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AERODYNAMICS 1

CHAPTER 8 – AIRCRAFT IN FLIGHT (S&L, CLIMB AND GLIDE)

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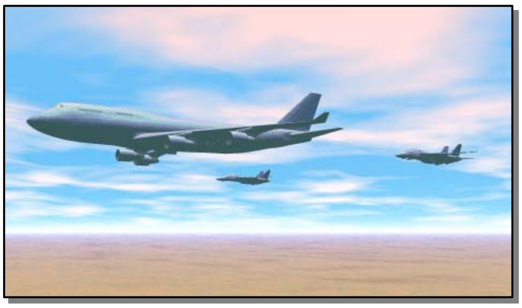
FORCES IN STRAIGHT AND LEVEL FLIGHT

INTRODUCTION

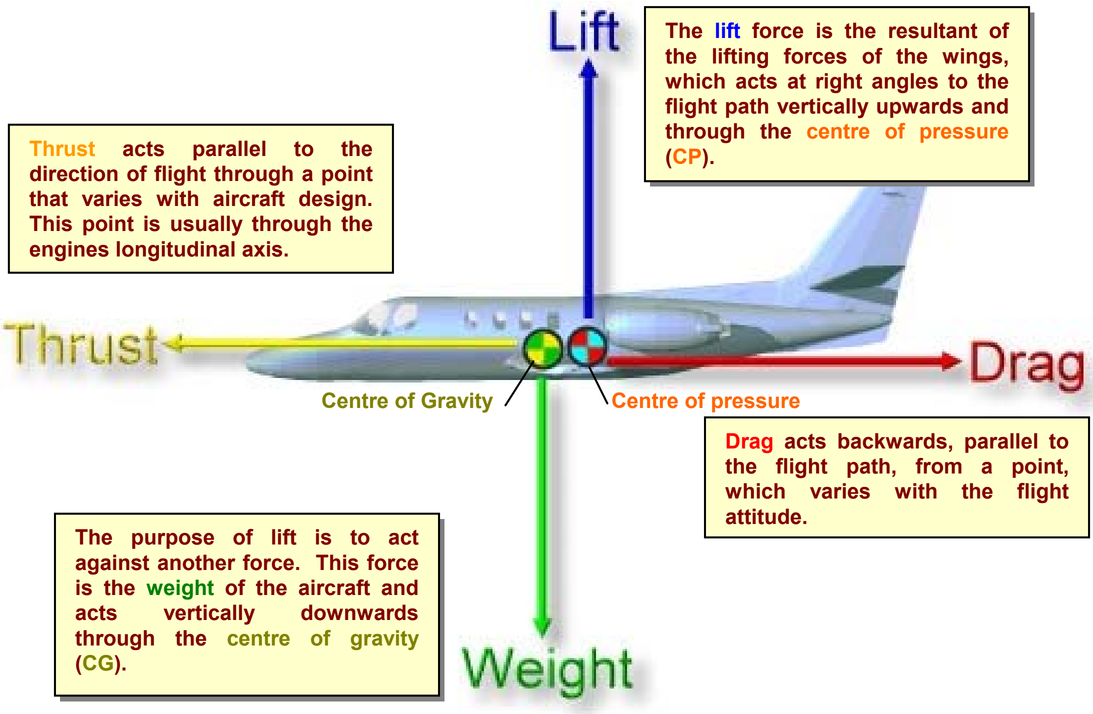


Straight and level flight is one of the basic building blocks in flight training. It forms the bulk of all types of flying - transport, chopper and fighter - and will always be present in a flight situation, whether it is training or operational.

The principles of aircraft performance learnt for straight and level flight lays the foundation for future lessons i.e. Climbing, Gliding, Turning and Manoeuvring.

FORCES

During flight four main forces act upon an aircraft: lift, weight, thrust and drag.



When an aircraft is in steady straight and level flight, it is trimmed for lift to equal weight and the engine is set for thrust to equal the aircraft drag. The aircraft is therefore in equilibrium. This means that all the forces acting on it are in balance and there is no resultant force to accelerate or decelerate it.

Acceleration:

Acceleration is a change in velocity, which means a change in speed or a change in direction, or both. In straight and level flight, the aircraft is not forced to change either speed or direction.

Therefore to summarise the requirements for an aircraft to maintain straight and level flight, regarding the four forces acting on it:

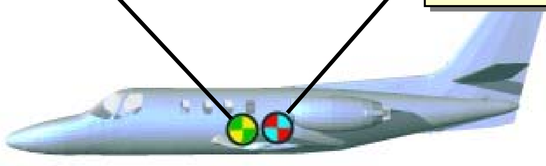
- Lift (**L**) = Weight (**W**)
- Thrust (**T**) = Drag (**D**)

Note: The configuration of the aircraft is not specified. An aircraft can fly straight and level with various undercarriage and flap selections.

PITCHING MOMENTS

The position of the centre of gravity (CG) is marginally under control of the pilot of the aircraft.

The centre of pressure (CP) moves forward as the angle of attack of an aerofoil increase. This means that the CP varies in position as the aircraft changes its angle of attack.

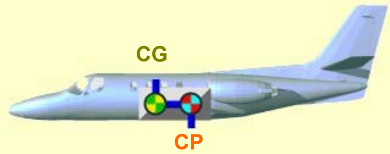


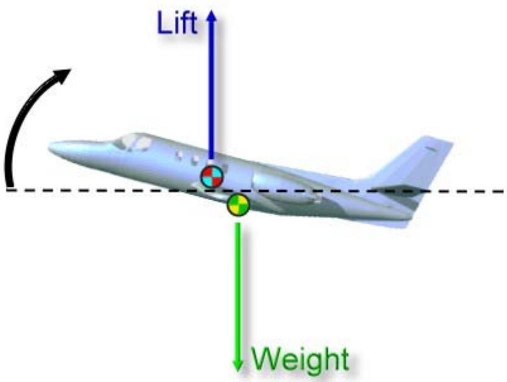
Therefore: **The position of the CP and CG are variable and under most conditions of level flight will never coincide.**

Seeing that the lift force acts through the CP and the weight force through the CG, combined with the fact that they never coincide, we get a situation where the opposing forces of lift and weight set up a couple.

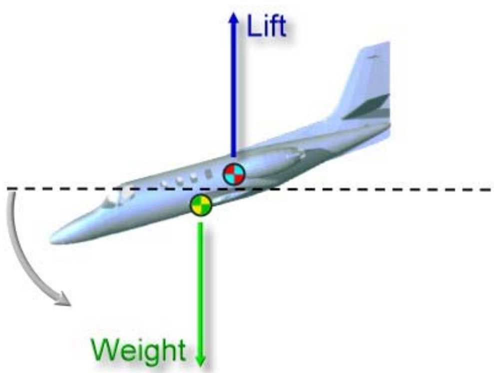
A couple :

A pair of forces acting in parallel but opposite directions, capable of causing rotation.





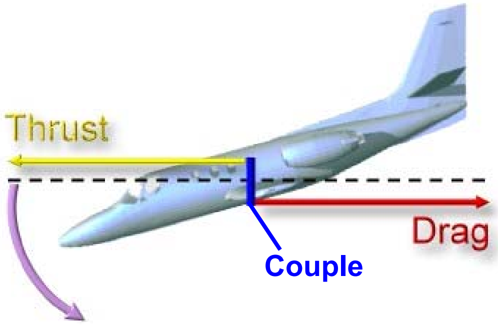
Due to the couple between the CP and CG and the two forces acting in opposite directions, if the lift force (and therefore the CP) is ahead of the CG the couple will cause a clockwise moment will occur about the couple. This results in a **nose-up** pitching moment.

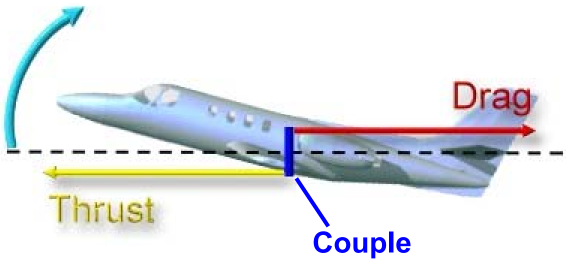


When the CP is behind the CG the aircraft will experience a **nose-down** pitching moment. This is how most aircraft are set up.

As a couple forms between the lift and weight forces a couple also forms between the thrust and drag forces. Again, the couple will cause a nose-up or nose-down pitching moment, depending upon the relationship between the points through which these forces act.

If the point through which the thrust force acts is above the point through which the drag force acts, the aircraft will experience a nose-down pitching moment.



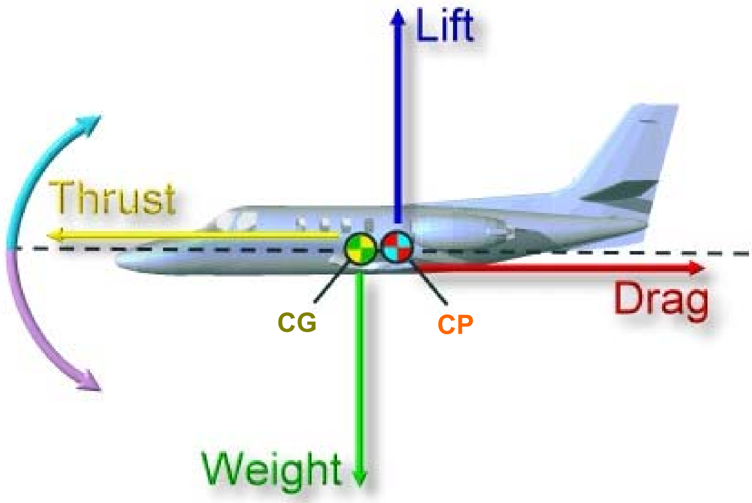


Vice versa, if the point through which the thrust force acts is below the point through which the drag force acts, the aircraft will experience a nose-up pitching moment.

The usual design is to have the CP behind the CG, so that the lift/weight couple is nose-down, and the thrust line lower than the dragline, so that the thrust/drag couple is nose-up.

Any loss in power will weaken the nose-up pitching moment and thereby causing the nose-down pitching moment to pitch the aircraft into a descent.

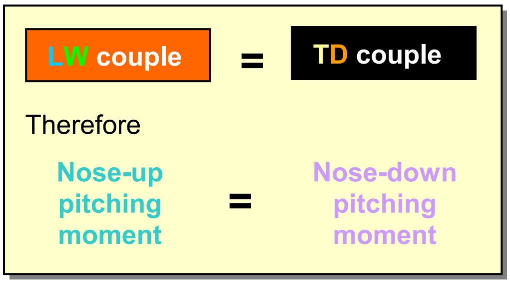
It is therefore a fairly safe arrangement of all these forces.

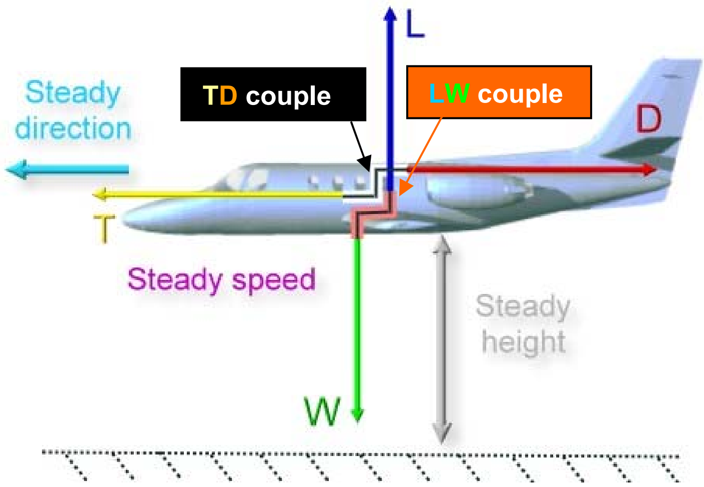


LEVEL FLIGHT

With the background knowledge of forces and moments, straight and level flight can be defined as:

A condition in which the aircraft flies at a steady height, direction and speed, with the sum of the moments acting about the aircraft being equal to zero.





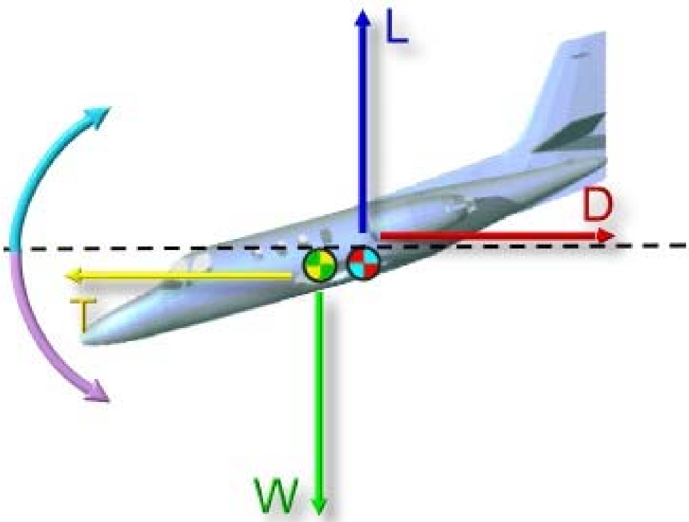
FUNCTION OF THE TAILPLANE AND ELEVATOR

Because of the movement of the CP and CG, the ideal situation ***(where resultant pitching moment equals zero)*** rarely exists. For this reason the tailplane/elevator is designed into the aeroplane to produce a balancing force.

It can therefore be said that the function of the tailplane is to stabilise the aircraft in pitch.

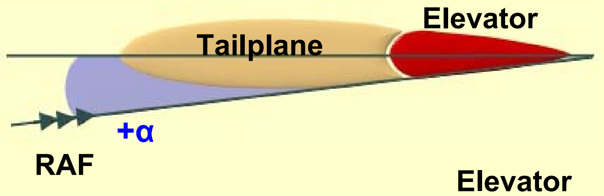
Refer to the following example where power is reduced and the aircraft pitches nose-down, due to the **reduced pitching moment** of the thrust/drag couple and **higher, unchanged, pitching moment** of the lift/weight couple.

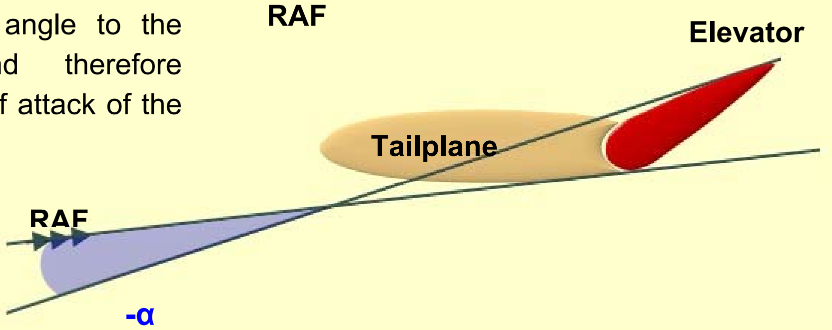
In order to pitch the nose of the aircraft up again for straight and level flight, without increasing power, the angle of attack of the tailplane must be changed to produce a downward lift force on the tailplane and therefore a clockwise moment about the CG of the aircraft.



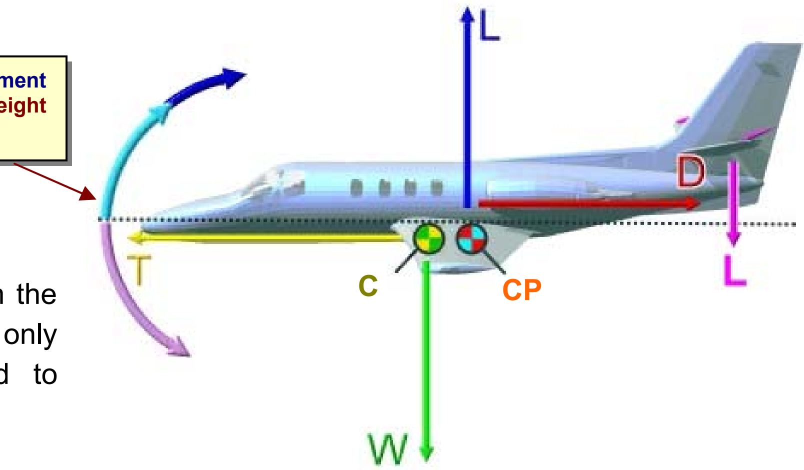
An up deflection of the elevator will be necessary for the change in angle of attack and downward lift force.

As the elevator gets deflected upwards, the chord line of the tailplane changes its angle to the RAF (reduced) and therefore decreasing the angle of attack of the





Moment due to thrust/drag couple + Moment due to tail lift force = Moment due to lift/weight couple.

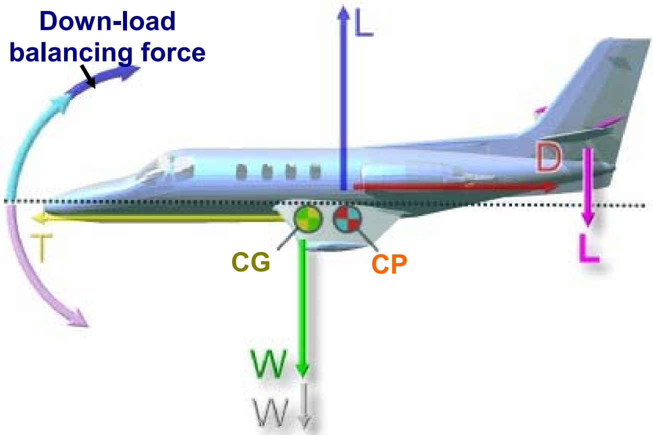


Since the tailplane is well away from the aircraft's CG (large moment arm), only small elevator forces are required to counter any residual unbalance.

TRIM DRAG

If, in level flight, an aircraft experiences any nose-up or nose-down tendency, the elevator position can be altered to provide an upward or downward force respectively to trim the aircraft.

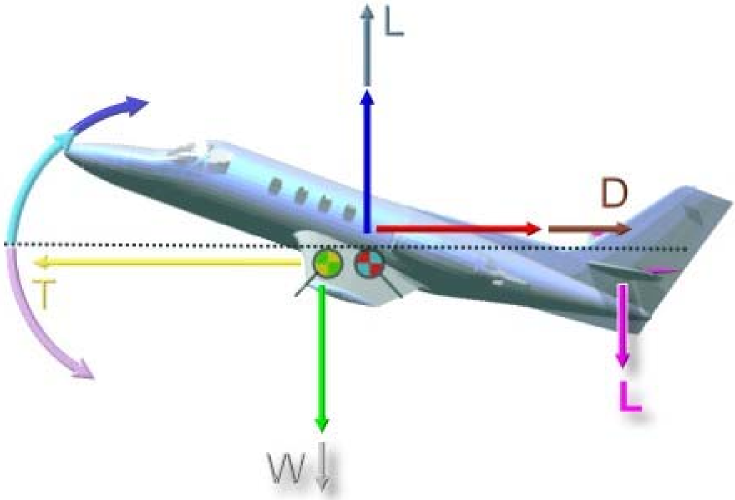
An aircraft is trimmed when all the forces acting on it is balanced.



In the situation, where the tailplane has to produce a **down-load** balancing force, the down-load will add to the **apparent weight** of the aircraft and it will therefore increase the weight vector acting vertically downwards.

Weight (W)+ Down-load (L)= Weight (W)

For the aircraft to maintain straight and level flight at the same speed the lift vector (C_L) must be increased to oppose the new weight vector. This can be done by increasing the AoA.



Increase in AoA to increase lift (L) will also increase drag (D)

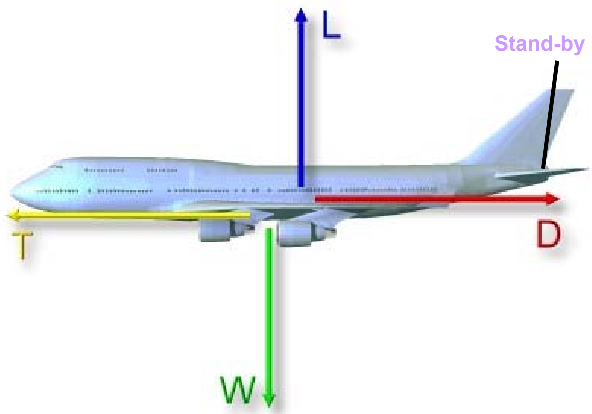
This increase in AoA and therefore lift is associated with an increase in **drag** and this associated drag is known as **Trim Drag**.

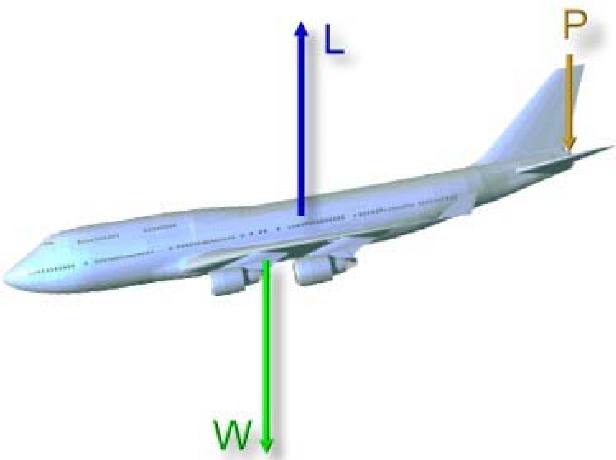
Trim Drag:

Trim drag must be kept a minimum to ensure efficient operation of the airframe. During low subsonic speeds the percentage increase in total drag is minimal but the effect of trim drag is marked during supersonic flight.

LOADS ON THE TAILPLANE

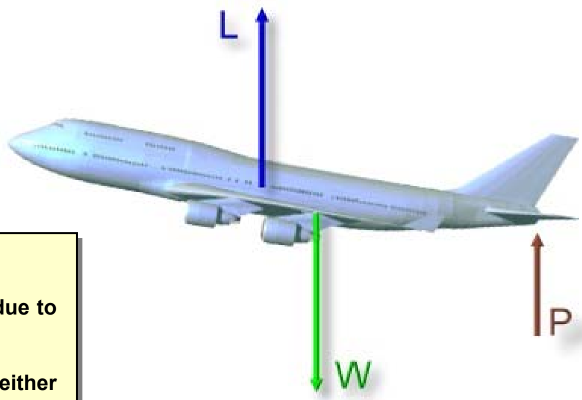
Where the four main forces can be satisfactorily balanced in themselves, the duty of the tailplane is merely to act as a stand-by. It is therefore set at such an incidence that it carries no load in normal flight.





At high speeds the tailplane must carry a **down-load** because, at high speeds the main wings will be at a small AoA, the CP will move backwards and the wing pitching moment about the CG will be nose-down.

At low speeds, where the AoA of the wings is large, the tailplane must carry an **upward-load.**



Changes in tailplane load:

The prime reason for a change in required load on the tailplane is due to the change in position of the CP with a change in AoA.

When the tailplane is called upon to provide a balancing force, either upward or downwards, it is called a lifting tail. To provide this lift it may be cambered in the same way as an ordinary aerofoil, or, as the force required is often a downward one, it may even be shaped like an inverted aerofoil.

VARYING THE SPEED

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

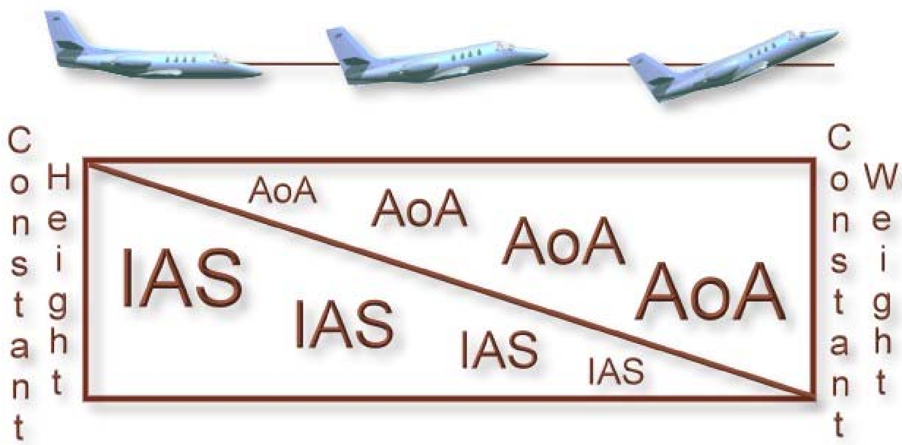
For level flight lift must be equal to weight. If the speed vector (**V**) is reduced ***(refer to the lift formula above)***, then the lift must be increased to retain the balance of Lift = Weight. For a pilot to maintain straight and level flight when the speed of his aircraft is reduced he/she will have to increase the angle of attack and therefore the **C_L**. The surface area (**S**) cannot be changed in flight and because the pilot wants to maintain straight and level flight, rho (ρ) will also be unchanged.

Therefore, to obtain the required lift to maintain level flight at low speeds a high AoA (high C_L) is required and vice versa at high speeds a small AoA (low C_L) is needed.

Since level flight is considered, the pilot will experience these angles as an aeroplane pitch attitude relative to the horizon i.e. nose-up at low speeds and fairly nose-level at high speeds.

The fact that indicated airspeed varies inversely with angle of attack can be represented by means of a graph:

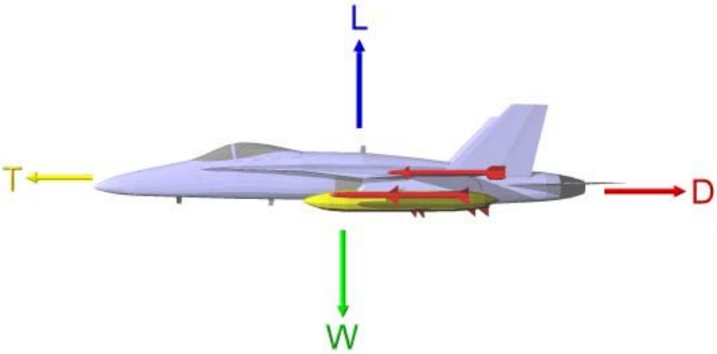
It is therefore clear that as IAS decreases AoA increases in level flight.

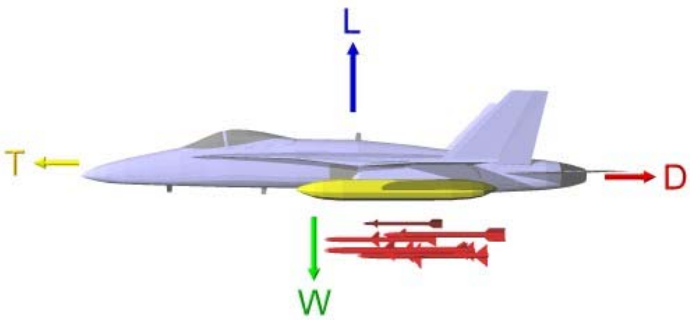


EFFECT OF WEIGHT AND ALTITUDE

Another important factor to keep in mind when flying straight and level is the weight of the aircraft. In normal flight the weight of an aircraft reduces gradually, as fuel is burned-off and during operational flying the change in weight can be sudden ***(parachutists leaping out the back of a transport aircraft or a fighter dropping heavy bombs)***.

Suppose a fighter is flying at an angle of attack that gives the best L/D ratio, to maintain the optimum airframe efficiency and at a known weight and speed.





If the pilot drops his stores the weight of the aircraft will decrease and to maintain level flight the lift will have to decrease as well.

In this case however, the pilot wants to maintain the same AoA for optimum airframe efficiency. Which component of the lift formula will therefore have to be reduced in order to reduce the lift?

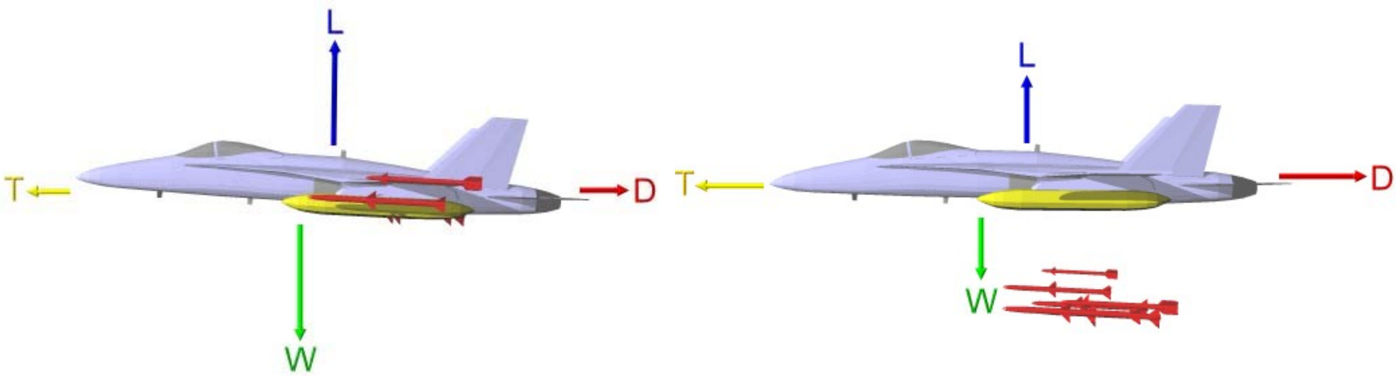
$$L = C_L \tfrac{1}{2} \rho V^2 S$$

Remember that in level flight rho (**ρ**) will not change and the wing surface (**S**) cannot be changed in flight. The pilot wants to maintain the same AoA (**C_L**) and the only remaining factor is the speed (**V**).

With all the other factors a constant, the speed (**V**) will have to be reduced in order to reduce the lift to the same value as the new weight.

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

If the pilot drops his/her stores and wants to maintain level flight while keeping the power a constant, the lift must be decreased by lowering the AoA (decrease the C_L). If the power is not reduced as the weight decreases, the airspeed will tend to increase.



A very practical relationship for a pilot to remember is that:

POWER + ATTITUDE = PERFORMANCE

The effect of an increase in weight will be the opposite to that of a decrease in weight. Weight can be increased by air to air refuelling or due to the formation of ice on the aircraft.

It should be kept in mind that ice formation not only increases weight but causes an all round reduction in aircraft performance regarding the following:

- Increased weight requires an increase in lift, resulting in an increase in power.
- Change in aerofoil shape and surface condition:
  - Drastic reduction in lift for any particular angle of attack.
  - Increase in drag.
  - Stall characteristics altered.
- Ice on propellers cause a reduction in thrust produced.

This is a very dangerous situation and should be avoided at all times.

EFFECT OF ALTITUDE ON LEVEL FLIGHT

Density (ρ) decreases with an increase in altitude. Therefore, there will be a reduction in lift with an increase in altitude.

$$\underset{\downarrow}{L} = C_L \tfrac{1}{2} \underset{\downarrow}{\rho} V^2 S$$

The decrease in Rho (ρ) with altitude can be compensated for with an increase in (**V**) so that the $\frac{1}{2}\rho V^2$ factor and therefore lift, remains the same.

Three conditions must be considered with respect to altitude changes:

- EAS/AoA relationship remains constant.

EAS/AoA relationship:

For a certain AoA there will be a certain EAS and this relationship remains constant for a constant weight, no matter what the altitude is. The moment the weight changes the relationship will also change because you will have a higher AoA for the same EAS or vice versa.

- At high Mach no. C_L is reduced for any given AoA due to compressibility.

Mach No:

This section will be discussed in high-speed aerodynamics.

- Effects on the power curves.

Effect on power curves:

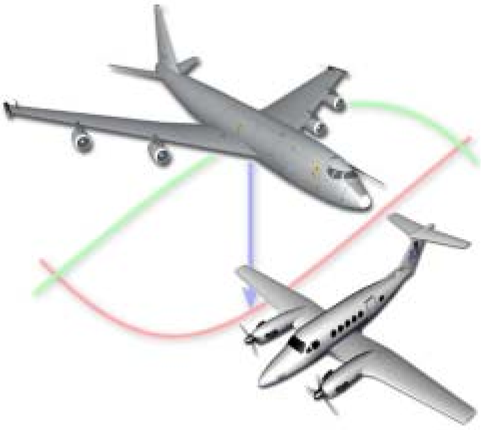
This section will be dealt with in the next lesson, "Level Flight Performance."

What it shortly boils down to is that:

Altitude increase - PAV reduce.
Altitude increase - PREQ increase

LEVEL FLIGHT PERFORMANCE

INTRODUCTION



Equilibrium conditions on an aircraft exist when the power developed by the engine is equal to the power required by the airframe for the same set of flying conditions.

When these conditions are met, the aircraft will fly at a constant altitude and airspeed.

The performance of an aircraft will therefore be determined by the balance of power available from the engine and the power required to maintain straight and level flight.

THRUST PRODUCING VERSUS POWER PRODUCING

In order to understand and derive the different power curves, it is important to understand the differences between thrust producing and power producing aircraft.

THRUST PRODUCING AIRCRAFT

Turbojet, fanjet, ramjet and rocket-driven aircraft produce thrust directly from their engines and are called thrust producers.

With a jet engine, the air mass is collected, compressed and burned. The whole air mass passes through the engine and is accelerated to provide the

POWER PRODUCING AIRCRAFT

In aircraft that have propellers (or rotors), the engine does not produce thrust directly. These aircraft are called power producers because the engine produces power that turns the propeller. The propeller in turn produces thrust.

A turboprop propulsion system is classified as a power producer although it produces both thrust and power.

Turboprop Thrust Vs Power

With a turboprop, the propeller produces the thrust required to propel the aircraft.

However, the air mass expelled through the exhausts normally possesses more energy than the surrounding air. Thus the exhausted efflux provides an amount of thrust (in some cases as much as 10 - 15% of the engine power rating).

THRUST CURVES: POWER PRODUCING AIRCRAFT

At any point in flight the performance of an aircraft will be dictated by the power available from the engine, balanced against the power required to maintain level flight.

Graphical means of expressing power available and power required, for power producing aircraft, will now be examined.

POWER REQUIRED

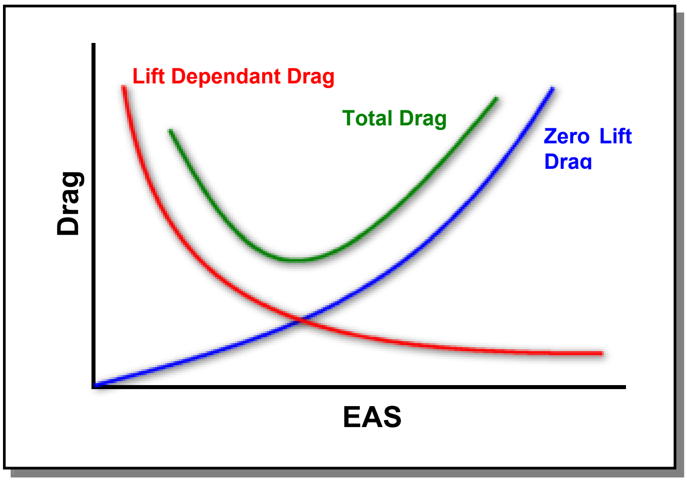
Power is the rate of doing work. It is a function of the speed at which an applied force moves a body.

$$\text{POWER} = \frac{\text{Force x Distance}}{\text{Time}}$$

Thus the power required depends on the force to be overcome and the true speed of the point where the force is applied. For an aircraft the force to be overcome is drag and the true speed is the TAS.

Power required for level flight is therefore the product of the drag in level flight and the TAS (V) at which the drag (D) occurs.

$$P_{REQ} = D \times V$$

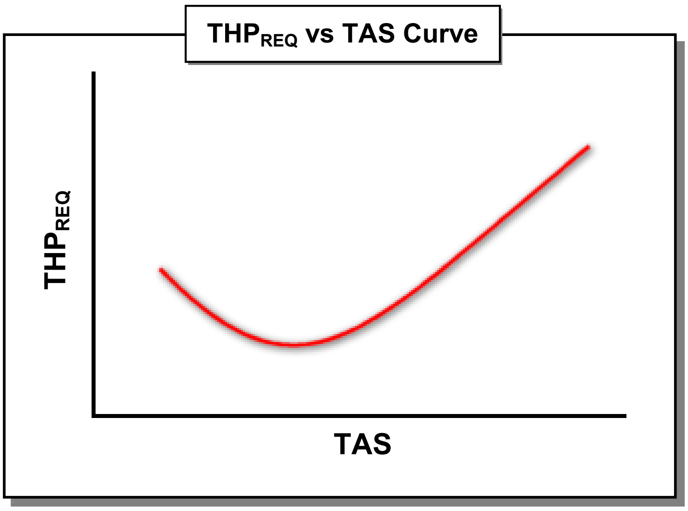


The graph on the left is a typical example of a total drag curve. Total drag can be broken up into zero lift drag and lift dependent drag.

It is essential to remember that the graph is valid for one weight only in level flight.

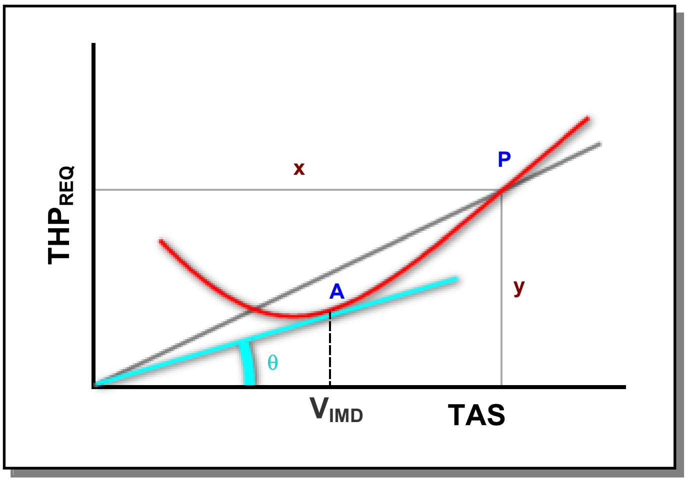
Each pound of drag requires a pound of thrust to offset it. The total drag curve can therefore represent the power required curve.

To derive this P_{REQ} curve the formula THP_{REQ} (in horsepower) = D x TAS is used and the following curve is obtained:



The following information may be derived from the THP_{REQ} curve:

MINIMUM DRAG (V_{IMD})

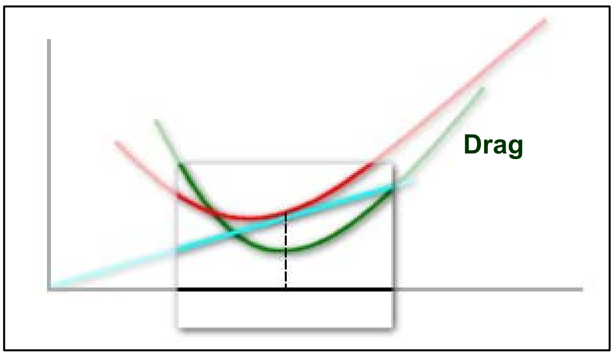


When a line is drawn from the graph origin to any point (**P**) on the plotted curve it forms the third side of a triangle, the other two sides being x and y of the point.

If the ratio of the values is of interest (THP_{REQ} : TAS) then the minimum values of this ratio will occur when θ is a minimum, i.e. when the line is drawn from the origin to form a tangent (just touching the bottom of the curve).

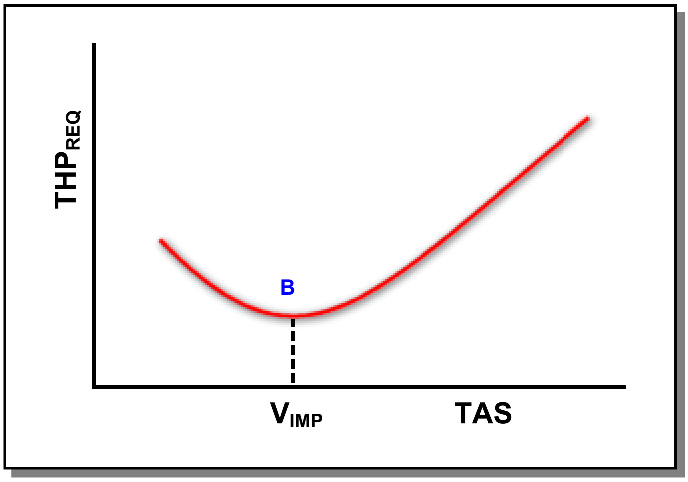
The point for minimum drag is therefore found as illustrated at point (**A**).

It is of interest to note that V_{IMD} is the lowest value (point) on the drag curve but it is the tangent to the power curve.

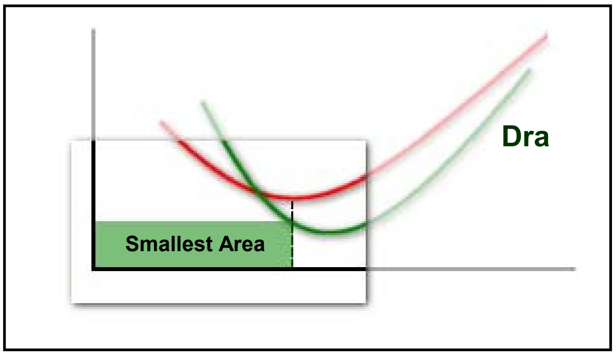


MINIMUM POWER (V_{IMP})

When considering the THP_{REQ} curve, power will be a minimum at the lowest point on the THP_{REQ} curve and this is indicated by point (**B**) on the graph.



It is of interest to note that V_{IMP} is the smallest area under the drag curve but it is the lowest value (point) on the power curve.



POWER AVAILABLE

Power available depends on the product of force (Thrust - T) and true air speed (TAS - V).

PAV = T x V

PAV will also be given as THP_{AV} (in horsepower)

therefore

THP_{AV} = T x V

When an aircraft is stationary there will be no THP_{AV} (no TAS).

With a piston aircraft, fuel is burnt to provide power (BHP) directly from the engine and a propeller is used to do work on the air to produce thrust. So when power available is considered it will depend on power produced within the engine and the efficiency of the propeller.

The **power delivered by a propeller** is measured in thrust horsepower (thp) while the **power delivered by the engine** is measured at the propeller shaft in brake horsepower (bhp).

The formula for Propeller efficiency is therefore: $$\textbf{Propeller Efficiency} = \frac{\textbf{Thrust Horsepower}}{\textbf{Brake Horsepower}}$$

From this formula, it can be seen that:

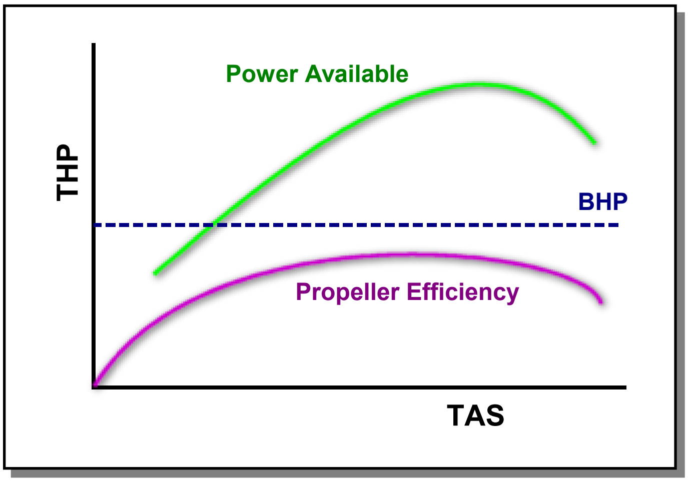
Thrust Horsepower = Brake Horsepower x Propeller Efficiency

or

THP_{AV} = BHP x Propeller Efficiency

BHP at a given RPM is fairly constant with increasing speed, but **propeller efficiency** varies from zero at zero speed to some peak value (80 - 85%) and then decreases again as TAS increases.

The two factors can therefore be represented on a graph as follows:



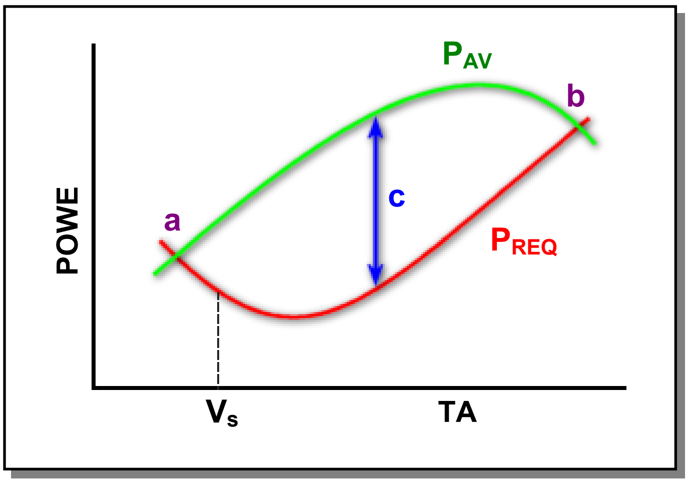
The result is that regardless of an aircraft being piston or turboprop, the power available curves of all power producing aircraft essentially look the same.

The **Power Available** curve takes up the shape as shown on the graph.

COMBINED POWER CURVES

If the level flight power available and power required curves are now put together, more performance criteria are revealed.

- The curves intersect at two points, (**a**) and (**b**). At these two points **Power REQ = Power Available**.
- At speeds lower than (**a**) and higher than (**b**), **Power REQ > Power Available**, thus level flight cannot be maintained.
- Between points (**a**) and (**b**), **Power Available > Power REQ**, resulting in acceleration if level flight is maintained or a climb if constant speed is maintained.



- Point (**a**) is the **minimum speed** at which level flight can be maintained. However this may not be aerodynamically possible as it may be below the stalling speed (**V_S**) of the aircraft.

- Point (**b**) is the **highest speed** at which level flight can be maintained. Normally this speed falls well within the manoeuvre envelope of a power producing aircraft.

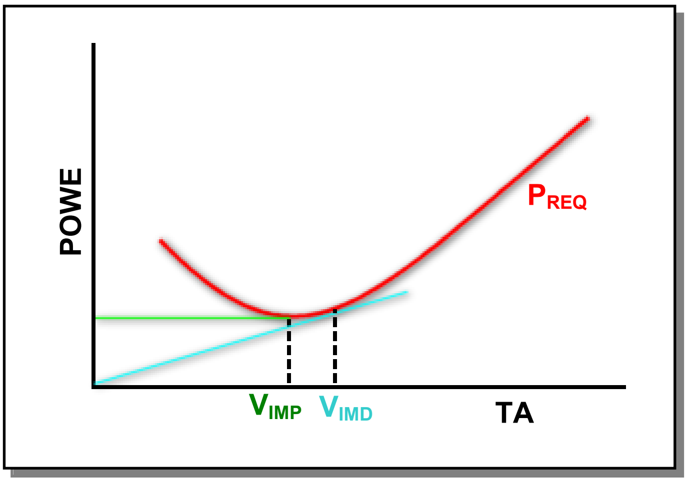
- Point (**c**) is the speed where Power Available - Power REQ = Max. This is therefore the speed for **Maximum Excess Power**. As can be seen from the graph, it is that speed where the P_{AV} and P_{REQ} curves are the furthest apart.

THRUST CURVES: THRUST PRODUCING AIRCRAFT

Level flight performance of a thrust producing aircraft is defined by comparing the thrust available from the engine to the thrust required in the form of drag at any particular airspeed.

Graphical means of expressing thrust available and thrust required, for thrust producing aircraft, will now be examined.

POWER REQUIRED



As P_{REQ} is simply a function of airframe drag, the **P_{REQ} curve** for thrust producing aircraft is identical to power producing aircraft, with **V_{IMP}** and **V_{IMD}** being derived in the same way.

POWER AVAILABLE

Thrust (**T**) is a force produced by accelerating a mass of air, which results in the formula:

T = Mass x Acceleration

Acceleration on the other hand is:

$$\frac{\textbf{Velocity change from intake to exhaust}}{\textbf{time}}$$

It therefore follows that:

$$\textbf{Thrust} = \frac{\textbf{Mass x Velocity change (}\textbf{\textit{exhaust - intake}}\textbf{)}}{\textbf{time}}$$

As $\frac{\textbf{Mass}}{\textbf{Time}}$ is equal to '***mass flow rate***' the formula for **Thrust** will be as follows:

Thrust = mass flow rate x velocity change through the engine

EFFECT OF SPEED INCREASE

Velocity change through the engine is limited, as the exhaust velocity cannot exceed the speed of sound in the hot gas. Therefore, as the aircraft speed increases, the **velocity change reduces** and the **Thrust** will decrease.

Thrust = mass flow rate x velocity change through engine

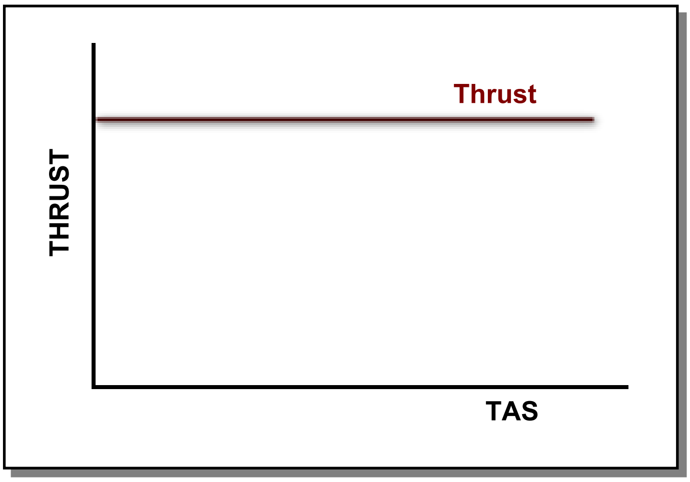
However, the increasing ram effect (due to an increase in speed) will produce a greater mass flow, and this counteracts the **Thrust** reduction.

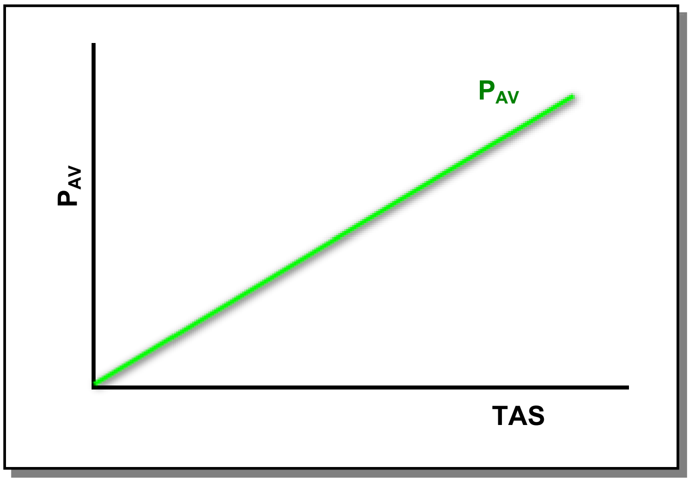
Thrust = mass flow rate x velocity change through engine

For most purposes thrust is regarded as constant in the subsonic speed range.

From the formula above, it can be seen that thrust will remain constant with a change in speed.

The Thrust vs. TAS curve will thus be a straight line and will look as follows:





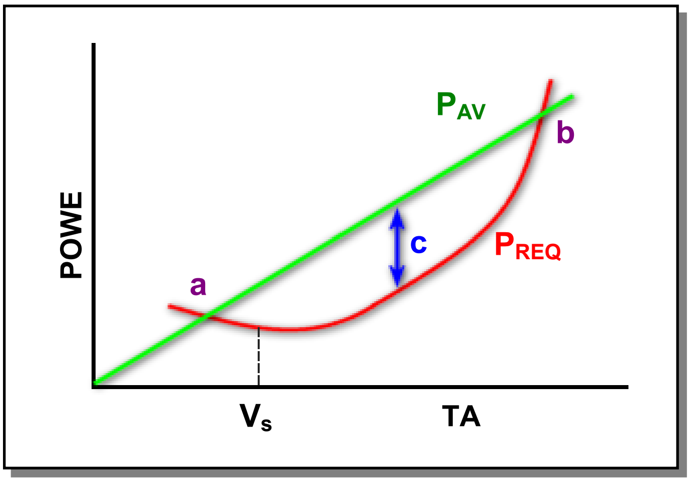
The formula; THP_{AV} = T x TAS is the same for power- and thrust producing aircraft.

For most purposes thrust is a **constant** in thrust producing aircraft and it follows that the P_{AV} curve is a straight-line variation with speed, starting (as the propeller did), at the origin.

COMBINED POWER CURVES

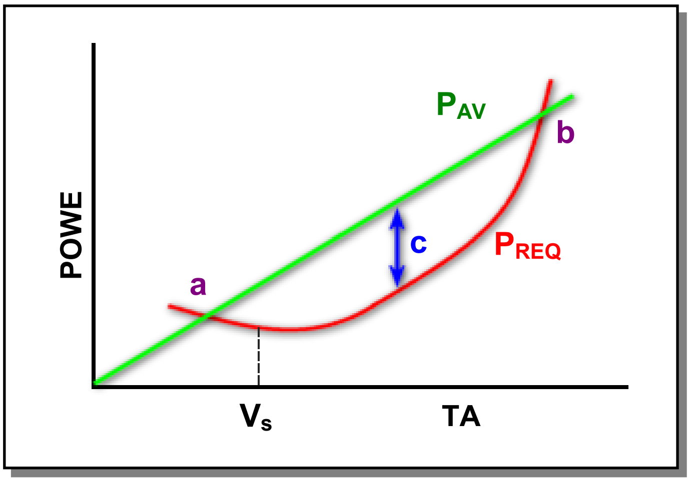
Combining the "available" and "required" curves again shows the leading performance details:

- The curves intersect at two points, (**a**) and (**b**). At these two points **Power REQ = Power Available**.
- At speeds lower than (**a**) and higher than (**b**), **Power REQ > Power Available**, thus level flight cannot be maintained.
- Between points (**a**) and (**b**), **Power Available > Power REQ**, resulting in acceleration if level flight is maintained or a climb if constant speed is maintained.



- Point (**a**) is the **minimum speed** at which level flight can be maintained. However this may not be aerodynamically possible as it may be below the stalling speed (**V_S**) of the aircraft.

- Point (**b**) is the **highest speed** at which level flight can be maintained. This point may be well in excess of the maximum permitted IAS of a jet eg. Lightning, Canberra and Buccaneer.



- Point (**c**) is the speed where Power Available - Power REQ = Max. This is therefore the speed for **Maximum Excess Power**. Compared to a power producing aircraft this speed is high and has little variation over a wide speed range.

FACTORS AFFECTING THE POWER CURVES

As there are certain factors affecting the THP_{REQ} curves, they will be discussed and plotted concurrent with THP_{AV} curves. The factors affecting the THP_{REQ} curve to be discussed are altitude and drag.

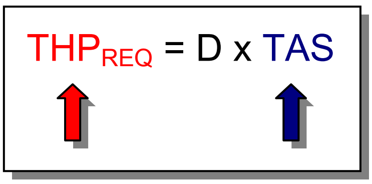
ALTITUDE

It is known that at a given IAS, an increase in altitude will result in an increase in TAS. This is due to a decrease in density as altitude increases.

Earlier the formula for THP_{REQ} was given as:

$$\mathbf{THP_{REQ} = D \times TAS.}$$

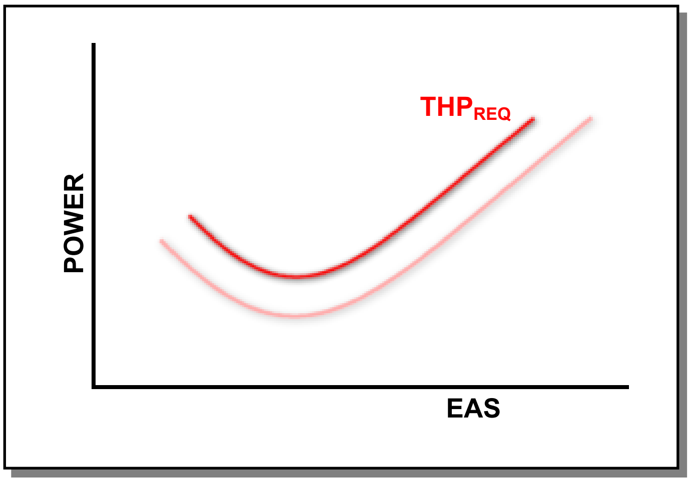
It therefore follows that THP_{REQ} will increase with an increase in TAS.



As THP_{REQ} increases with an increase in altitude, it follows that the THP_{REQ} curve will move upwards from its initial position.

This effect will be the same for both power and thrust producing aircraft.

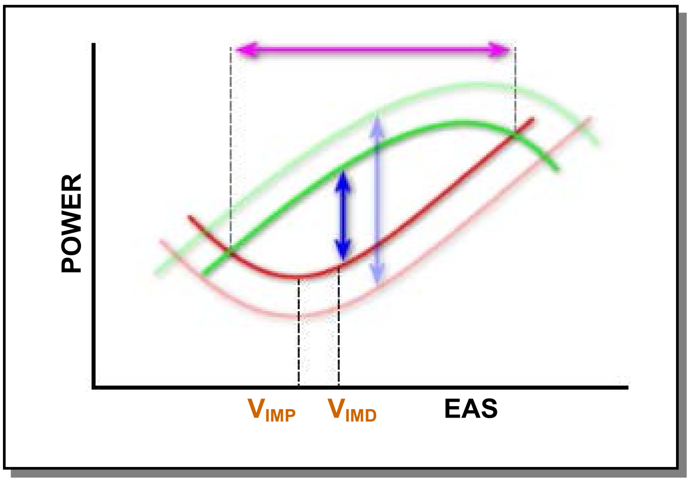
The effect on power available curves will be examined individually.



POWER PRODUCING AIRCRAFT

The THP_{AV} formula for a power producing aircraft was given as:

$$THP_{AV} = BHP \times \text{Propeller Efficiency}$$



As an increase in TAS will lead to a decrease in propeller efficiency, it follows that a decrease in THP_{AV} will result.

Therefore the THP_{AV} curve will move down.

The following can be seen from the two curves.

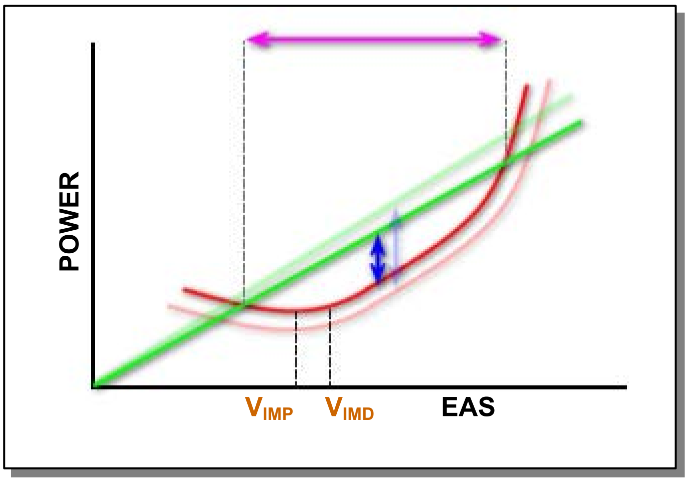
- **A reduced speed range.**
- **Reduced excess power available at a lower speed.**
- **Minimum drag and minimum power EAS are unchanged.**

THRUST PRODUCING AIRCRAFT

The formula for THP_{AV} of thrust producing aircraft is:

$$THP_{AV} = T \times TAS$$

Thrust **reduces** with an increase in altitude roughly in proportion to the reduction in density, and TAS only **increases** (and therefore THP_{AV} according to the formula above) as the inverse of the square root of density.



Thus the total effect is a decrease in THP_{AV}, and the curve moves down.

The following can be seen from the two curves.

- **A reduced speed range.**
- **Reduced excess power available at a lower speed.**
- **Minimum drag and minimum power EAS are unchanged.**

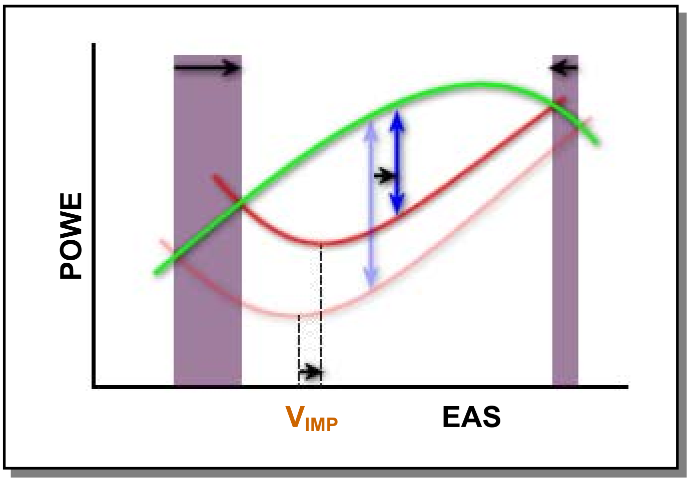
DRAG

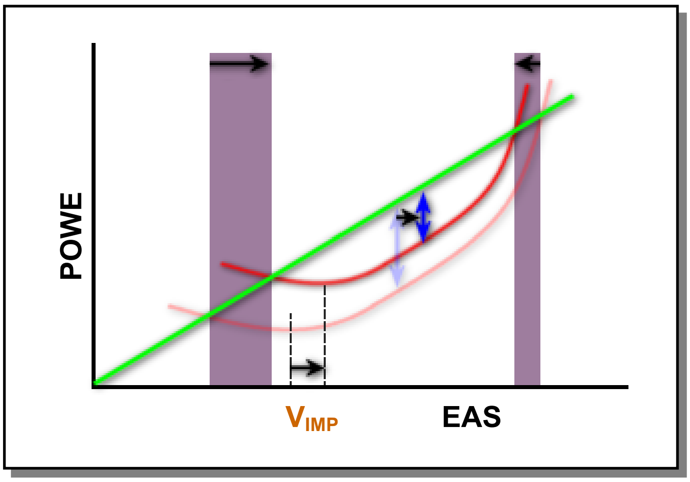
Drag changes will also have an effect on the power curves. The exact manner with which the curves will vary will depend on whether the drag increment is **weight induced** (induced drag) or if it is **high drag device** related (zero lift drag).

WEIGHT INDUCED DRAG

The effect of increasing induced drag on the power curves is as follows:

- **Speed range reduced, but more in the lower speed region than high speed.**
- **Speed for minimum power increases.**
- **Speed for maximum excess power increased.**

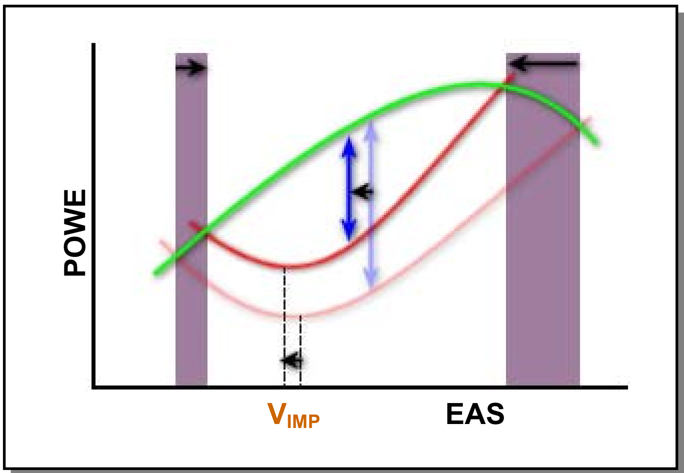


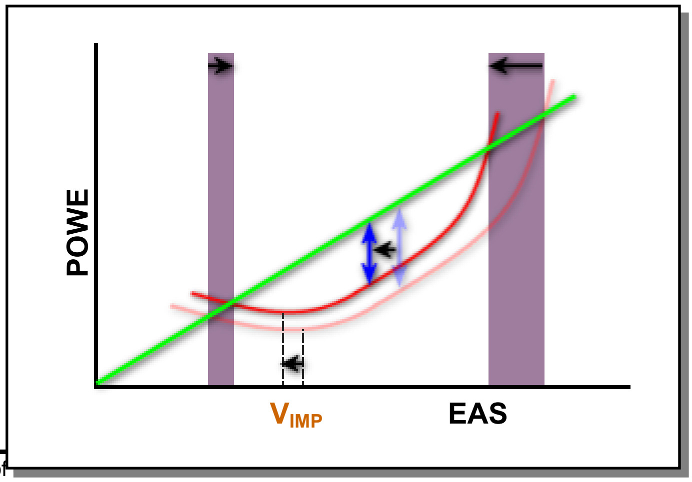


ZERO LIFT DRAG

The effect of drag devices (undercarriage, flaps, airbrakes etc) on the power curves will be:

- **Speed range reduced, but more in the higher range than lower.**
- **Speed for minimum power decreases.**
- **Speed for maximum excess power decreased.**

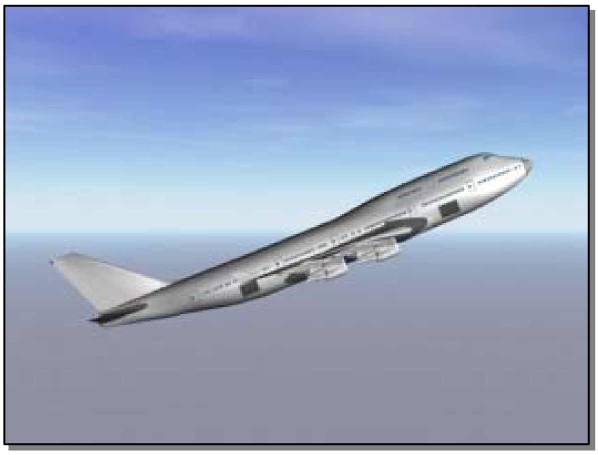




THE CLIMB

INTRODUCTION

Every flight requires that the pilot climb the aircraft to altitude. The way in which the climb will be executed will depend on the mission requirements i.e. an intercept mission would require that altitude be gained rapidly, while a mission of long range would require that much distance be covered in the climb.



ENERGY USED IN THE CLIMB

During a climb an aircraft gains potential energy by virtue of elevation.

Potential Energy:

The energy of a particle or system of particles derived from position, rather than motion, with respect to a specified reference state taken as zero energy.

This is achieved by one, or a combination of two means:

- The expenditure of propulsive energy.
- The expenditure of aircraft kinetic energy.

The expenditure of propulsive energy

The major portion of climb performance for most aircraft is a near steady process in which additional propulsive energy is converted into potential energy.

It can be said that this additional propulsive energy is the expenditure of propulsive energy above that required to maintain level flight.

Aircraft that uses propulsive energy to climb has a low nose attitude and therefore **a gentle ascending path**. These are usually transport type aircraft.

The expenditure of aircraft kinetic energy

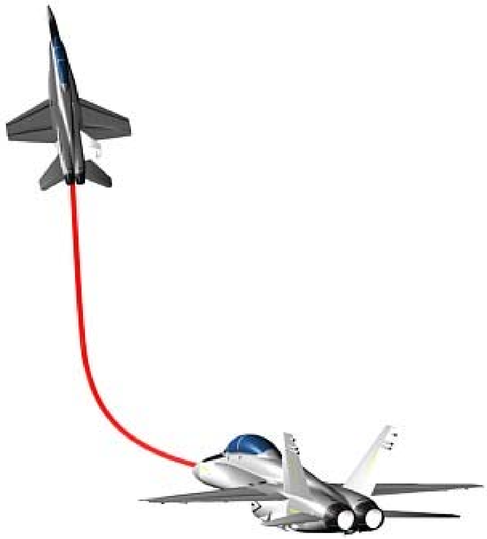
Fighter type aircraft use the expenditure of aircraft kinetic energy to climb, i.e. loss of velocity by a zoom. Zooming for altitude is a transient process of exchanging kinetic energy for potential energy.

Kinetic Energy:

Energy associated with motion, equal for a body in pure translational motion at no relativistic speeds to half the product of its mass and the square of its speed.

To do a zoom climb, the pilot increases airspeed ***(kinetic energy)*** before initiating the climb. The nose attitude of the aircraft is then raised. This produces a very high rate of climb ***(thus the term zoom climb)*** as the kinetic energy is converted into potential energy ***(height)***. As the kinetic energy decreases, the rate of climb reduces until the pilot has to level off. Now the whole process can start again.

The zoom manoeuvre is mostly used by fighter pilots in intercept tactics. Modern fighters can maintain a very steep nose-up attitude and the **ascending path** is near vertical due to the fact that most new fighter aircraft ***(such as this F-18 Hornet)*** possess a power to weight ratio greater than 1.



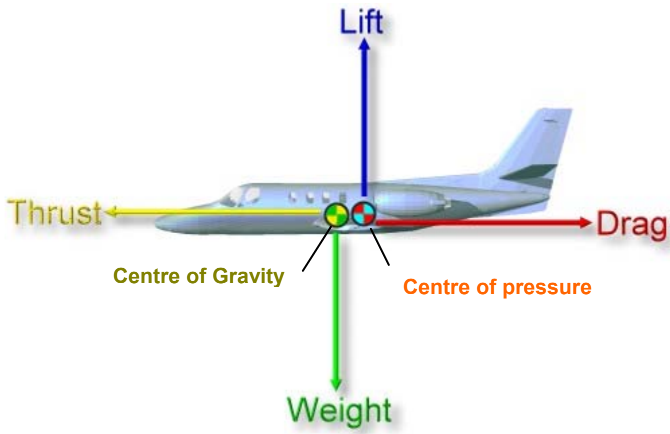
Power to Weight Ratio:

Most aircraft have a power to weight ratio of less than 1. This means that the power produced in pounds of thrust is less than the weight of that aircraft.

Some modern fighters are equipped with such powerful engines that the thrust produced is more than the weight of the aircraft and these aircraft can actually accelerate while in a vertical climb.

FORCES IN THE CLIMB

During flight four main forces act upon an aircraft: **lift**, **weight**, **thrust** and **drag**.



For the aircraft to climb and maintain the climb at a given EAS, more power has to be provided (**T**) than in level flight for the following reasons:

1. To overcome drag (**D**) as in level flight.

2. To lift the weight (**W**) at a vertical speed, which is known as the rate of climb.

3. accelerate the aircraft slowly as the TAS steadily increases with increasing altitude.

The increase in power to climb is the PREQ. By joining 1, 2 and 3 in the PREQ formula the formula will look as follows :

The formula for PREQ is:

PREQ = D x V

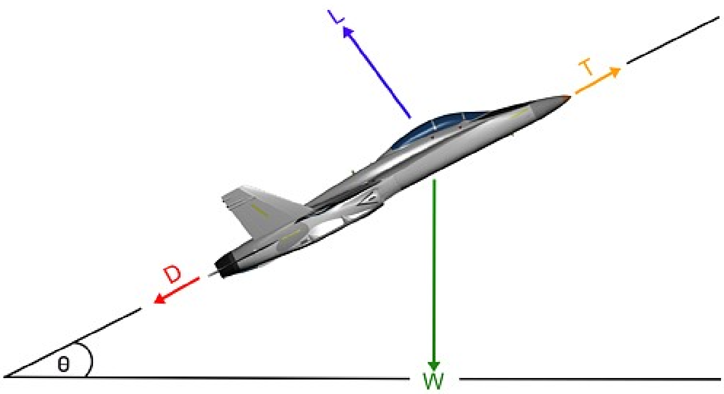
PREQ = DV + WVc + WV $\frac{a}{g}$

Vc = Rate of Climb

a = Acceleration.

The acceleration term can be ignored in low performance aircraft but has to be taken into account in jet aircraft with high rates of climb.

Let's have a look now at what happens to the four forces acting on an aircraft in a climb.



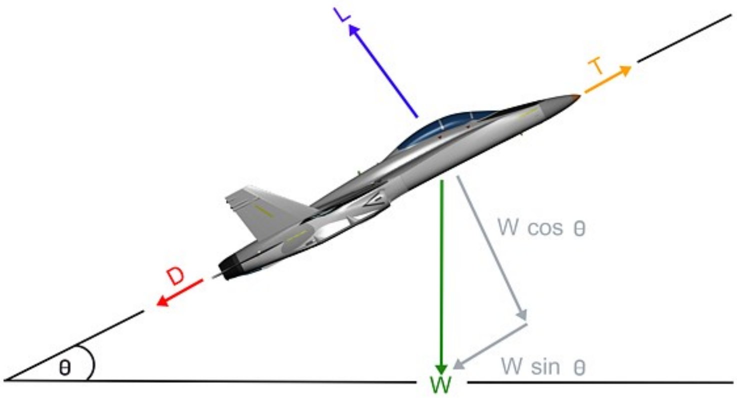
The two forces acting along the flight path are still thrust and drag. **Thrust** acting in the direction of flight and **Drag** acting in the opposite direction as thrust.

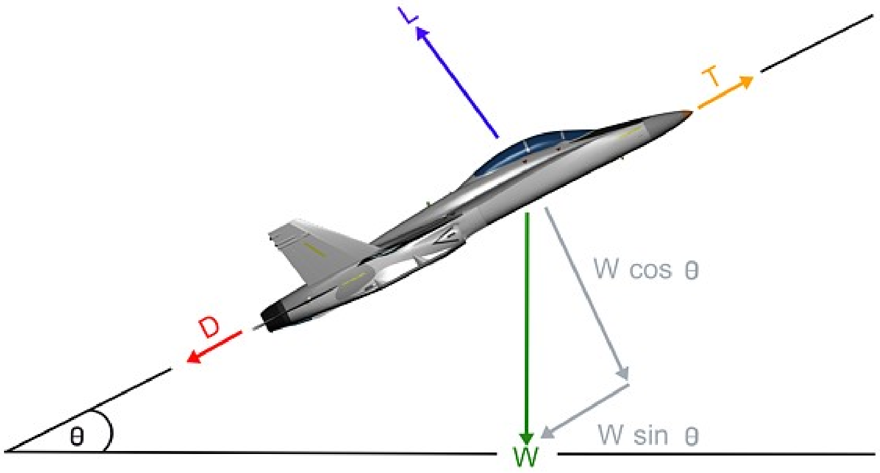
Lift acts 90º to the flight path and **Weight** acts vertically downwards.

The climb angle is shown by (θ).

The weight vector is resolved into two other vectors. One is perpendicular to the flight path (**W cos** θ) and the other is parallel to the flight path (**W sin** θ).

It therefore follows that: **L = W cos** θ
T = D + W sin θ





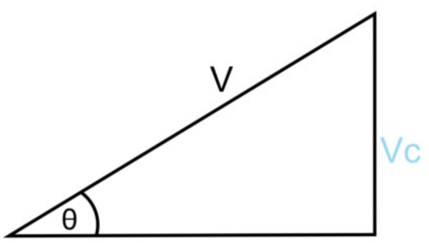
When climbing, the Lift force is marginally less than the Weight.

> **Lift vs Weight during the climb:**
>
> **The equilibrium is possible because the excess force of (Thrust - Drag) has a vertical component to help balance the weight force.**

From the formula **T = D + W sin** θ, it follows that the angle of climb is determined by the amount of excess thrust left after opposing drag. ***(The greater the thrust, the greater the angle of climb.)***

> **Excess thrust in the climb:**
>
> **From the formula T = D + W sin** θ **it follows that:**
>
> $$\sin\theta = \frac{T - D}{W}$$
>
> **As excess thrust is (T – D) it is clear that an increase in excess thrust, with weight a constant, will increase sin** θ**.**
>
> $$\uparrow \sin\theta = \frac{\text{Excess thrust } (T - D)}{W} \uparrow$$

One of the requirements to climb is that the weight must be lifted at a vertical speed **Vc** (Rate of Climb). The following diagram can be used to illustrate this requirement:



From the diagram on the left it can be deducted that rate of climb is determined by the amount of excess power. Therefore, the greater the excess power (**V**), the greater the rate of climb (**Vc**).

The rate of climb is determined by the amount of excess power. This can be proven as follows:

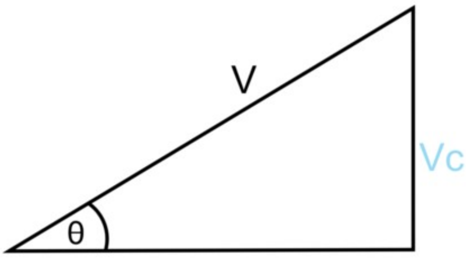


Fig 1

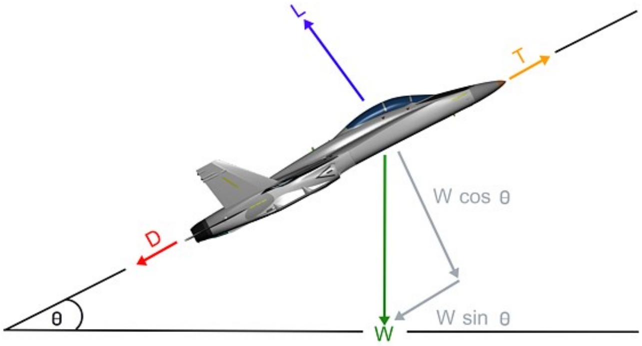


Fig 2

In Fig 1: $\sin\theta = \frac{\text{Rate of Climb}}{V}$

Since θ is the same in each case:

$$\frac{\text{Rate of Climb}}{V} = \frac{\text{Thrust - Drag}}{\text{Weight}}$$

Therefore,

$$\text{Rate of Climb} = \frac{V\,(\text{Thrust - Drag})}{\text{Weight}}$$

$$\text{Rate of Climb} = \frac{\text{PAV - PREQ}}{\text{Weight}}$$

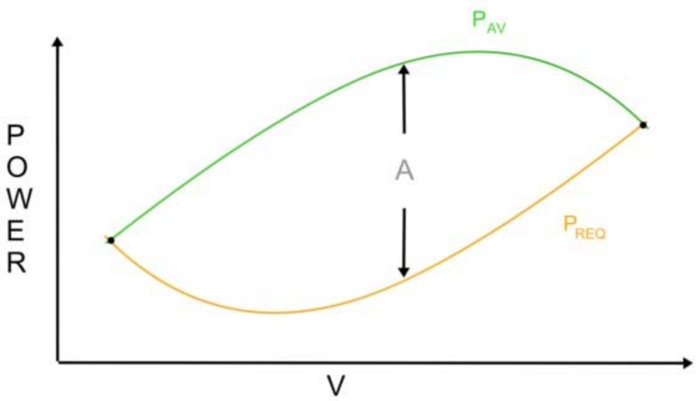
$$\text{Rate of Climb} = \frac{\text{Excess Power}}{\text{Weight}}$$

For a maximum rate of climb the excess power must be a maximum.

TYPES OF CLIMB

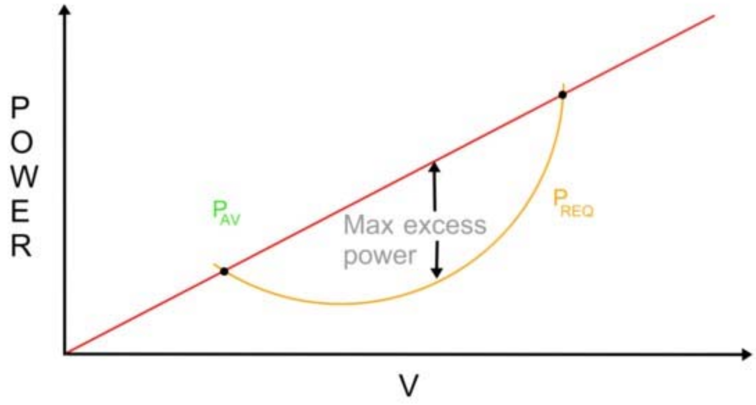
The following types of climb will be discussed:

- Maximum rate of climb,
- Maximum angle of climb, and
- Climb for range.



Power Producing Aircraft

According to the performance criteria of the combined power curves of **power producing aircraft**, point **A** represents the maximum excess power on the P_{REQ} vs P_{AV} curves.



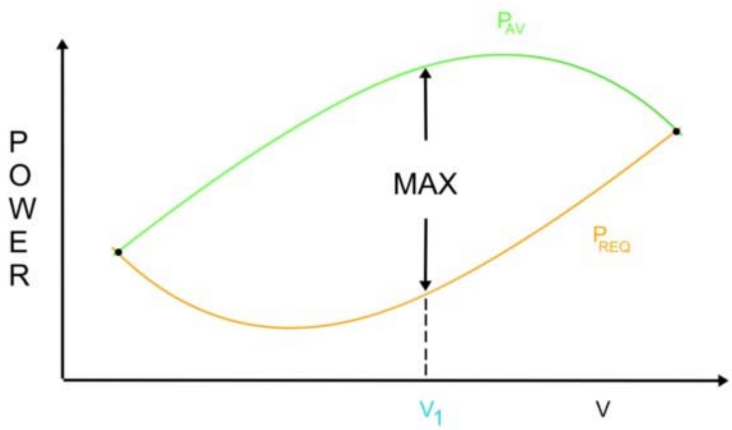
Thrust Producing Aircraft

The maximum excess thrust of **thrust producing aircraft** is also found at the point where P_{AV} - P_{REQ} is a maximum.

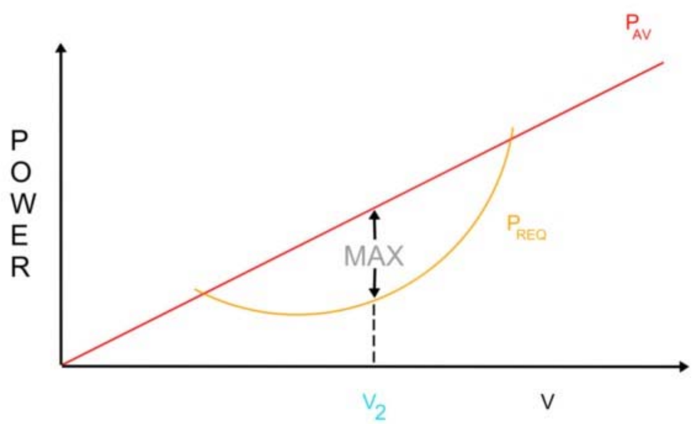
The requirements for the types of climb are as follows:

MAXIMUM RATE CLIMB

The speed for maximum excess power/thrust, for power- and thrust producing aircraft, is the speed where P_{AV} - P_{REQ} = MAX. This is indicated on the two graphs by (V_1) and (V_2).



Power Producing Aircraft



Thrust Producing Aircraft

It therefore follows that the requirements for **maximum rate of climb** are:

- **Maximum excess power** (P_{AV} - P_{REQ}). The greater the excess power the greater the rate of climb.
- **Minimum weight**. The lower the weight the greater the rate of climb.

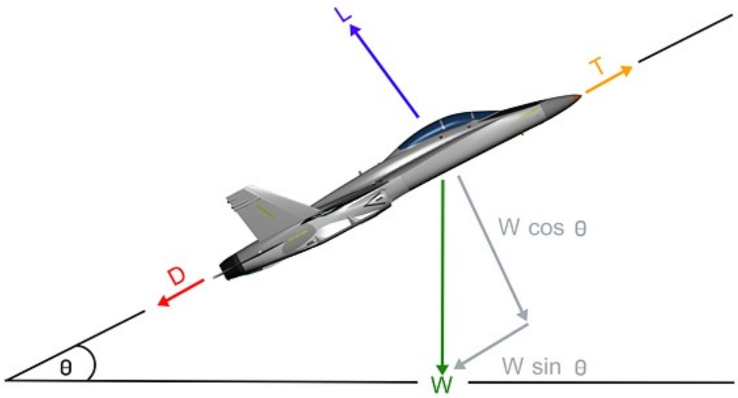
Effect of weight on rate of climb:

As weight decreases the PREQ to maintain a climb will decrease. If the PREQ decreases the maximum excess power will increase and it therefore follows that the rate of climb will increase.

The best rate of climb speed will gain altitude in the shortest time and is usually found near the speed for the best Lift/Drag ratio.

MAXIMUM ANGLE CLIMB

Earlier in the lesson it was said that the angle of climb is determined by the amount of excess thrust left after opposing drag.



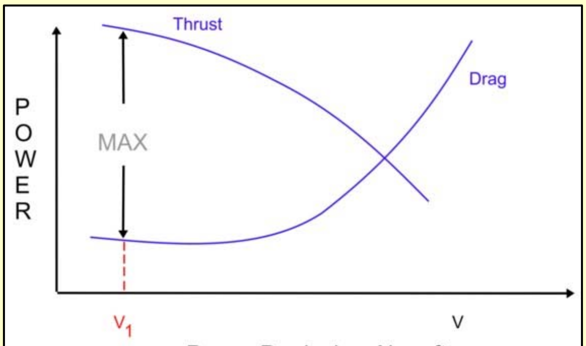
From the formula $T = D + W \sin\theta$, it follows that

$$\sin\theta = \frac{T - D}{W}$$

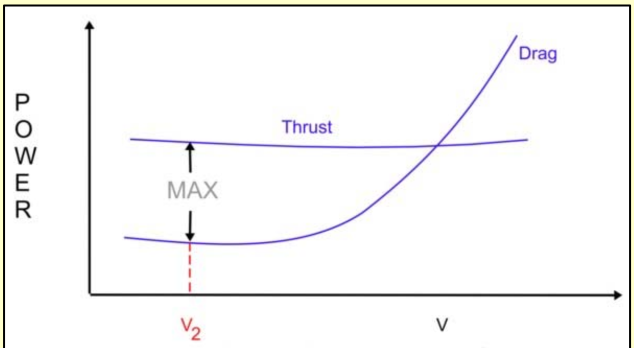
Therefore, if excess thrust $(T - D)$ increases and weight remains constant, $\sin\theta$ will increase.

Effect of excess thrust on climb angle

The following two graphs can also be used to show that for maximum climb angle the aircraft should be flown at the speed where excess thrust (T - D) is a maximum.



Power Producing Aircraft



Thrust Producing Aircraft

CLIMB FOR RANGE

Climbing for range is the method of climbing economically to the cruising altitude.

Piston engined aircraft	Jet engined aircraft
The most economical method depends, amongst other things, on the airframe and engine characteristics, and the auw. **auw = All Up Weight** A general consideration is that weak mixture climbs are the most economical, provided that the rate of climb is not to slow and that engine cooling difficulties can be overcome. Although the rich mixture climb uses less fuel to reach the required height ***(time spent at high power is reduced)*** the weak mixture climb is more profitable when the same ground distance has been covered.	Since flying at high altitudes is all-important for SAR it is essential that the initial cruising altitude is reached as quickly as possible. **SAR = Specific Air Range** Thus, the climb is made at maximum permitted climbing (intermediate) rpm and at the correct climbing speeds. **Use of maximum climb power** **If there is a time limit on the use of intermediate power, and the time for the climb exceeds this, then a quicker climb is achieved by using maximum continuous rpm initially, and intermediate (climb) rpm, for the full time period allowed, during the latter period of the climb.**

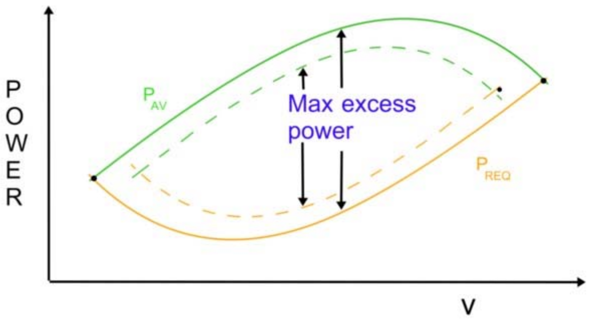
FACTORS AFFECTING CLIMB PERFORMANCE

The flying environment is a very dynamic environment and changes occur all the time. Not one moment goes by where the aircraft is not affected by external factors. As with any other flight situation the climb is also affected by certain factors such as the following:

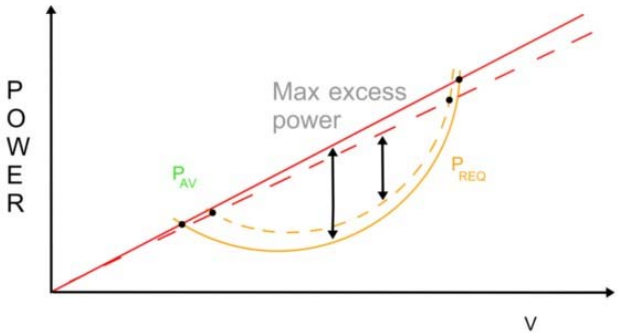
- Altitude,
- Weight,
- Drag devices, and
- Wind.

ALTITUDE

An increase in altitude will cause the P_{AV} curves, of power - and thrust producing aircraft, to move downwards and the P_{REQ} curves of these aircraft will move upwards. The excess power (P_{AV} - P_{REQ}) will decrease and the effect of this decrease will also affect the rate of climb and the angle of climb.



Power Producing Aircraft



Thrust Producing Aircraft

Refer to the formula for rate of climb and the formula for angle of climb it follows that:

$$\text{Rate of Climb} = \frac{\text{Excess Power}}{\text{Weight}}$$

$$\sin\theta = \frac{\text{Thrust - Drag}}{\text{Weight}}$$

As P_{AV} decreases and P_{REQ} increases with altitude, excess power will **decrease** and therefore rate of climb will also **decrease**.

$$\downarrow \text{Rate of Climb} = \frac{\text{Excess Power} \downarrow}{\text{Weight}}$$

As thrust decreases with an increase in altitude sin θ will **decrease** and this means that the angle of climb will decrease with an increase in altitude.

Effect of altitude on climb performance:

As Thrust = 'mass flow rate' x velocity change,

it can be seen that a reduction in density (as altitude increases) will lead to the reduction in 'mass flow rate' and therefore a reduction in Thrust.

$$\downarrow \sin\theta = \frac{\downarrow\text{Thrust} - \text{Drag}}{\text{Weight}}$$

The altitude at which the climb performance falls close to zero and a steady climb can no longer be maintained, is known as "**ceiling**".

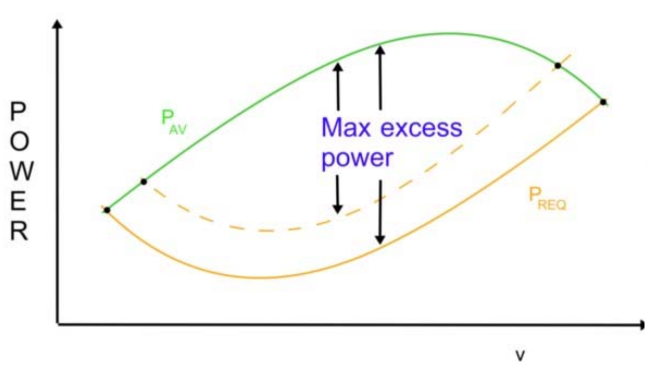
WEIGHT

If the weight of an aircraft should increase, the drag of the aircraft will also increase ***(more weight requires more lift: thus there will be an increase in induced drag)***.

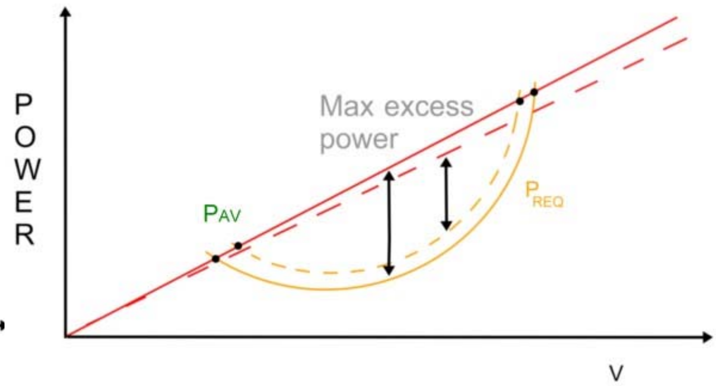
With any increase in weight, the PREQ will increase. The PREQ curve will **move up and to the right**. Thus with an increase in weight, the **maximum excess power** will decrease, but at the same time the speed for optimum rate of climb will increase.

Optimum climb rate speed:

An increase in weight will increase the Preq at any speed, but more so at lower speeds as weight primarily affects induced drag. Therefore, as weight increases, so will the speed for optimum rate of climb. This effect is found on all types of aircraft (piston, jet and turbo-prop).



Power Producing Aircraft



Thrust Producing Aircraft

The effect of increased weight on rate of climb and climb angle can again be demonstrated by using the formulas for rate of climb and climb angle.

As PREQ increases as the weight, and therefore the drag, of an aircraft increases, the excess power will **decrease** and therefore rate of climb will also **decrease**.

$$\downarrow \text{Rate of Climb} = \frac{\text{Excess Power}\downarrow}{\text{Weight}}$$

As drag **increases** with an increase in the weight of an aircraft sin θ will **decrease** and this means that the angle of climb will decrease with an increase in weight.

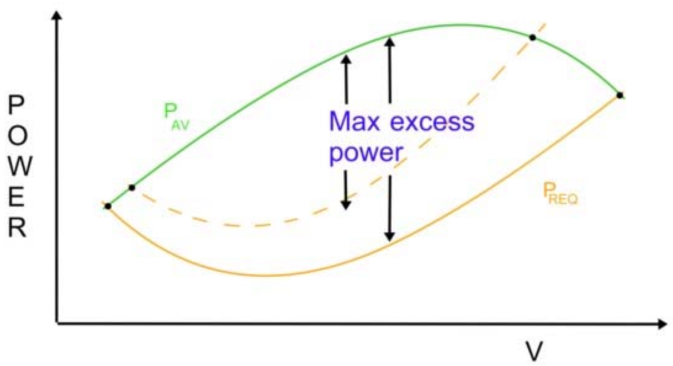
$$\downarrow \sin\theta = \frac{\text{Thrust} - \text{Drag}\uparrow}{\text{Weight}}$$

DRAG DEVICES

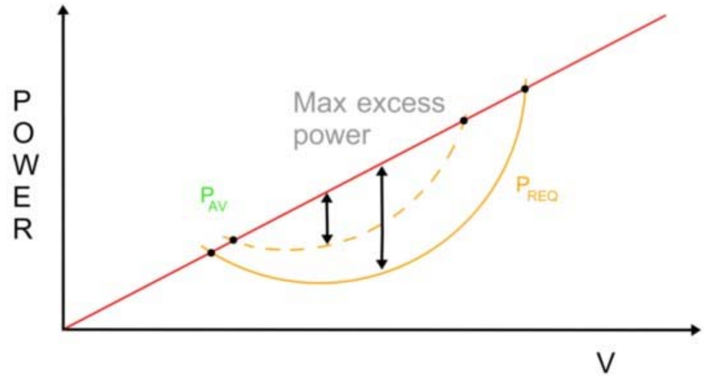
Any increase in drag ***(undercarriage, flaps, airbrakes etc)*** increase the **P_{REQ}**. The **P_{REQ}** curve will move up and left. P_{AV} will remain unchanged. As with an increase in weight, the **maximum excess power** will decrease, but the speed for optimum climb rate decreases.

Optimum climb rate speed:

As Zero Lift Drag is proportional to the square of EAS, it is logic that as the ZLD coefficient increases, the speed for optimum rate of climb will decrease. This applies to all types of aircraft (piston, jet and turbo-prop).



Power Producing Aircraft



Thrust Producing Aircraft

P_{REQ} increases with a drag increase and this means that excess power **decreases**. It therefore follows that rate of climb will also **decrease**.

$$\downarrow \text{Rate of Climb} = \frac{\text{Excess Power}\downarrow}{\text{Weight}}$$

As drag **increases** sin θ will **decrease** and the angle of climb will therefore decrease.

$$\downarrow \sin\theta = \frac{\text{Thrust} - \text{Drag}\uparrow}{\text{Weight}}$$

WIND

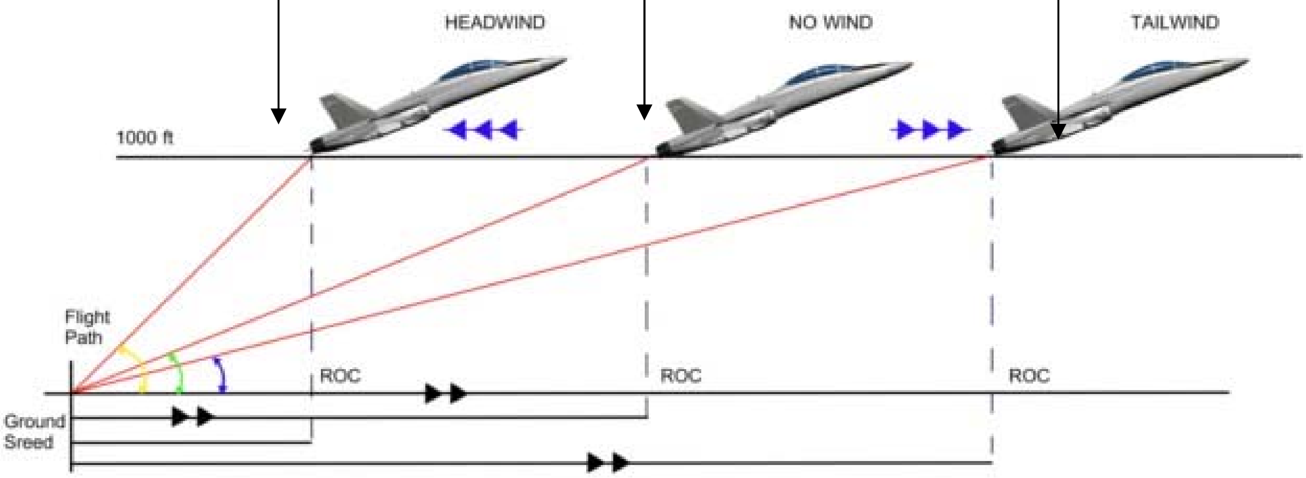
Wind as such has no effect on power available or power required. Similarly, rate of climb and angle of climb, through the air, will not be affected by a steady wind.

However, if the angle of climb (or the gradient of climb) over the ground, i.e. the flight path, is considered, the following differences in the gradient of climb with wind can be seen:

If the aircraft experiences a headwind, the ground speed will decrease and the climb gradient will increase. ROC remains the same and 1000 ft will be reached over a shorter ground distance.

An aircraft experiencing no wind, will climb at a certain rate of climb (ROC), climb gradient and ground speed to 1000 ft altitude.

If the aircraft experiences a tailwind, the ground speed will increase and the climb gradient will decrease. ROC remains the same and 1000 ft will be reached over a longer ground distance.



CEILINGS

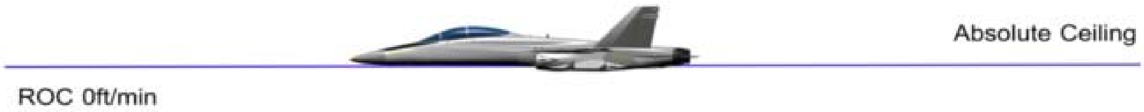
The altitude at which the climb performance falls close to zero and a steady climb can no longer be maintained is known as the 'ceiling'.

In technical terms, the altitude at which the steady rate of climb of an aircraft has fallen to:

- 100 ft/min for propeller aircraft
- 500 ft/min for jet aircraft

is known as the **Service Ceiling** for that specific aircraft.

The slightly higher altitude at which the steady rate of climb achievable at climbing speed is zero (and therefore almost impossible to climb to) is known as the **Absolute Ceiling**.



THE GLIDE

INTRODUCTION

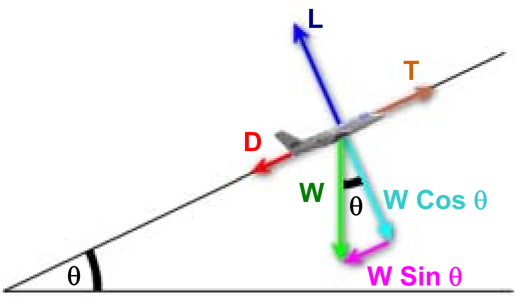
One of the most spectacular "gliders" in the world must be the Space shuttle.

This craft literally glides down from outer space to land on a runway back on earth. Really the ultimate "forced landing without power".

The glide and the forces that act on the aircraft during the glide, as well as the interplay of forces, will now be discussed.

FORCES IN THE GLIDE

Before the forces in the glide are discussed, it is first necessary to revise the forces in the climb.



The forces in the climb are:

- **Lift**, acting perpendicular to the flight path.
- **Thrust**, acting along the flight path.
- **Drag**, opposing thrust.
- **Weight**, acting vertically downwards, and resolved into two vectors:
    - o one opposing lift (**W Cos θ**)
    - o one opposing thrust (**W Sin θ**)

During the glide, the engine is no longer producing any thrust.

But to maintain a constant airspeed, energy is needed to overcome the drag.

The source of the required energy is the **potential energy** (altitude) of the aircraft.

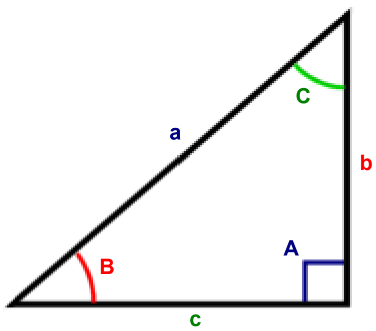
The aircraft will thus follow a flight path that is angled downwards.

Trigonometrical Ratios

Sin B = $\frac{\text{opposite}}{\text{hypotenuse}} = \frac{b}{a}$

Cos B = $\frac{}{} = \frac{c}{a}$

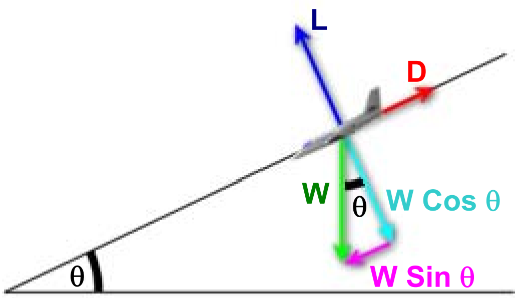
Tan B = $\frac{\text{opposite}}{\text{adjacent}} = \frac{b}{c}$



Cosec B = $\frac{1}{\text{Sin B}} = \frac{a}{b}$

Sec B = $\frac{1}{\text{Cos B}} = \frac{a}{c}$

Cot B = $\frac{1}{\text{Tan B}} = \frac{c}{b}$



The forces in the glide are similar to those in the climb.

- **Drag** still opposes flight along the flight path.
- **Lift** acts perpendicular to the flight path.
- **Weight** acts vertically downwards.

As in the case of the climb, the weight vector is divided into two vectors:

- one opposing lift (**W Cos θ**)
- one opposing drag (**W Sin θ**)

The vector opposing drag (W Sin θ) provides the "thrust" to maintain a constant airspeed. For this reason W Sin θ is also known as "*weight apparent*

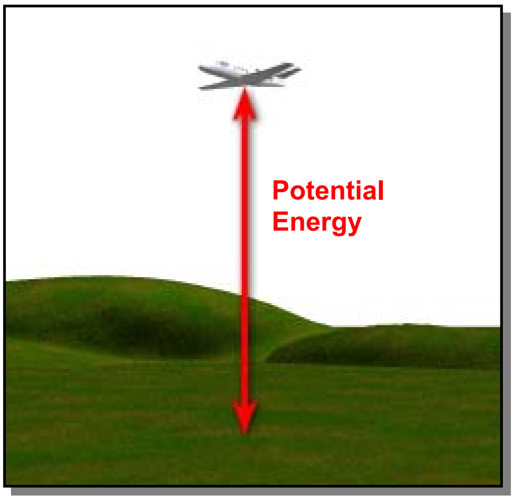
GLIDING FOR ENDURANCE

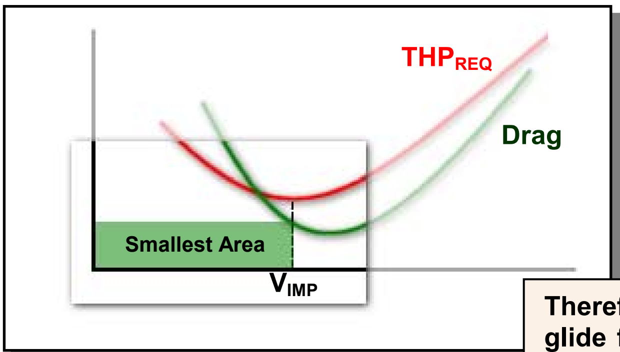
During the glide, potential energy is used to overcome the drag of the aircraft.

For the aircraft to have the greatest endurance**,** the **least amount of energy** (or in this case altitude) must be used.

The vertical velocity (rate of descent) must thus be as small as possible.

The airspeed where the least amount of energy is used is of course the speed for minimum power (**V_{IMP}**).





V_{IMP} is read off at the lowest point on the **Power Required** curve and a point giving the smallest area underneath the **Drag** curve.

Therefore, for a given weight, the aircraft will glide for the longest endurance when the rate of descent is the least.

GLIDING FOR RANGE

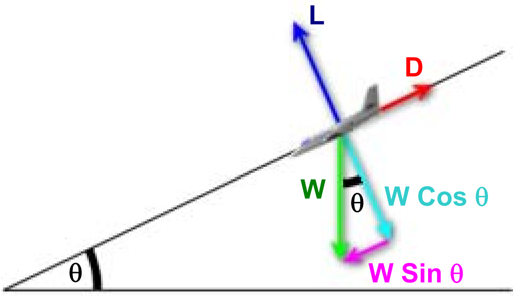
The glide for range is the more commonly used of the two types of glides, for example during a forced landing.

To glide for range, the **distance** covered must be a maximum. To achieve this, the glide angle (θ) must be a minimum.

From the figure it can be seen that:

$$\text{Tan } \theta = \frac{W \text{ Sin } \theta}{W \text{ Cos } \theta} = \frac{D}{L} = \frac{C_D}{C_L}$$

$$\text{Cot } \theta = \frac{W \text{ Cos } \theta}{W \text{ Sin } \theta} = \frac{C_L}{C_D}$$



Remember:

W Sin θ opposes drag, therefore will equal drag in a stable glide.
W Cos θ opposes lift, therefore will equal lift in a stable glide.

The best angle of glide thus depends on maintaining an angle of attack that gives the best **lift/drag** ratio i.e. when the drag is a minimum.

Since, ignoring compressibility, drag depends on EAS, the best gliding speed at a given weight is at a constant EAS regardless of altitude.

FACTORS AFFECTING THE GLIDE

There are a number of factors that affect the gliding performance of an aircraft.

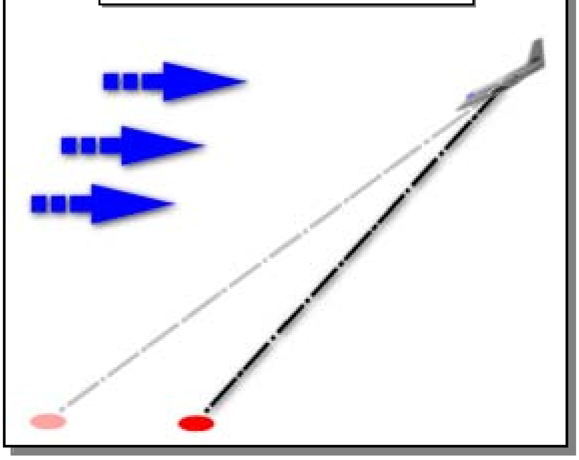
WIND

During the glide for endurance the distance covered over the ground is irrelevant but in the glide for range the distance covered becomes vitally important.

When an aircraft in flight experiences a headwind its groundspeed will reduce as a result. This will decrease the distance covered in a specified time.

This principle of a decreased ground distance when experiencing a headwind also applies to the glide.

Headwind reduces Range



The decrease in ground distance is approximately equal to the **ratio between the wind speed and the TAS**.

An increase in airspeed, thereby reducing the time the headwind effect could act, could improve the ground distance travelled.

Wind speed vs. TAS Ratio

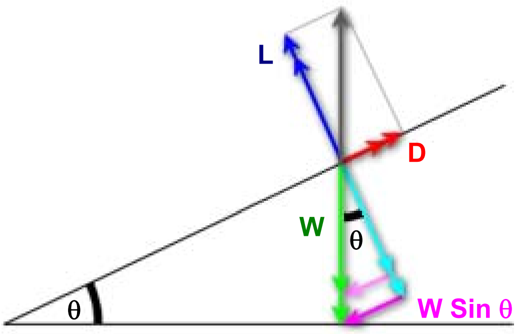
TAS: 350 KIAS   Wind speed: 25 Kts (head wind)

The ratio between the wind speed and the TAS is: 25/350 = 7%

The ground distance will thus be reduced by 7%.

Similarly, if there was a tailwind the ground distance travelled could be increased by reducing the airspeed. This decrease in airspeed would allow more time for the wind to act on the aircraft.

WEIGHT



Consider the forces in the glide. An increase in the **weight** will upset the equilibrium between the forces.

To restore the equilibrium the total reaction must increase a corresponding amount.

The increase in the total reaction will increase the values of both **lift** and **drag**.

The increase in weight also increases the value of weight apparent thrust (**W Sin** θ), so as to balance the increased drag.

The restoring of equilibrium after the increase in weight happens without changing the gliding angle (θ). The only change is a higher airspeed due to the increased weight apparent thrust.

Since the gliding angle is unchanged, the range, in still air, is also unchanged.

Since the airspeed increases with an increase in weight, it will mean that the rate of descent during the glide will also increase. The effect of an increase in weight is thus to reduce the endurance. The opposite will happen if the weight is decreased.

In still air a change in weight will have no effect on range but will reduce the endurance if the weight is increased and increase the endurance if it is decreased.

An increase in weight will be beneficial for range if a headwind is experienced (due to the increase in airspeed).

ALTITUDE

With reference to gliding for range, the value of the Lift/Drag ratio must be a maximum for the minimum glide angle.

Generally there is **no noticeable variation** of the value of the lift/drag ratio with a change in altitude. This means that the glide angle and glide ratio will not differ between high and low altitudes.

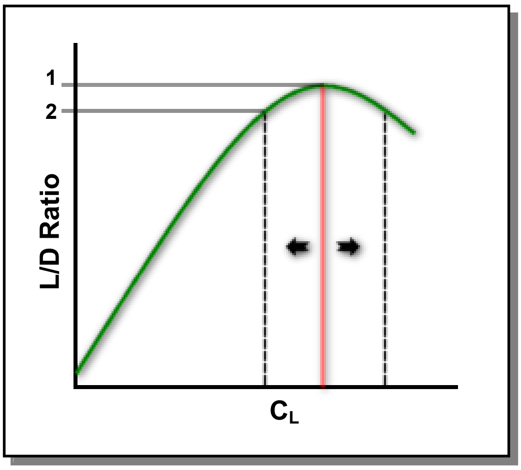
Glide ratio

The glide ratio is another way of expressing the glide angle of an aircraft.

A glide ratio of 1:200 means that for every foot the aircraft descends, it moves forward by 200 ft. This gives a glide angle of approximately 0,3% which is typical of a high performance glider.

The principle effect of altitude is that at high altitudes the TAS and the rate of descent along the optimum glide path is increased above the low altitude

L/D RATIO



The graph shows the change in the lift/drag ratio with a change in C_L.

Any movement left or right of the **L/D max point**, by changing the angle of attack, will result in a reduced value of the lift/drag ratio (point 2).

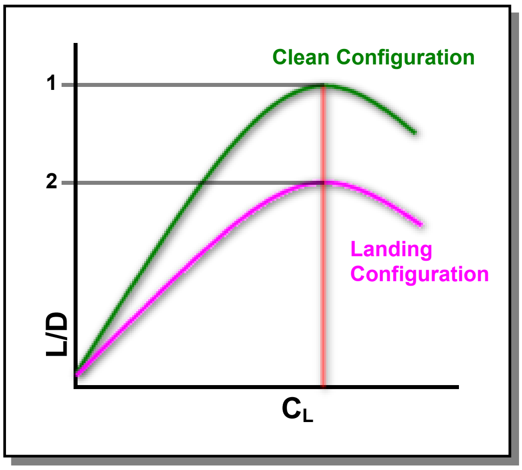
The result of any reduction in the value of the lift/drag ratio is to increase the glide angle, thereby **reducing both range and endurance**.

IMPORTANT!!

Thus, any attempt to "stretch the glide" by increasing or decreasing the angle of attack will only degrade the gliding performance.

CONFIGURATION

When discussing the effect of the lift/drag ratio it was noted that any deviation away from the maximum value would decrease both the range as well as the endurance during the glide.



Any additional drag due to flaps or landing gear being lowered, or airbrakes being deployed, will increase drag while lift remains largely unchanged.

This will also reduce the value of L/D max (point 2).

It is for this reason that, especially in the glide for range, the aircraft is flown in the clean configuration, at the angle of attack and airspeed where the lift/drag ratio is a maximum.