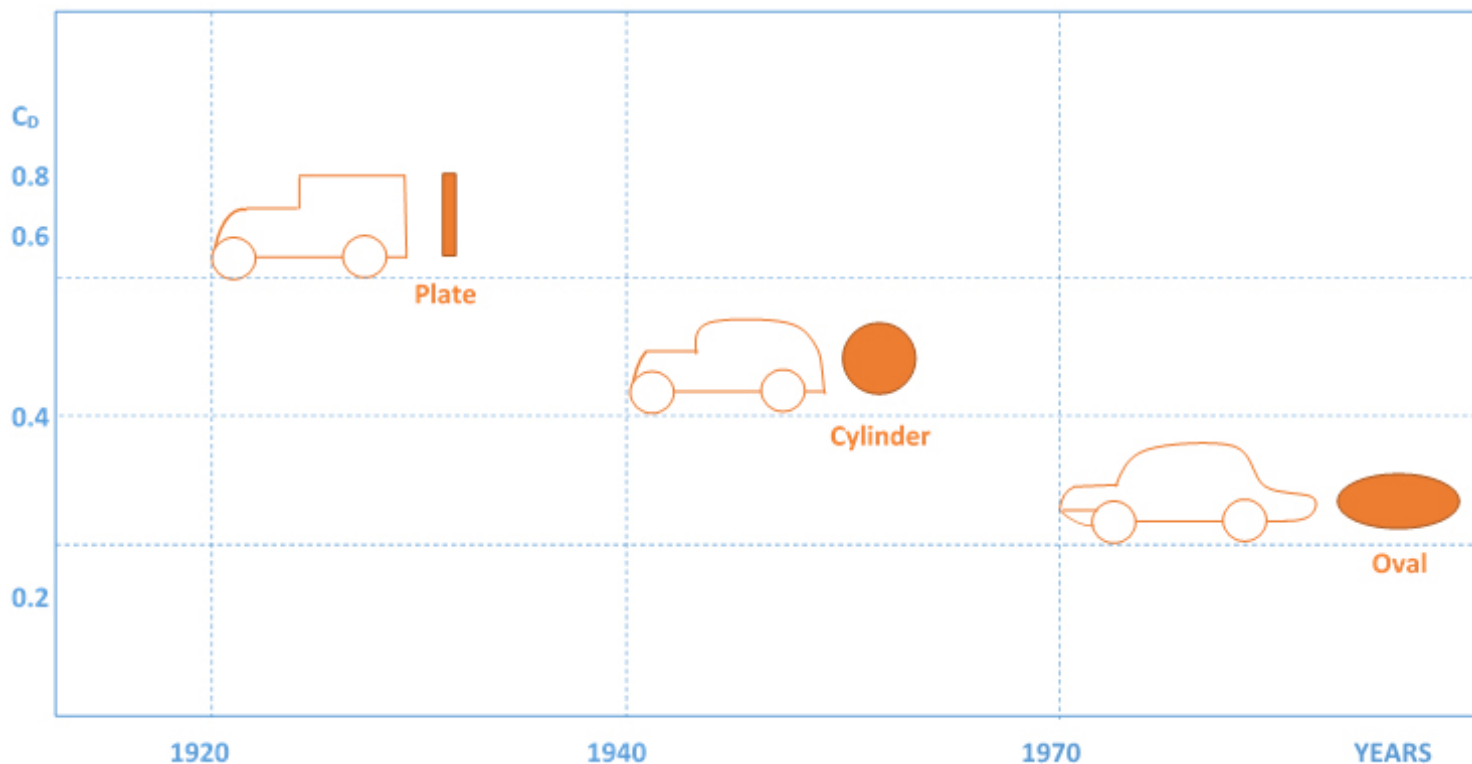
The aerodynamic design of cars has evolved from the 1920s to the end of the 20th century. This change in design from a blunt body to a more streamlined body reduced the drag coefficient from about 0.95 to 0.30.



Flow across an airfoil showing the relative impact of drag force to the direction of motion of fluid over the body. This drag force gets divided into frictional drag and pressure drag. The same airfoil is considered as a streamlined body if friction drag (viscous drag) dominates pressure drag and is considered a blunt body when pressure drag (form drag) dominates friction drag.



Trade-off relationship between zero-lift drag and lift induced drag



Time history of cars' aerodynamic drag in comparison to change in geometry of streamlined bodies (blunt to streamline).

See also

- [Automotive aerodynamics](#)
- [Automobile drag coefficient](#)
- [Ballistic coefficient](#)
- [Drag crisis](#)
- [Zero-lift drag coefficient](#)

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