DOCUMENT
GSM-G-CPL.002

DOCUMENT TITLE
AERODYNAMICS 1

CHAPTER 4 – DRAG

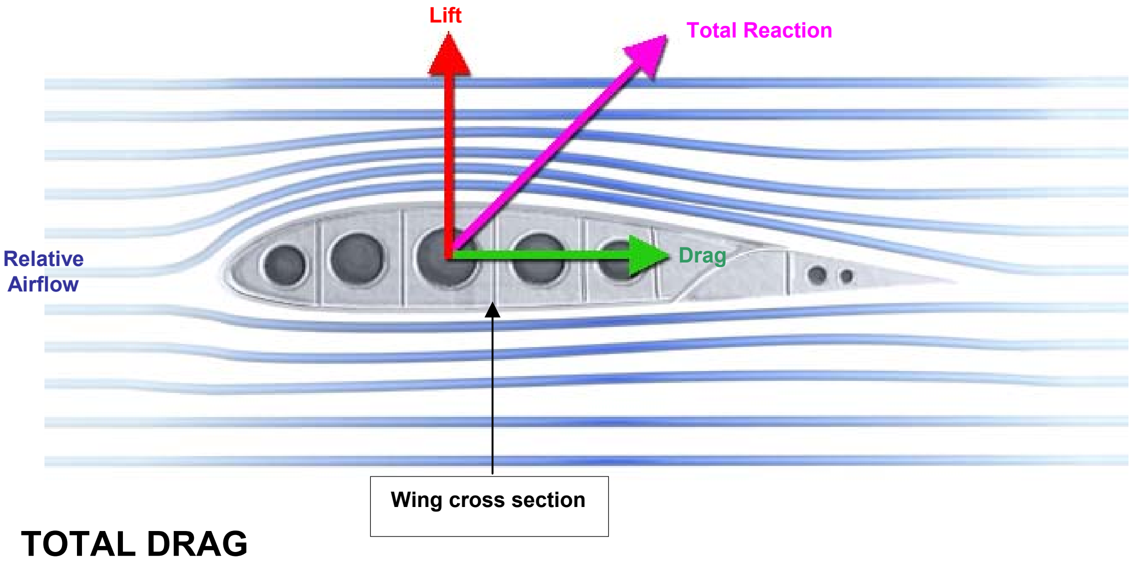
Version 1.2
October 2013

CONTENTS .... PAGE

DRAG AS A FORCE

INTRODUCTION

Drag is the component of the Total Reaction (TR), which is tangential to the flight path, that is, parallel to the Relative Airflow (RAF).



TOTAL DRAG

Total Drag is the sum of all the components of the aerodynamic forces that act parallel and opposite to the direction of flight.

Total Drag has two main components:

- **Zero Lift Drag**

Even when an aircraft flies at zero lift angle of attack ***(no Lift is being produced)***, there is obvious drag on the aircraft not associated with the production of Lift. This Drag is known as Zero Lift Drag. **Zero Lift Drag or Parasite Drag increases as the square of the speed, so double the speed, 4 times the drag.**

Lift Production:

When no Lift is being produced during flight, the resultant of all the aerodynamic forces (Total Reaction), act parallel and opposite to the direction of flight.

- **Lift Dependent Drag**

While an aircraft produces Lift, it will also produce additional Drag known as Lift Dependent Drag.

There are three points to be kept in mind when considering Total Drag:

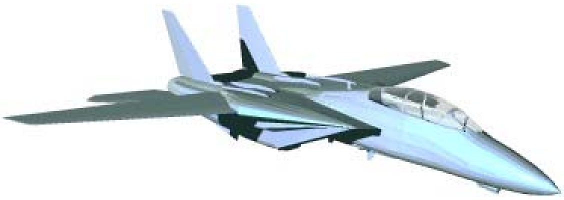
- Over the years the causes of subsonic Drag have changed very little, but the balance of values has changed.
- An aircraft in flight will have Drag even when it is not producing Lift.
- While producing Lift, the whole aircraft will produce additional Drag. Some of this Drag will be increments in those components that make up Zero Lift Drag.

ZERO LIFT DRAG (PARASITE DRAG)

Aircraft are built for different roles and therefore their shape, size and configuration differ greatly.

A transport aircraft has a much larger surface area compared to a fighter aircraft. The fighter on the other hand is much sleeker and more streamlined than the transport aircraft. All these aspects affect the Total Drag characteristics of the aircraft; and in particular a specific component of Total Drag - namely **Zero Lift Drag**.

Note the difference in shape and configuration between the following two aircraft:



The aircraft on the left has much more Zero Lift Drag due to components such as the fixed undercarriage, etc, that produce Drag without producing Lift.

The aircraft on the right has much less Zero Lift Drag due to the fact that the airframe is much cleaner. There are few components that protrude into the airflow that could produce additional Drag without producing Lift.

Zero Lift Drag is composed of three components:

- **Surface Friction Drag** is caused by the viscous friction within the Boundary Layer. The total area of the aircraft skin that is exposed to the air stream will be affected by this type of drag.
- **Form Drag** is generated because of the shape or form of the aircraft.
- **Interference Drag** is caused by the interference of Boundary Layers from different parts of the airplane such as the wing and fuselage junction or the engine pylon and wing junction.

SURFACE FRICTION DRAG

Surface Friction Drag does not play a very important role in small aircraft because this type of Drag is very small per square foot and the surface area is small.

However, when this Drag force is applied to large aircraft it becomes quite large and forms a significant part or Zero Lift Drag.

Surface Friction Drag is determined by two factors:

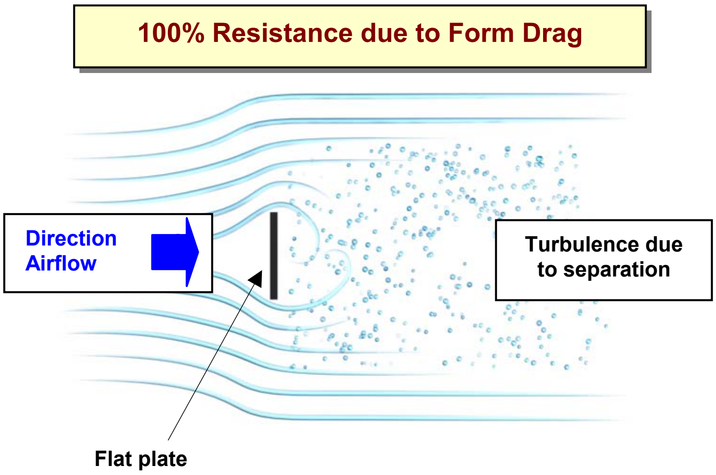
- **Surface Area.** The total surface area of an aircraft is covered by the Boundary Layer. On small aircraft with a small surface area, the contribution to the Surface Friction Drag will be very much less than on a large aircraft.
- **The Coefficient of Viscosity.** The higher the viscosity, the greater the resistance to flow and therefore the more drag it produces.

FORM DRAG

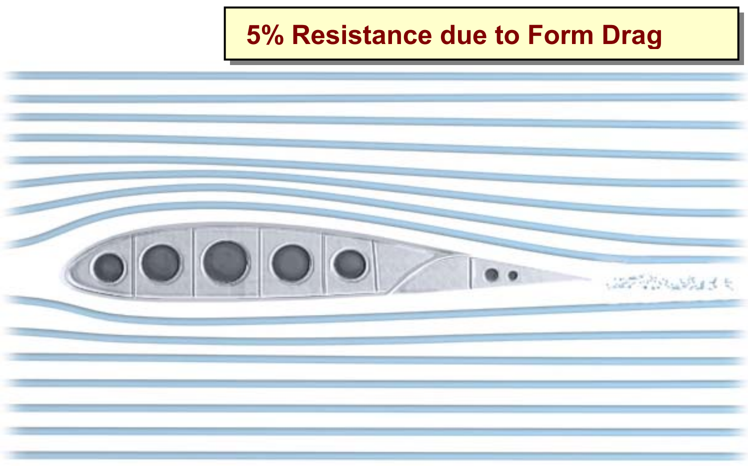
Form drag is created by structures on an aircraft such as engines that are uncowled, as well as where the undercarriage is fixed. Furthermore the shape of the biplane and the configuration (struts, cables etc) increase Form Drag.

On the other hand Form Drag is minimised by design features such as a retractable undercarriage, monoplane wing design, engines that are buried inside the fuselage etc.

In order to demonstrate the difference between Form Drag and Surface Friction Drag, a flat plate is placed perpendicular to the airflow as well as an aerofoil section at zero angle of attack.



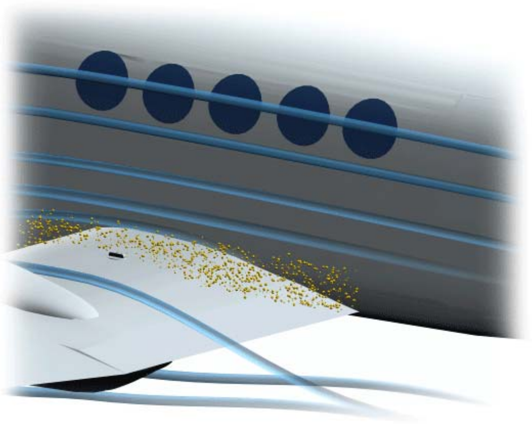
With the flat plate all the drag is Form Drag due to the Separation of the airflow from the surface.



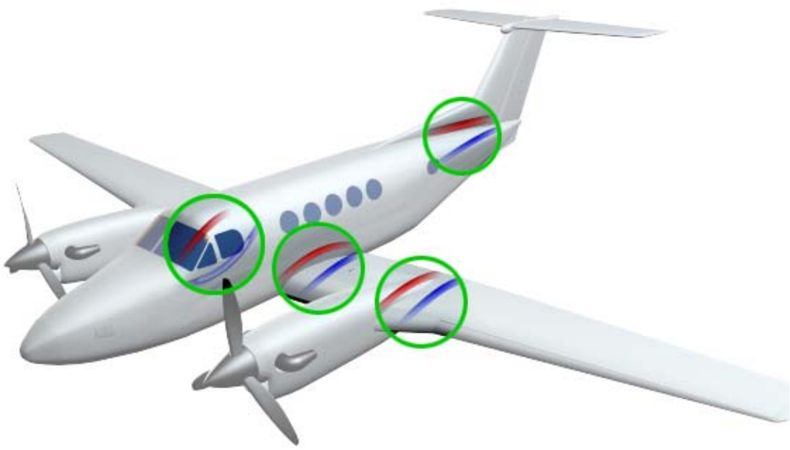
With the aerofoil only a small portion of the drag is Form Drag. The flow stays attached to the surface, thus most drag is Surface Friction Drag.

INTERFERENCE DRAG

Interference Drag is generated when several objects are placed in the same air stream. This creates turbulence and restricts smooth flow.



On this graphic the air flowing along the fuselage collides with air flowing over the wing. The interference of the Boundary Layer at the fuselage/wing junction causes turbulence that increases the Drag on the aircraft. Areas such as the wing/pylon and empennage/fuselage junctions also contribute to Interference Drag.



On a complete aircraft the total drag is greater than the sum of the values of drag for the separate parts of the aircraft.

ZERO LIFT DRAG REDUCTION

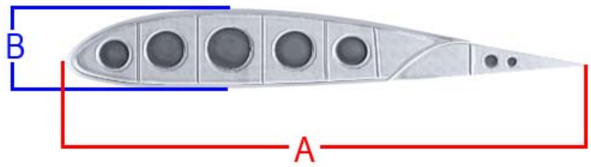
Because Zero Lift Drag can have a large negative effect on the performance of any aircraft, it is very important to keep Zero Lift Drag to a minimum.

- Surface Friction Drag. This type of Drag can be decreased by making use of flush head rivets, polishing the skin surface and removing any oxide build-up.

- Form Drag. Sleeker aircraft design is used to reduce form drag. This is done by **streamlining** the fuselage, engine nacelles, pods and external stores.

- Interference Drag. Turbulence and therefore Drag at the fuselage/wing junction will be reduced if the airflows are allowed to merge smoothly. This is accomplished by incorporating smooth fairings at surface junctions.

Streamlining:



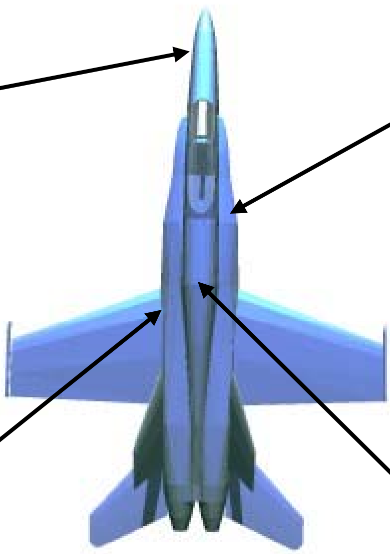
Fineness Ratio = $\frac{A}{B}$

Streamlining an object increases the fineness ratio and reduces the curvature of the surfaces and thereby reduces the adverse pressure gradient.

Modern aircraft are designed to reduce Zero Lift Drag as much as possible. This improves the aerodynamic efficiency and the overall performance of the aircraft. Here follows examples of how the designers have gone about reducing Zero Lift Drag.

The frontal area of modern aircraft is kept as small as possible for low form drag.

The engines are not mounted on pylons and in nacelles, but internally; thereby reducing surface friction, form and interference drag.



All airframe junctions are very smoothly faired over (fuselage/ wing, etc.). This reduces interference drag.

Most modern fighter aircraft have a relatively small surface area and therefore a small surface friction drag component.

LIFT DEPENDANT DRAG (INDUCED DRAG)

The vapour trails coming off the wing tips are a common sight with high-speed aircraft manoeuvring hard while flying. Propeller driven aircraft sometimes have similar vapour trails at the tips of the propellers during take-off.

A vapour trail is the core of a vortex that is formed at the wing tip or tip of the prop. These vortices are the tell tale of the second component of Total Drag - **Lift Dependent Drag.**

Where Zero Lift Drag is present even when no lift is produced, Lift Dependent Drag only arises when **lift is actually being produced**. Combined, Lift Dependent Drag and Zero Lift Drag affect the aircraft in all flight regimes and performance aspects.

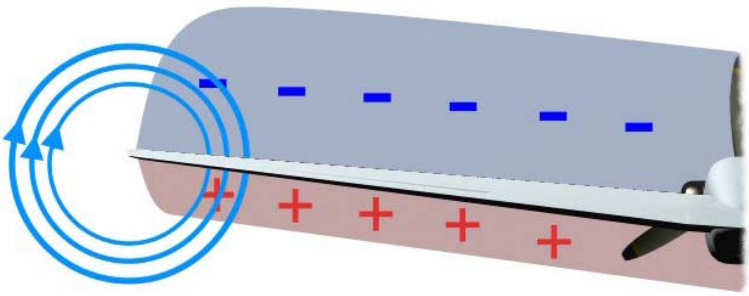
Lift Dependent Drag consists of two components:

- **Induced Drag (Vortex Drag)**
- **Increments of Zero Lift Drag**

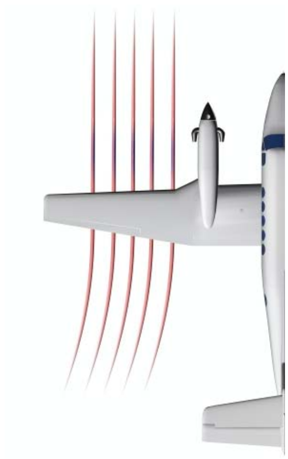
INDUCED DRAG (VORTEX DRAG)

Three-dimensional flow causes vortices at the wing tips, which again causes additional drag - Induced, or Vortex Drag.

The low pressure above an aerofoil producing lift is of greater intensity than the low pressure below the aerofoil. The graphic below gives an indication of the span wise pressure distribution on a rectangular wing.

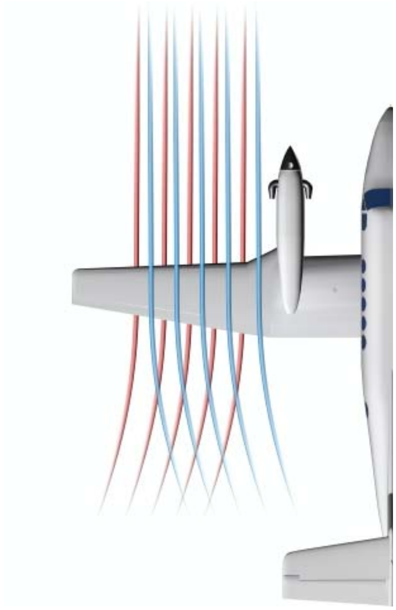


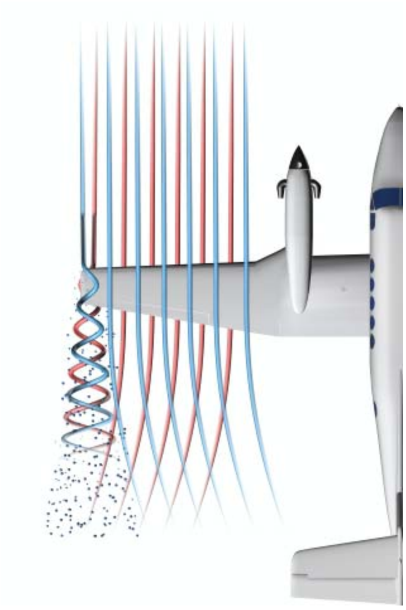
Due to the fact that air normally flows from a high to a low pressure, the higher intensity of the low pressure above the wing will cause the air below the wing to **spill around the wing tip** towards the upper surface.



Due to the air spilling around the wing tips, the airflow under the wing is deflected towards the wing tip.

At the same time the airflow over the wing is deflected towards the fuselage.





When the airflows meet behind the trailing edge, a sheet of vortices is formed. These vortices tend to drift towards the wing tip where a large vortex is formed.

During high lift manoeuvres the pressure difference between the upper and lower surface of the wing increases dramatically. This results in strong wing tip vortices and the drop in pressure at the core of these vortices may be enough to cause vapour trails to form.

The vortices produce extra downwash behind the wing ***(in addition to the downwash resulting from lift)*** and this down flow is known as **Induced Downwash**.

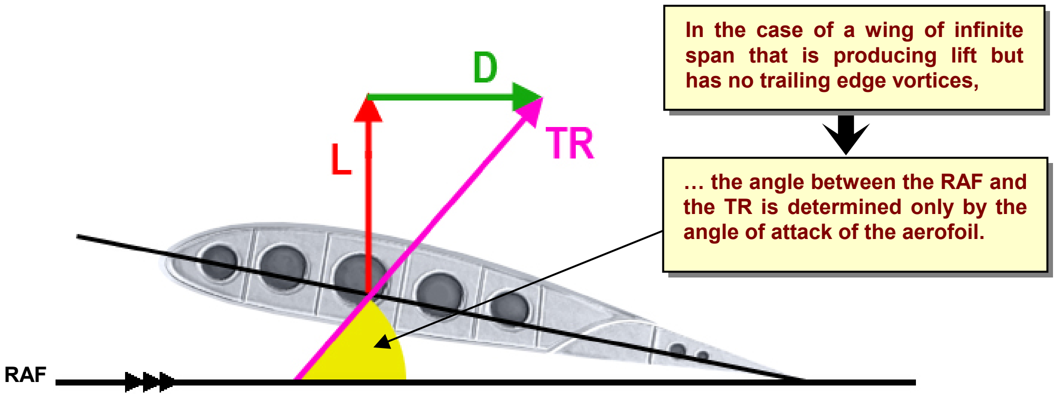
Downwash behind the Wing:

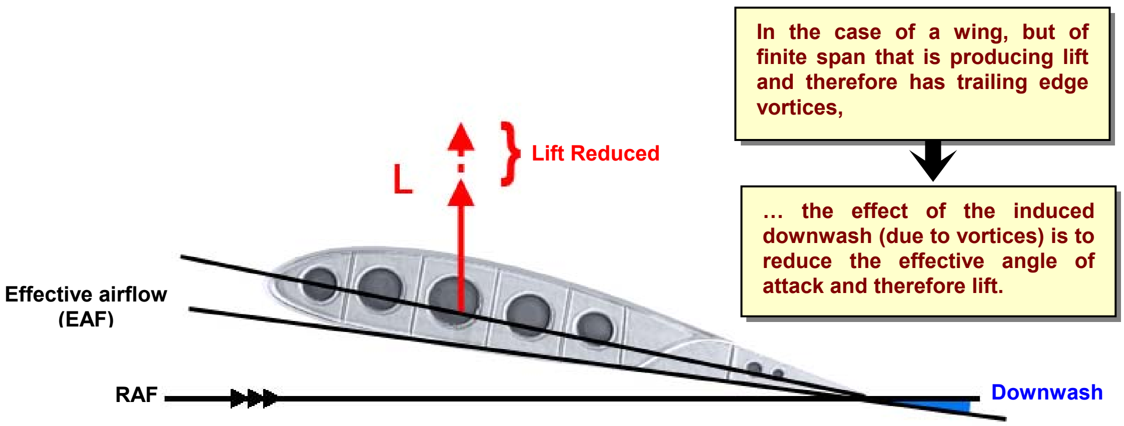
This downwash forms two strong vortices that spiral in behind the aircraft. The vortices can remain stationary on a runway in no wind conditions. These wing tip vortices can be extremely dangerous to light aircraft taking off or landing behind large aircraft.

The vortices and the resultant downwash cause acceleration ***(Change of speed and direction of the airflow)***. The power absorbed by this acceleration may be expressed in terms of an additional drag force - **Induced Drag**.

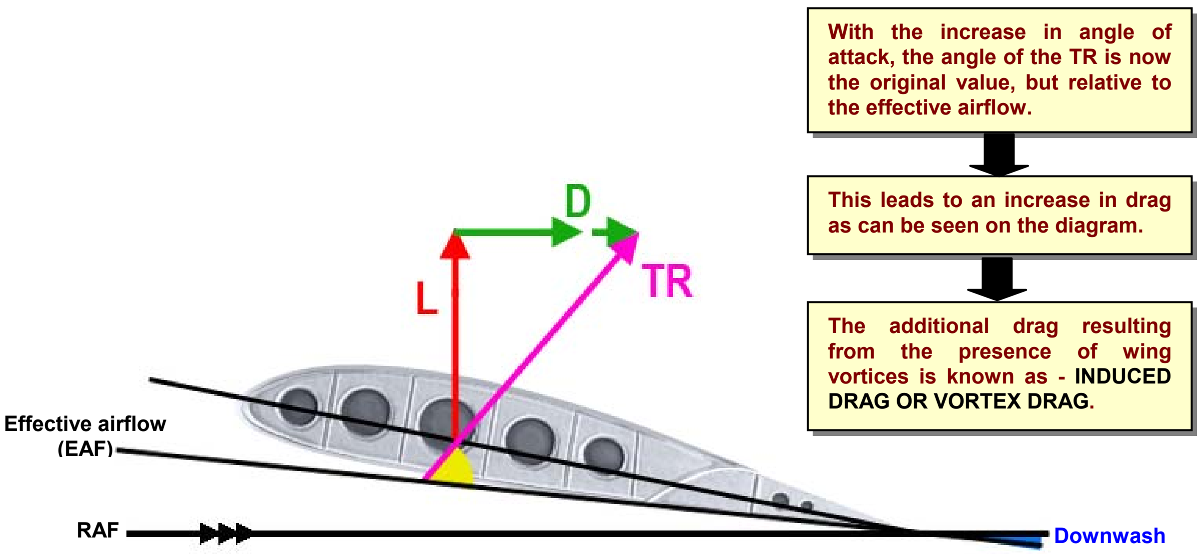
Induced drag can also be explained by means of a Diagram.

DIAGRAMMATIC EXPLANATION: INDUCED DRAG





To counter the lift reduction, the angle of attack must be increased until the original lift value is reached. However an increase in the angle of attack will increase the downwash. What will happen to the value of Drag?

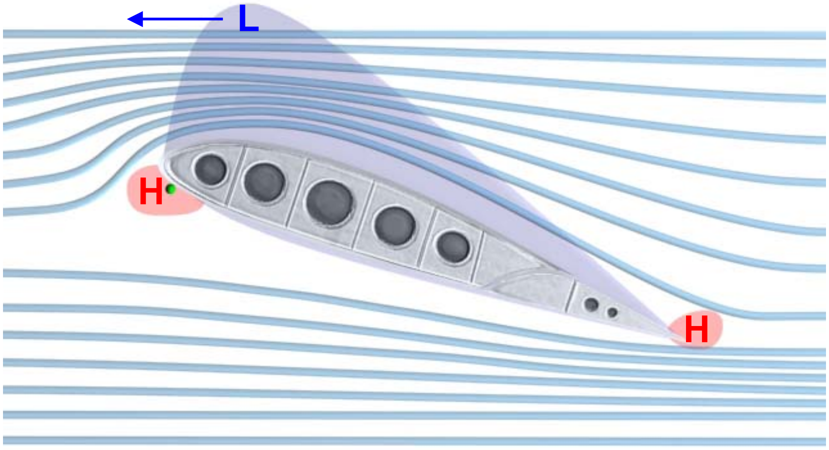


ZERO LIFT DRAG INCREMENTS DUE TO LIFT

An earlier transition to turbulence and a stronger adverse pressure gradient will increase Zero Lift Drag

The further forward the Transition point moves, the greater the area of the surface that is covered by turbulence and that means an increase in Zero Lift Drag. It is therefore important to delay the forward movement of the Transition Point for as long as possible.

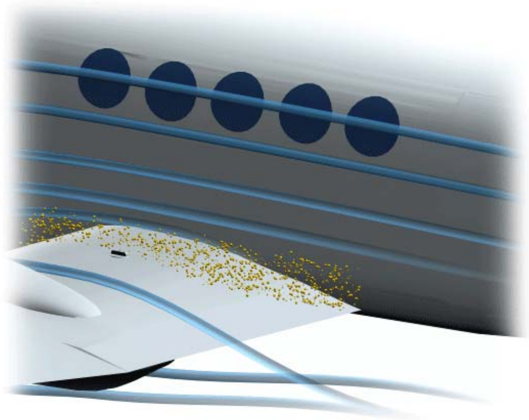
With an Adverse Pressure Gradient there is a pressure increase in the direction of the flow. This leads to lower KE levels and relatively higher pressures that assist in the airflow separating from the surface and increases Form Drag.



As lift increases, the peak of the low pressure above the wing moves forward. This leads to earlier transition to turbulence of the boundary layer.

The adverse pressure gradient will also increase and this in turn will lead to earlier separation of the airflow.

Earlier transition to turbulence of the boundary layer increases surface friction drag and earlier separation of the airflow increases the form drag (***Referring to the lesson on Boundary Layer Theory***).



Interference drag is due to the mixing of the boundary layer at the junctions of the airframe.

As soon as an aircraft starts to produce lift, the boundary layer thickens and becomes more turbulent. This leads to greater energy losses at the points where the mixing takes place.

These increments of surface friction-, form- and interference drag are due to lift production and are normally included in lift dependent drag. From this it can be seen that the greater the lift produced, the greater the zero lift drag increments. The additional drag increments are only noticeable at high angles of attack.

FACTORS AFFECTING LIFT DEPENDANT DRAG

The factors affecting vortex formation and therefore induced drag are:

- **Planform**
- **Aspect Ratio**
- **Lift and Weight**
- **Speed**

PLANFORM

The amount of induced drag is affected by the size of the vortices.

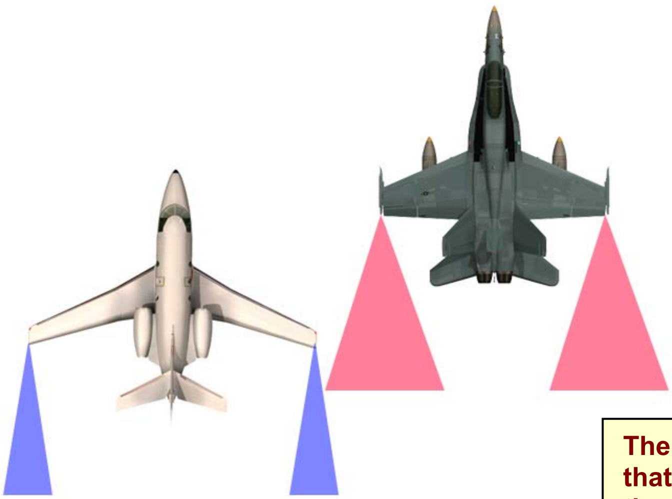
The largest and strongest vortex formation is found at the wingtip. The ideal is therefore to achieve an even span wise pressure distribution. This will ensure that the induced downwash stays constant along the entire wingspan.

A wing with an elliptical planform has an even spanwise lift distribution. For a given lift, span and velocity; an elliptical wing creates the minimum induced downwash and therefore the minimum induced drag.

The Spitfire is the most famous example of an aircraft with a wing of elliptical planform. Although an elliptical wing is a very efficient wing and has many advantages with regards to performance; it's difficult and extremely expensive to manufacture.

ASPECT RATIO

With a low aspect ratio wing the transverse flow due to the longer chord causes increase tip spillage and aggravates the wing tip vortices. The greater induced downwash also affects a larger portion of the shorter wingspan.

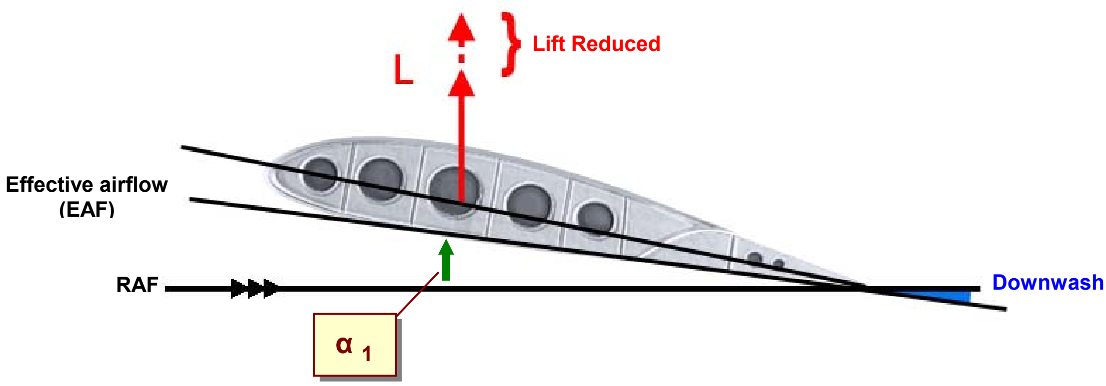


Therefore induced drag is inversely proportional to the aspect ratio. If the aspect ratio is halved, the induced drag is doubled and vice versa.

The aircraft on the left has high aspect ratio wings that are closer to the ideal of an infinite wing than the aircraft on the right. The higher the aspect ratio, the less the induced drag due to the decreased amount of induced downwash and weaker wing tip vortices.

LIFT AND WEIGHT

The induced downwash angle (α_1) - and therefore the induced drag depend upon the pressure difference between the upper and lower surface of the wing. This pressure difference is also the lift produced by the wing.



This means that an increase in C_L due to manoeuvres or a weight increase will increase the induced drag at a specific speed.

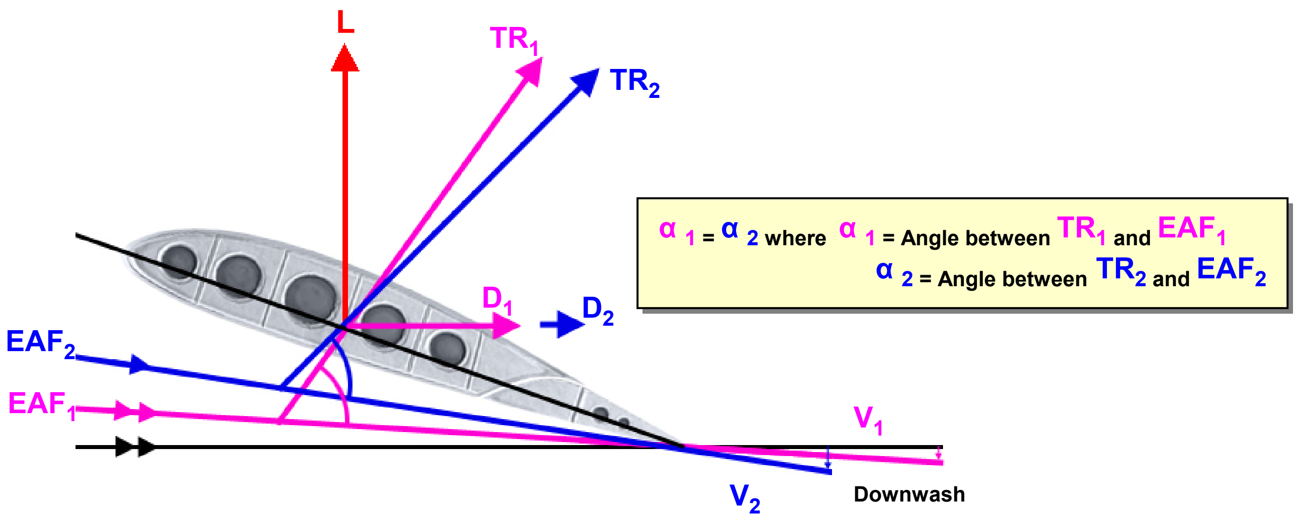
The induced drag varies as C_L^2 , and therefore as weight^2 , at a given speed.

SPEED

Since the value of C_L is directly proportional to the value of the low pressure above the aerofoil, it means that as the angle of attack increases, the value of C_L will also increase.

If the speed is reduced during level flight the angle of attack must be increased to maintain level flight (***constant lift value***).

$L = C_L \frac{1}{2} \rho V^2 S$



The increased angle of attack that is necessary to increase the C_L, inclines the **TR** to the rear (**TR_2**) and this increases the induced drag (**D_2**). However the vortices are not affected because **lift** does not change and aerofoil pressure on the top and bottom stay the same.

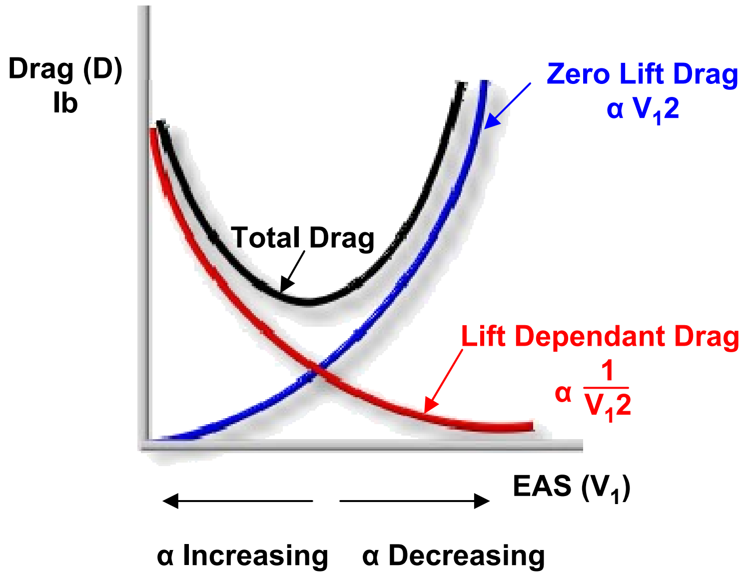
At high angles of attack ***(such as during take-off)*** the induced drag can account for nearly three-quarters of the total drag. Induced drag decreases to insignificant figures at high speed.

DRAG CURVES

TOTAL DRAG CURVE

As was stated previously, Total Drag is made up of two components: Zero Lift Drag and Lift Dependent Drag.

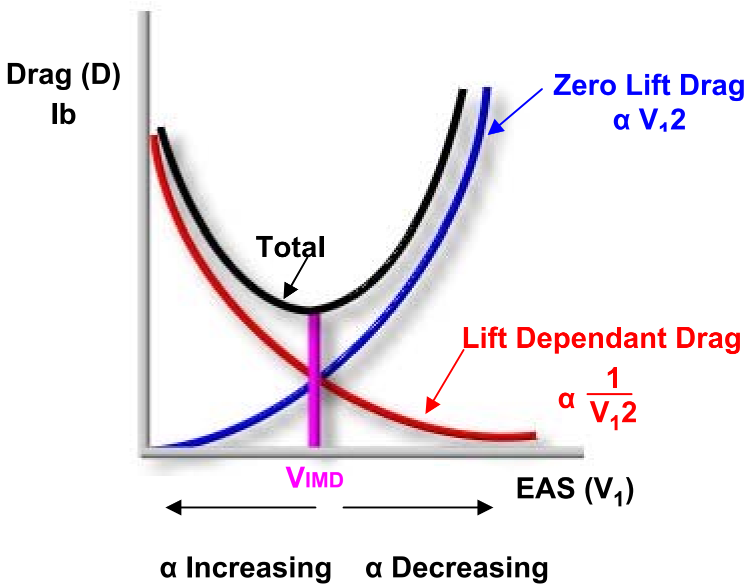
Graphically they can be represented on a graph of drag against EAS and α. From these two graphs the total drag curve can be drawn as follows:



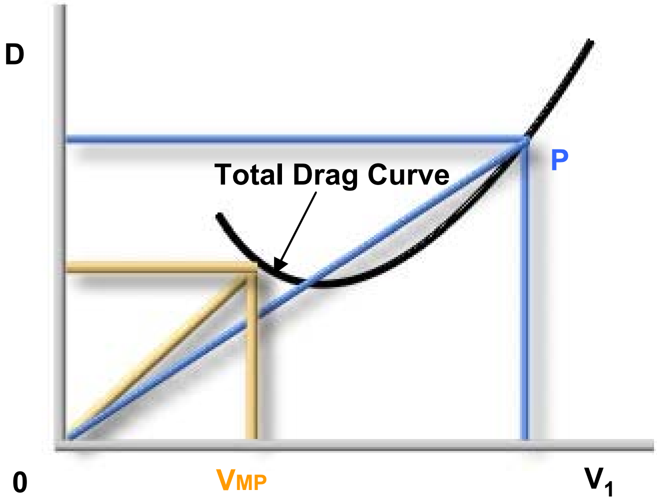
This graph is very important when it comes to performance theory and it must be remembered that **one graph is valid for one specific weight** only.

MAXIMUM L/D RATIO

To have the L/D Ratio a maximum and lift stays constant, the value of drag must be a minimum. The point where drag is the minimum will be found at the lowest part of the total drag curve. The corresponding speed at this point is known as **VIMD** or Minimum drag speed. This speed is used for gliding.



MINIMUM POWER



Consider a point **P** on the Zero Lift Drag curve and use the coordinates to construct a **rectangle**.

The area of this rectangle is the product of drag and speed. From this it can be seen that: drag x speed = force x velocity = work done per unit time = power

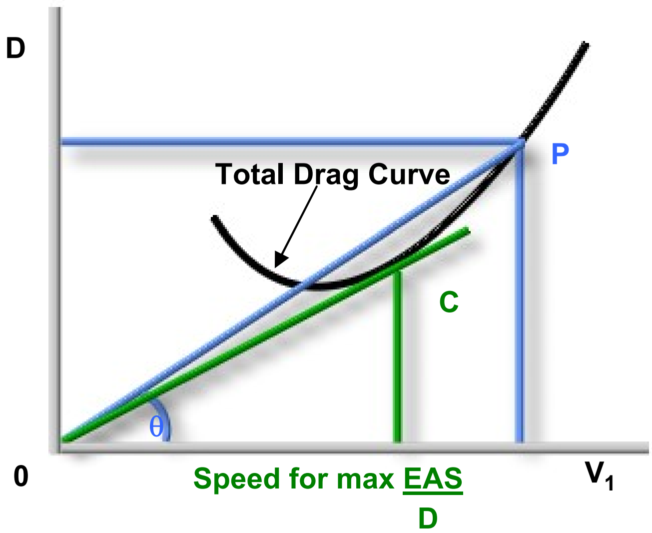
Therefore the area under **P** is a measure of the power required to fly the aircraft in level flight at that speed.

The smallest area possible under the graph represents the **minimum value of drag x speed** for level flight and is found to the left of the minimum drag speed. This corresponding speed is known as **V_{MP}** or the minimum power speed. This speed is used for endurance flying.

MAXIMUM EAS/D RATIO

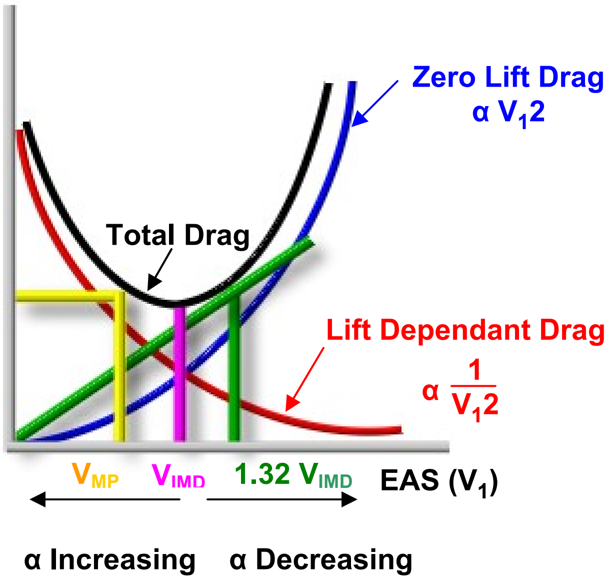
The angle θ is subtended by the line drawn from point **P** on the Total Drag Curve to the origin.

This angle is a measure of the ratio of $\mathbf{\frac{EAS}{D}}$. **(Cot** $\theta = \mathbf{\frac{EAS}{D}}$**)**. This ratio of $\mathbf{\frac{EAS}{D}}$ is therefore a maximum when θ is a minimum.



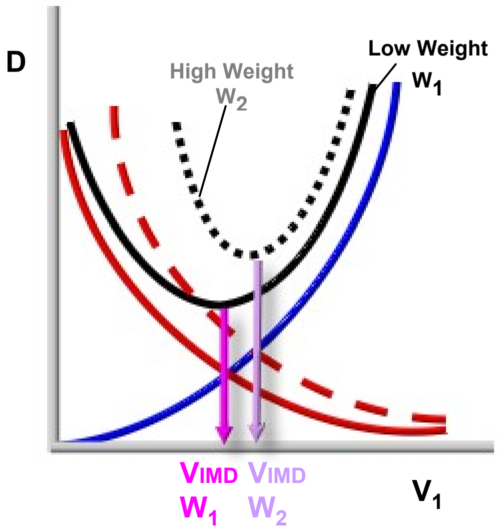
There is only one point on the total drag curve where that is true; and that is C on the tangent to the drag curve drawn through the origin. This speed corresponding to this value is normally expressed as a function of minimum drag and is known as **1.32 V_{IMD}.** This speed is used for jet engine range flying, but not turboprop or piston engines.

V_{MP}, V_{IMD} and 1.32 V_{IMD} can be plotted on the Total Drag Curve as follows:



WEIGHT

It was emphasized that the drag curves on the previous graphs were only valid for level flight ***(i.e. one stated weight or lift)***.



When the weight is changed - and therefore the C_L there will be a corresponding change in the lift dependent drag to maintain level flight.

Since lift dependent drag varies as C_L^2 (or weight^2) the difference in total drag will be greatest at high angles of attack and least at lower angles.

A change in weight will alter the point at which the lift dependent and zero lift drag curves cross, resulting in a change of the minimum drag speed, *eg* an increase in weight will increase the V_{IMD} as well as the total drag.

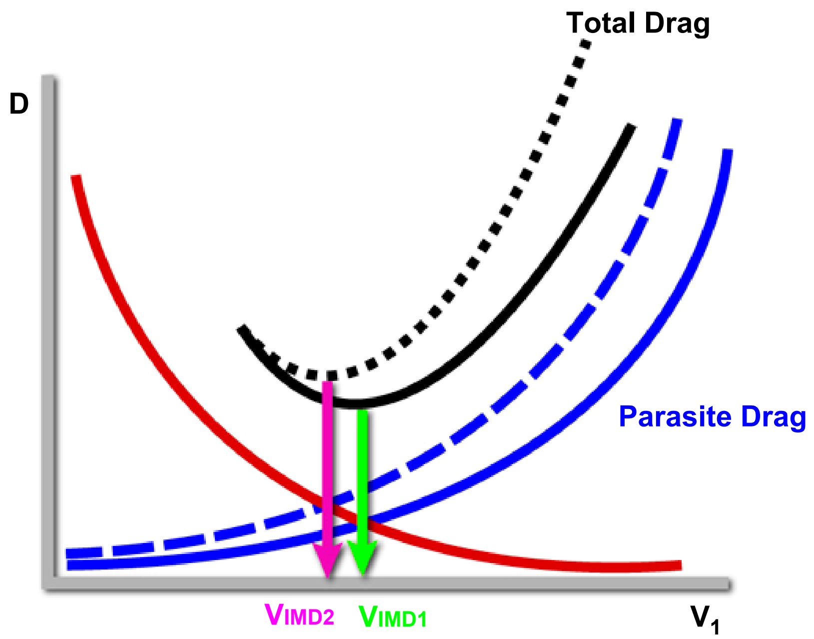
HIGH DRAG DEVICES

It is sometimes necessary to decrease the **VIMD** by deliberately increasing the **total drag**.

This is done by using airbrakes, drag parachutes etc, which have the effect of increasing the **zero lift drag**.

Drag Parachutes: A drag parachute is used mainly on fighter aircraft to reduce their after landing roll because of the high speeds that they are landing at.

Airbrakes: Airbrakes are used on fighter aircraft to reduce speed rapidly in flight. On landing they are deployed to help reduce the landing roll by increasing drag.



COEFFICIENT OF DRAG (C_D)

The equation for Aerodynamic Force ***(Referring to the lesson on lift)*** is:

½ρV²S x a coefficient

Where the coefficient indicates the change in the force, which occurs when the angle of attack is altered.

Therefore the equation for Drag = C_D ½ρV²S

The coefficient of drag (C_D) of a wing is found experimentally at a given RN from the drag formula. It also allows for angle of attack and all the unknown quantities, which are not represented in the force formula.

Therefore the equation for C_D is:

$$C_D = \frac{Drag}{\frac{1}{2}\rho V^2 S} = \frac{Drag}{qS}$$

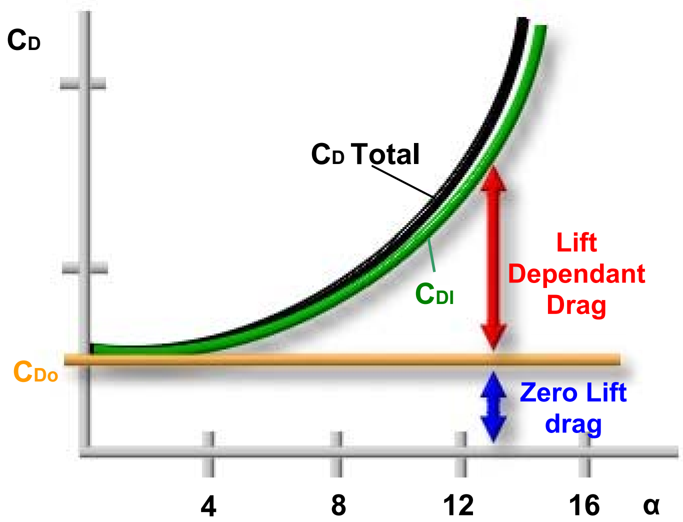
FACTORS AFFECTING DRAG COEFFICIENT

The Coefficient of drag is dependent upon:

- **Angle of attack**,
- **Shape and Planform**,
- **Surface roughness**,
- **Reynolds number** and
- **Speed of sound.**

ANGLE OF ATTACK

As was stated previously, total drag (**C_D**) is divided into two parts, into **C_{Do}** (**Zero Lift Drag Coefficient**) and **C_{DI}** (**Lift Dependent Drag Coefficient**). On the graph **C_D** is plotted against angle of attack although it is usually plotted against C_L.

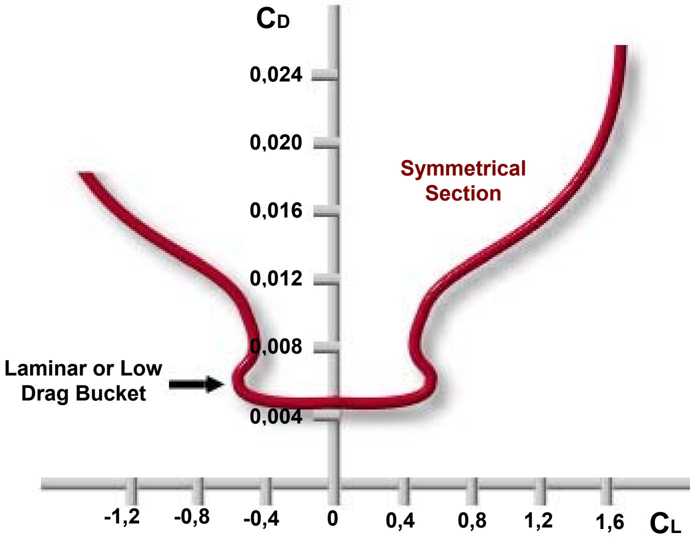


At low angles of attack (low C_L) the drag is mostly zero lift drag. The zero lift drag does not increase with an increase in angle of attack but stays constant. Therefore **C_{Do}** remains constant.

As was stated previously, at high angles of attack (high C_L) lift dependent drag increases due to an increase in induced drag. This leads to an increase in **C_{DI}** and therefore C_D (total).

SHAPE AND PLANFORM

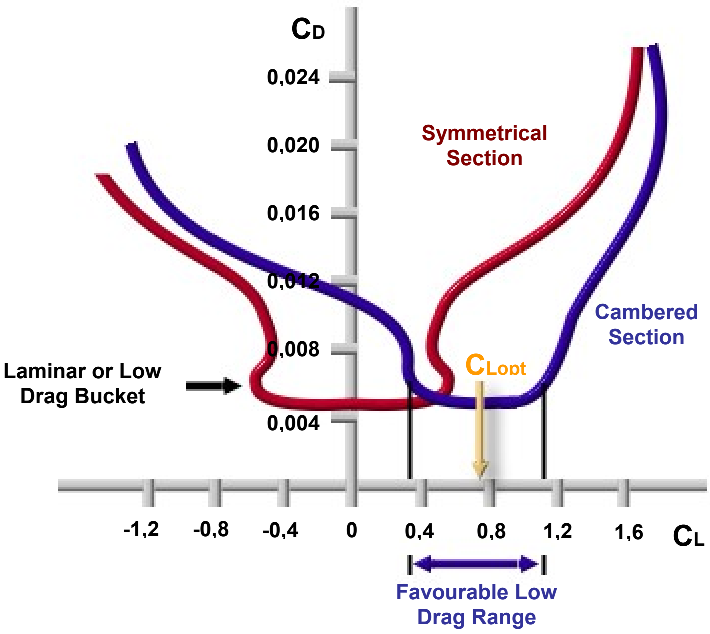
The C_D of an aerofoil can be influenced by many subtle changes in section, but thickness/chord ratio and camber are the two aspects that have the greatest influence and are therefore the most important.



On the graph C_D is plotted against C_L and shows the curve for a symmetrical aerofoil section such as found on high-speed aircraft. These types of aerofoils are very thin and have a low minimum value of C_D because they have a low C_L.

The curve also shows the laminar (low drag) bucket. Laminar airflow covers the largest part of the aerofoil thus reducing drag. This is found on high-speed wings where the maximum thickness is 40% - 50% aft of the leading edge.

With an increase in camber, C_L increases and this causes the Laminar Bucket to move to the right on the C_L axis.

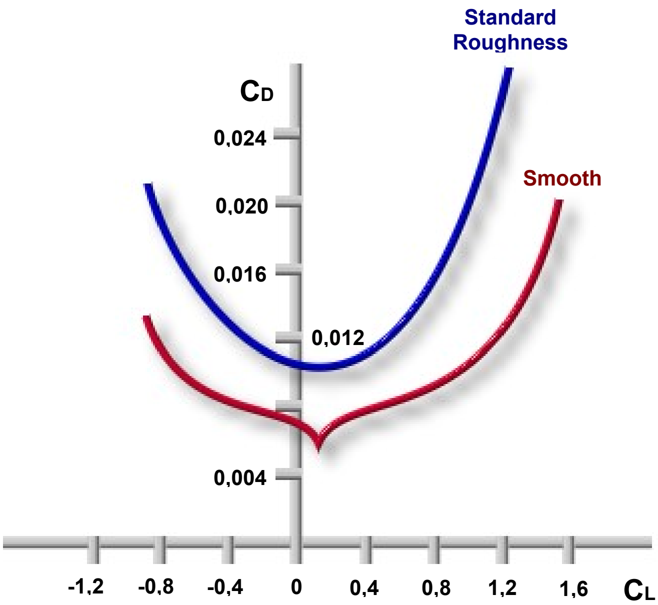


The central value of the bucket is known as **C_{Lopt}** (**Optimum C_L**) and the value is determined by the amount of camber and the shape of the mean camber line.

A wing can be designed to position the favourable range to cover the most common range of C_L for a particular aircraft. This leads to increased performance and benefits economy.

SURFACE ROUGHNESS

Increased surface roughness will increase surface friction drag. Any roughness on the surface (especially the leading edge) that can be felt by hand will cause the laminar boundary layer to become turbulent. The turbulent flow spreads out in a fanwise pattern behind this point of roughness. This increase in turbulence in the boundary layer leads to an increase in surface friction drag.



On the graph C_D is plotted against C_L and a curve for a smooth surface is indicated.

The earlier transition to turbulence due to surface roughness increases the surface friction drag. ***(Surface Friction Drag is an increment of Zero Lift Drag that forms part of Lift Dependent Drag.)***

This again increases total drag and causes the C_D curve to move up - indicating a higher C_D value.

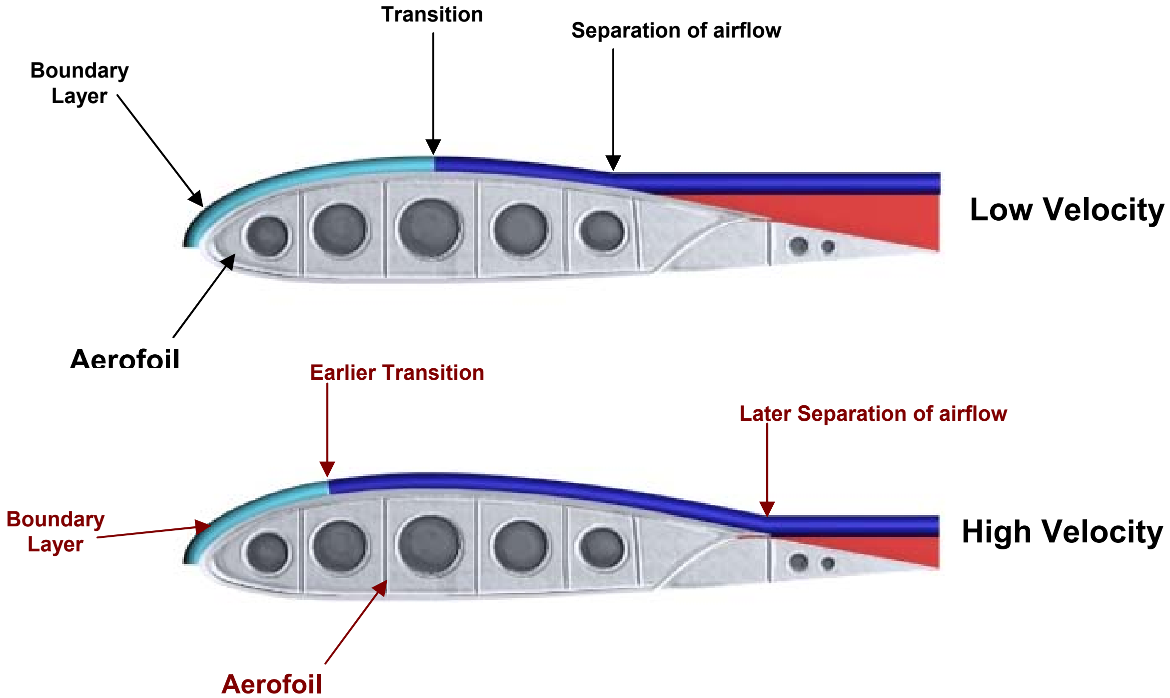
REYNOLDS NUMBER

Lift will increase with an increase in Reynolds Number. (***Referring back to the lesson on lift)***

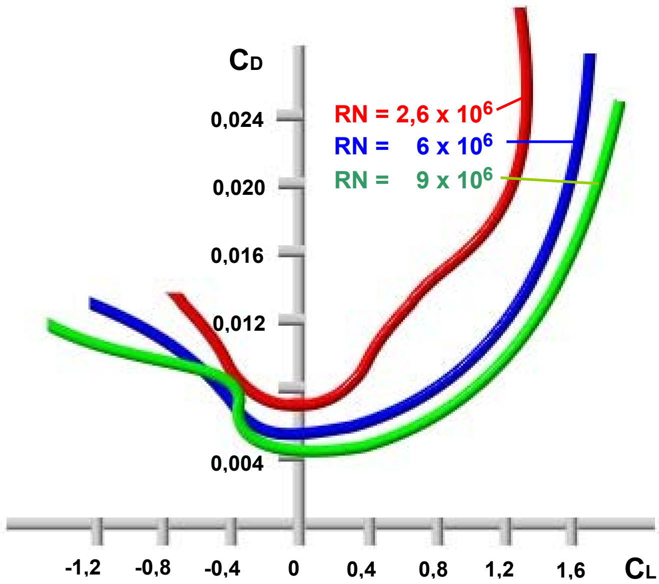
The only component of the RN that changes is the velocity. With an increase in velocity, transition occurs earlier and the turbulent boundary layer has more kinetic energy. This allows the boundary layer to separate later (closer to the trailing edge).

Reynolds Number: $\frac{\rho VL}{\mu}$

With an aircraft flying at a specified altitude, the only variable in the formula is velocity. If velocity increases, RN will increase and as RN is part of C**L** - Lift will increase.



Although surface friction drag increases due to the fact that a larger area is covered by turbulent boundary layer, the fact that separation of the airflow is delayed, leads to a reduction in form drag as can be seen on the graph ***(The graph shows the effect of increase in RN on an aerofoil section)***.



If only an aerofoil in a wind tunnel is considered, the form drag has the greater effect and drag due to the boundary layer will actually decrease. However, the thicker boundary layer increases the interference drag when applied to a complete aircraft.

Therefore with a higher Reynolds Number, there is a decrease in form drag, but the increase in surface friction and interference drag will lead to an overall increase in total drag.

SPEED OF SOUND

The effect of speed of sound (Mach Number) on the C_D during transonic and supersonic flight will be discussed in detail in High Speed Aerodynamics. Aspects covered will include wave drag, trim drag and interference drag.