SKILLS · FOR · FLIGHT

Aeroplane Performance

5

OXFORD AVIATION TRAINING

IRANBOOKLET

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AEROPLANE PERFORMANCE

CHAPTER I
INTRODUCTION

INTRODUCTION.

Figure 1.1 Take-off.

The section on **Mass and Balance** in the **Aeroplanes** volume of this series of text books emphasised the need for a pilot to ensure that his aircraft was properly **loaded**, whether be it with passengers, baggage or fuel, so that both the **centre of gravity** and the **all-up mass** (or **weight**) remains within prescribed limits. With the **centre of gravity position** and **all-up mass** within limits, the pilot can be confident that the aircraft will be controllable and not susceptible to overstress, during flight.

This section on **Aircraft Performance** is devoted to explaining how the performance of a correctly-loaded aircraft must be matched with the environment in which it will fly; that is to say, the **dimensions of the airfield and runways** and the **prevailing amospheric and meteorological conditions**. For instance, if the aircraft is loaded to its maximum authorised mass, and the centre of gravity is within limits, but the runway is not long enough for the aircraft to get airborne, then the aircraft's load will have to be reduced. In other words, the total mass of the aircraft and the published performance figures for the aircraft must be matched to the space available to the aircraft to operate in (e.g. the **surface dimensions and conditions of runways**, and the **obstacles** surrounding an aerodrome) and to the **meteorological conditions** prevailing in that space.

The consequences for a pilot of failing to take into account the performance of his aircraft, and the physical and meteorological conditions prevailing at an aerodrome he intends to use, are potentially serious. His aircraft may fail to get airborne, fail to clear obstacles on the climb-out, or over-run the runway, on landing.

There are very strict requirements for calculating the performance of public transport aircraft. However, these rules are not normally applicable to light aircraft operations. Nevertheless, the United Kingdom Civil Aviation Authority (UK CAA) strongly recommends that the safety factors which apply to public transport flights should be applied to general aviation flights too.

The CAA strongly recommends that public transport safety factors should be applied to private flights.

UK CAA Safety Sense Leaflet No 7 contains valuable advice from the UK CAA on **Aeroplane Performance** in respect of light aircraft.

Under JAR-FCL/EASA performance regulations, light, single-engined piston aircraft are classified as **Category B aircraft**. (In the former UK-only Categorisation System, the Performance Group of this class of aircraft is **E.**) The performance figures for **Category B aircraft** provided by the manufacturer are known as **gross performance figures**.

The most simple way to define the expression **"gross performance figures"** is to say that the figures assume that an aircraft is new, and that it is flown from a hard runway by a professional test pilot, in ideal conditions. When these **gross performance figures** are **factored** to allow for an in-service aircraft flown by an average pilot, the **gross performance figures** are adjusted to give what are known as **net performance figures**. **Net performance figures** define lower performance than **gross performance figures**.

The CAA strongly recommends that **net performance figures** should be applied to general aviation flights.

The CAA-approved performance charts for any given aircraft contain **unfactored data.** Consequently, the UK CAA recommends that a **safety factor** of **1.33** be applied to published **take-off performance** figures obtained from performance documentation. The CAA likewise recommends that a safety factor of **1.43** be applied to the manufacturer's published landing figures.

This section on **Aircraft Performance**, then, examines how pilots should interpret the performance figures for aircraft, published in an aircraft's **Flight Manual,** or **Pilot's Operating Handbook**, and in other performance documentation. The performance documents applicable to any given aircraft are specified in the aircraft's **Certificate of Airworthiness**.

Performance figures in light aircraft manuals do not usually include any safety factors.

As we have discussed, the performance figures contained in the above documents are **gross performance figures**. This section will teach you how to interpret those figures in order to predict the performance of your aircraft in **actual and expected flight conditions**. You will learn, therefore, how to take the **gross performance figures** for your aircraft and turn them into more realistic **net performance figures**.

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It is the pilot's legal obligation, in accordance with Article 38 of the Air Navigation Order, to assure himself that his aircraft can deliver the required performance to carry out safely any planned flight. The pilot, therefore, must always study carefully the performance data that apply to his aircraft **and apply any mandatory limitation published by the CAA**. He should also give serious consideration to applying any **CAA recommended safety factors** to aircraft performance figures.

Figure 1.2 Landing.

CHAPTER 2
TAKE-OFF

TAKE-OFF.

An aircraft's take-off performance is dependent on several variables which include:

- **Aircraft mass (or weight).**
- **Aerodrome pressure altitude.**
- **Air temperature.**
- **Air Humidity.**
- **Wind strength and direction.**
- **Runway length and slope.**
- **Nature of runway surface (including contaminants).**
- **Flap settings.**

Definition of "Take-Off".

The **take-off** stage of flight is defined as being from brakes-off until the aircraft reaches a defined **screen height** following **lift-off**. For light aircraft this **screen height** is 50 ft.

After **lift-off**, a specific speed needs to be gained at the **screen height**. This is called the **take-off safety speed** which must be at least **20%** greater than the stalling speed (V_S). The **take-off safety speed**, then, must be greater than **1.2** V_S.

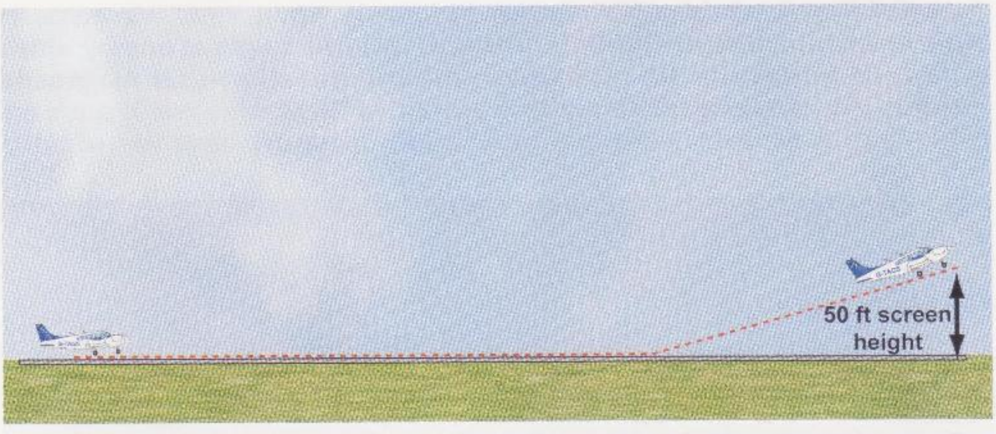


Figure 2.1 The take-off stage of flight for a light aircraft: from brakes-off until the aircraft reaches 50 feet.

Take-Off.

The take-off can be divided into the two parts. The first is the **take-off roll** or **take-off run** which is the distance travelled while the aircraft is still on the ground, in other words, from **brakes-off** to **lift-off**. When calculated for a particular aircraft on a particular day, this distance is called the **Take-Off Run Required (TORR)**.

The second part of the **take-off** is the **initial climb** which is the distance covered from **lift-off** until the aircraft reaches the **screen height of 50 feet**. The combined length of the **take-off run** and **initial climb** is known as the **take-off distance.** When **take-off distance** is calculated for a particular aircraft on a particular day, **take-off distance** is called the **Take-Off Distance Required**.

Pilots need to make sure that the **Take-Off Distance Required** does not exceed the **Take-Off Distance Available**, at the airfield in use. This may seem an obvious statement, but many incidents have occured which suggest that this important consideration is often forgotten.

We will now examine the various distances relevant to the take-off.

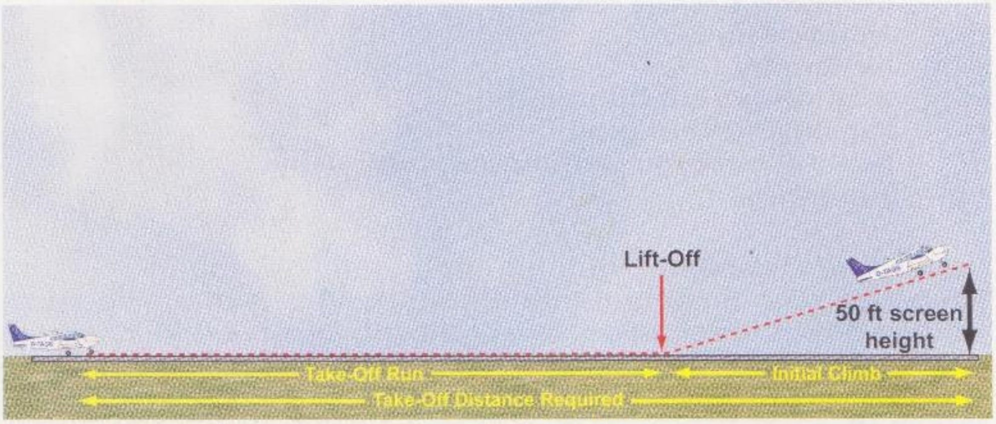


Figure 2.2 Take-Off Distance Required.

Take-Off Run.

Take-Off Run Available (TORA).

The **take-off run available (TORA)** is defined as being **the length of runway which is declared available by the appropriate authority and suitable for the ground run of an aircraft taking off**. Generally speaking, the **TORA** is the total length of the runway from **threshold** to **threshold**, excluding any **stopway**.

Take-Off Run Available is the length of runway available for an aircraft's ground run, threshold to threshold, excluding any stopway or clearway.

Figure 2.3 Take-Off Run Available - The length of runway suitable for the ground run of an aircraft on taking off.

Stopway.

Some runways have a **stopway** at either or both ends of the **TORA**. The **stopway** is an extension to the runway, able to support the weight of an aircraft, which is to be used to bring an aircraft to a stop in the event of an abandoned take off, and may not be used for any other purpose. The **stopway** is not included in the length of the **TORA**. The **TORA** plus any length of **stopway** is called the **Accelerate Stop Distance Available** or **ASDA**. The **ASDA** is sometimes also known as the **Emergency Distance Available (EMDA or EDA)**.

The Stopway is an extension to the runway for emergency use only.

That part of the take-off strip which indicates the Take-Off Run Available and the Stopway is called the Accelerate-Stop Distance Available or the Emergency Distance Available.

Figure 2.4 ASDA (Acceleration Stop Distance Available) = TORA + Stopway

Clearway.

The term **clearway** is defined as an area beyond the end of the runway, in the direction of take off, under the airport's authority, which is clear of any significant obstacles and suitable for an aircraft to make its initial climb to the **screen height** *(See Figure 2.5)*. Note that a **clearway** may include the **stopway** but need not be a surface in any way suitable to bear the weight of an aircraft; in fact, the **clearway** could be over water.

The Clearway is an area beyond the end of the TORA under the airport's authority, clear of obstacles.

Take-Off Distance Available.

The **TORA** plus any **clearway** gives a distance known as the **Take-Off Distance Available (TODA)**. If a runway possesses neither **stopway** nor **clearway, TODA** and **ASDA** are the same as **TORA**. For many small aerodromes, the **TODA** is declared to be the same distance as the **TORA**. Always check this fact in the **Aerodrome Section (AD)** of the **AIP.**

The Take-Off Distance Available (TODA) is defined as the TORA plus any clearway available.

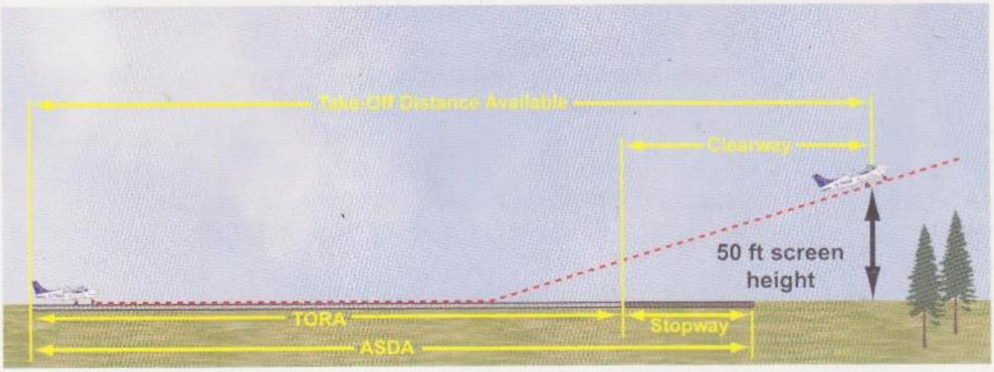


Figure 2.5 The declared distances.

For any given runway, the **TODA**, **ASDA** and **TORA,** together with the **Landing Distance Available (LDA)** (*See Chapter 4*), are known as the **declared distances**.

Take-Off Distance Required.

Based on the **take-off performance** of his aircraft, a pilot must be able to calculate the **Take-Off Distance Required** for the aircraft in prevailing meteorological conditions for a given runway state. Having calculated **Take-Off Distance Required** and applied the necessary **correction factors** and **safety factors**, the pilot must be able to see a healthy margin between the **Take-Off Distance Required** and the **Take-Off Distance Available**. Calculating **Take-Off Distance Required** is the subject of the rest of this chapter.

TAKE-OFF PERFORMANCE.

In considering the factors which influence **take-off performance**, it will help you to recall two equations that you met in the **Principles of Flight** section of this book: the **lift equation** and the equation derived from **Newton's 2nd Law** linking the **thrust force** developed by the engine-propeller combination (or jet engine) with the **mass** of the aircraft and the **acceleration** that the aircraft is capable of achieving. These equations are as follows:

$$\text{Lift} = C_L\ \tfrac{1}{2}\rho v^2 S \ \ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

and

$$\text{Thrust (T)} = \text{mass (m)} \times \text{acceleration (a)} \ \ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

The latter equation, following simple mathematical transposition, may be written as

$$a = \frac{T}{m} \ \ldots\ldots\ldots\ldots\ldots\ldots\ (3)$$

Furthermore, it is straightforward, using Newton's **equations of motion**, to derive a third equation relating **velocity, v, acceleration, a,** and **distance, S**:

$$s = \frac{v^2}{2a} \ \ldots\ldots\ldots\ldots\ldots\ldots\ (4)$$

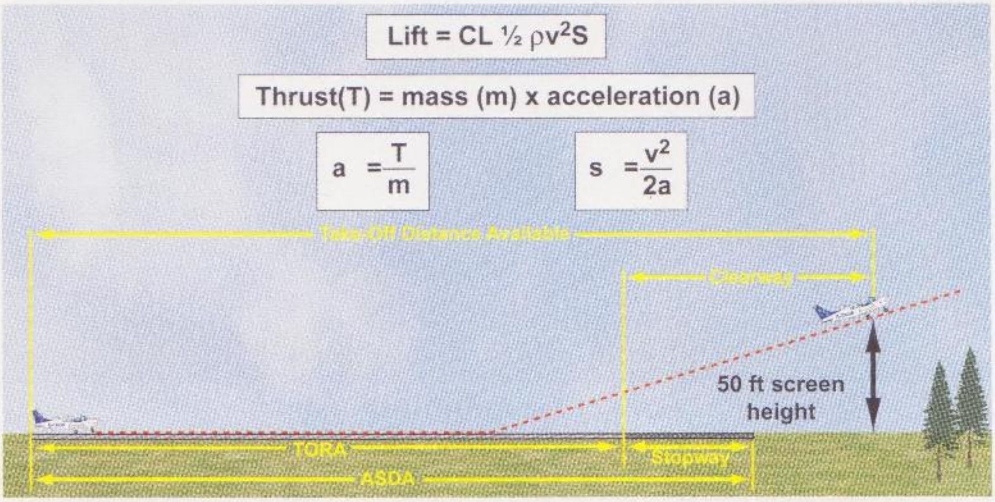


Figure 2.6 The Take-Off Distance formulae.

Let us consider the **lift equation** first for the moment of **lift-off**. In order to **lift off**, the **lift** produced by the wings must equal the total (all-up) **weight** of the aircraft. The **lift equation** tells us that If we assume fixed values of C_L, **coefficient of lift** (a number which accounts for a **wing's shape** and **angle of attack**), ρ, **air density**, and **S**, **effective wing area**, the aircraft will **lift off** at a given **airspeed, v**. Remember that, in the lift equation, **v** represents the aircraft's **true airspeed**. The aircraft, therefore, accelerates along the runway until it reaches a **true airspeed, v**, at which **lift** equals the aircraft's **weight**. If the aircraft is allowed to continue accelerating, the aircraft will literally fly off the ground. However, at the **take-off speed, v**, published in the **Pilot's Operating Handbook** as an **indicated airspeed**, not as a **true airspeed**, the pilot normally eases back on the control column, increasing C_L (by increasing **angle of attack**) and, thereby, further increasing **lift** and positively "unsticking" the aircraft from the ground. After **lift-off** in a light aircraft, it is normal piloting practice to lower the nose very slightly to allow the aircraft to accelerate rapidly to the **take-off safety speed**.

The **distance** required by the aircraft to reach its **take-off speed** is dependent, among other factors, on the **net average thrust** developed by the engine-propeller combination, and the **mass** of the aircraft. The expression **net thrust** means the **total thrust** produced by the propeller **minus aerodynamic drag** and wheel **drag**. The expression **average thrust** means the average value of the propeller's thrust force generated during the take-off run, the instantaneous value of thrust decreasing with increasing forward speed for a fixed-pitch propeller. In the equation , $a = T/m$, as we have seen, **a** is acceleration, **T** is the net, average thrust developed during the take-off run, and **m** is the aircraft's mass.

Remember that **in a constant gravitational field** such as that of the near-Earth region where aircraft fly, **a given mass will always have the same weight**, so although **mass** and **weight** are two very different concepts, they may be considered as being of equal value for our purposes in this section on **Aircraft Performance**.

It is straightforward to see, from **Equation (3)**, that if thrust, **T**, is increased, acceleration, **a,** is increased, too. With higher acceleration, the aircraft will, of course, reach its **take-off speed** sooner. The equation also shows us that for a given average, net thrust, **T**, if mass, **m,** is increased, **a** will decrease, causing the aircraft to take longer to reach its **take-off speed**.

Finally, **Equation (4)** links acceleration, **a**, with **take-off ground speed, v,** and the **take-off distance**, **s**, required to reach that **speed**. It is fairly easy to see from **Equation (4)** that, if acceleration, **a**, is reduced, distance, **s**, increases for any given **take-off ground speed, v**. Increasing **a** will, on the other hand, decrease **s**. Of course, the **groundspeed** for any given **airspeed** depends on the **headwind** or **tailwind component**, discussed later in this chapter.

Having looked briefly at some useful equations which should help you understand how various factors affect aircraft performance on take-off, we now go on to look at the factors themselves.

So, **thrust**, **acceleration**, **take-off speed**, and **take-off distance** are all vital to an aircraft's **take-off performance**. We will now examine the various factors which affect that performance.

FACTORS AFFECTING TAKE-OFF PERFORMANCE.

The principal factors affecting an aircraft's take-off performance are as follows:

- Aircraft Mass/Weight.
- Air Density (Aerodrome Elevation, Temperature, Humidity).
- Wind Strength and Direction.
- Runway Gradient (Slope).
- Runway Surface Conditions.

Aircraft Mass/Weight.

In general, an increase in an aircraft's mass will lead to a decrease in take-off performance and *vice versa*.

As we have just seen, **increasing an aircraft's mass** for a given average net **thrust force** developed by the propeller will **decrease acceleration** and **increase distance required to achieve take-off speed**.

Greater mass means greater weight, so **increasing mass** will put a greater load on the aircraft's wheels and **increase wheel drag**.

An increase in mass will increase stalling speed, lift-off speed, take-off safety speed and Take-Off Distance Required.

Increased weight means that **more lift will have to be generated** by the wings to lift the aircraft off the ground. The **lift equation** shows us that for a given wing shape and angle of attack, C_L, air density, ρ, and wing area, **S**, **greater lift requires a higher take-off speed**. The higher take-off speed, for a given acceleration, will take longer to achieve and require **increased distance**. But, of course, we have already seen that an **increase in mass** not only **reduces acceleration** for a given **thrust**, but also, because the greater **mass** increases wheel **drag**, it actually reduces **net thrust**, thereby further decreasing **acceleration** and, in consequence, further increasing the **distance** to reach the higher take-off **speed**.

You will recall from **Chapter 13 of Principles of Flight** that an increase in **weight** causes an increase in the aircraft's **stalling speed** from straight flight, which is the **stalling speed** quoted in the **Pilot's Operating Handbook**. The straight flight **stalling speed** is, of course, closely related to an aircraft's **lift-off speed**. The aircraft will **lift-off** as soon as the **straight flight stalling speed** is achieved and just exceeded, which is why the aircraft must be accelerated to the **take-off safety speed** as expeditiously as possible. Consequently, as an increase in **weight** increases the **lift-off speed** and the closely related **straight flight stalling speed**, the **take-off safety speed** must increase, too.

Finally, the **increase in mass and weight reduces the aircraft's angle and rate of climb**, thereby **increasing** the overall **Take-Off Distance Required** to reach the **screen height of 50 feet**.

It can be calculated that an increase in aircraft mass of 10% will increase the overall Take-Off Distance Required by 20%, in other words, by a factor of 1.2.

Of course, decreasing the aircraft's **mass** will reduce the lift-off speed, give the aircraft greater acceleration, and decrease the distance required to achieve take-off speed. Decreasing **mass** will also improve both angle and rate of climb and, thus, decrease the overall **Take-Off Distance Required**.

Air Density.

In general, a decrease in an air density will cause a decrease in take-off performance and lead to an increase in the Take-Off Distance Required.

Air density is a function of **airfield elevation (altitude), air temperature, air pressure** and the **humidity of the air**.

Considering the above factors separately:

- The higher an airfield is situated, the lower will be the air density.
- The higher the air temperature, the lower will be the air density.
- The lower the air pressure, the lower will be the air density.
- The higher the humidity of the air, the lower will be its density.

An increase in altitude, temperature or humidity will decrease air density and increase Take-Off Distance Required.

The relationships between **air density**, **altitude, temperature, pressure** and **humidity** are explained in **Chapter 2** of the **Principles of Flight** section of this Volume.

Reduced **air density** will have an adverse effect on take-off performance in the following principal areas:

- Propeller thrust will be degraded.
- Engine performance will be degraded.
- The lift force required to counterbalance the aircraft's weight will be generated at a higher true airspeed.
- Directly related to the above point, the indicated take-off airspeed, quoted in the **Pilot's Operating Handbook**, will be reached at a higher true airspeed.
- The initial climb performance will be degraded.

- ***Propeller Thrust.*** **Propeller thrust** is generated by imparting a rearwards acceleration to a **mass** of air. The magnitude of the **thrust** force is a function of the rate of change of momentum imparted to the air passing through the propeller disk. Rate of change of momentum is a function of a mass and acceleration. The lower the **air density** the smaller the **mass** of air which is accelerated rearwards and the lower the **thrust force**. The lower the **thrust force**, the lower the **acceleration** and the longer the **distance required to achieve take-off speed**.

In conditions of low air density, the reduction in engine power and the decrease in lift for a given true airspeed will increase Take-Off Distance Required.

- ***Engine Performance.*** The **power** developed by an internal combustion engine depends, among other things. on the **mass** of air drawn into the cylinders. **Mass** is equal to **density multiplied by volume**. The lower the **air density**, the lower the **mass** of the volume of air inducted into the cylinders of the aircraft's engine and the lower will be the engine's **power output**. This factor will further reduce the **thrust** generated by the propeller.

- ***Lift Force.*** From the lift equation, $\mathbf{Lift = C_L \frac{1}{2} \rho v^2 S}$, for a given value of $\mathbf{C_L}$ and **S**, you can see that if **air density**, ρ, decreases, the **lift force** will require **v**, the aircraft's true airspeed, to increase in value before **lift** is equal to the aircraft's **weight** in order to achieve **lift-off**. As a decrease in **air density** already leads to a degradation in engine **power** and propeller **thrust**, the lower resultant **acceleration** will mean that there is a significant increase in **time** and **distance** required to reach the higher true **take-off speed**.

- ***Indicated Take-Off Speed.*** With decreasing **air density, the indicated lift-off speed**, quoted in the Pilot's Operated Handbook, **remains nevertheless unchanged** because **indicated airspeed** is a measure of **dynamic pressure**, expressed by the term, $\frac{1}{2} \rho v^2$. The **dynamic pressure** required to cause a given **airspeed indication** on the **Airspeed Indicator** will be the same in all circumstances, **indicated airspeed** is the same as true airspeed, only when **air density** has its ICAO Standard Atmosphere sea-level value. But as **air density** decreases, the magnitude of the **dynamic pressure**, $\frac{1}{2}\rho v^2$, for a given **true-air speed**, decreases, too, and the difference between the true airspeed and the corresponding **indicated airspeed** will grow. Therefore, the lower the **air density**, the higher the **true airspeed** for any given **indicated airspeed**, and the greater the **Take-Off Run** and the **Take-Off Distance Required**.

- ***Initial Climb Performance.*** A decrease in **air density** will degrade both **angle and rate of climb**, thus increasing the distance required to achieve the **screen height of 50 feet**, following lift-off. The reasons for the degradation in **climb performance** will be explained in the next chapter.

A decrease in air density, then, will cause a degradation in all the principal aspects of an aircraft's take-off performance, despite the fact that there will be a small decrease in drag force for any given true airspeed.

A decrease in air density will, therefore, increase the Take-Off Distance Required. Conversely, in conditions of **high air density**, **Take-Off Distance Required will be reduced** compared to that required in conditions of low **air density**.

Consequently, if, on a hot, humid day, you are considering operating from an airfield whose elevation is high, think carefully about the effect of this combination of conditions on your aircraft's performance.

Accounting for Air Density in Performance Calculations.

For every 1 000 feet increase in altitude the Take-Off Distance Required increases by 10%, or a factor of 1.1. Similarly, for every rise in temperature of 10°C, Take-Off Distance Required increases by 10%, or a factor of 1.1.

Be aware that when applying these factors to the Take-Of Distance Required, if more than one factor has to be applied (for instance, if temperature, airfield elevation and mass are all high) all factors are multiplied together. So if the airfield elevation is 1 000 feet above the assumed elevation in your aircraft performance figures and the all-up mass is 10% higher than the assumed mass, you must multiply the Take-Off Distance Required in the published figures by 1.1 and then again by 1.2. Then, of course, you should apply the CAA's recommended take-off safety factor of 1.33.

Later on in this Chapter, you will learn how to use a take-off distance graph to calculate the **Take-Off Distance Required** for different physical and meteorological conditions prevailing at a given airfield on any given day. Always remember that the **elevation (altitude)** of the airfield asked for in the graph will be the **pressure altitude** of the airfield; that is, **its altitude (elevation) measured from a pressure datum of 1 013.2 millibars or hectopascals**. In order to find the **pressure altitude** of the airfield you are operating from, simply select **1 013** on your aircraft's altimeter subscale while it is parked.

Temperature information is usually entered separately into aircraft performance graphs, but occasionally **air density** has to be accounted for by a pilot having to calculate **density altitude**. **Density altitude** is simply **pressure altitude** corrected for **air temperature**. Calculations of **density altitude** are easy to perform using a stantdard **flight navigation computer**. (See **Volume 3** of this series: **Navigation and Radio Aids**.)

Wind Strength and Direction.

Headwinds.

An aircraft will lift off at a certain indicated air speed quoted in the Pilot's Operating Handbook. Consequently, if a stationary aircraft is pointing into a wind of, say, 15 knots, it will already register an indicated airspeed of 15 knots and be 15 knots closer to its lift-off speed, even though its ground speed is zero. An aircraft whose lift-off speed is 60 knots will, therefore, only have to accelerate to a ground speed of 45 knots in order to get airborne. Therefore, when taking off **into wind**, the aircraft reaches its lift-off speed in a shorter distance, than if the wind were calm or blowing from a different direction.

Following lift-off, the aircraft's angle of climb relative to the ground is also steeper, when climbing **into wind**, than if the wind were calm. This is because the aircraft's initial angle of climb, which is always close to its maximum angle of climb, is achieved at a given airspeed. Obviously, when flying into a **headwind**, the corresponding ground speed is lower, so a given climb gradient is always steeper relative to the ground when flying into a **headwind**.

Taking off into a headwind decreases the groundspeed of an aircraft at lift-off and decreases the Take-Off Distance Required.

With a **headwind**, the **50 ft screen height** will, consequently, be achieved over a shorter distance than in calm conditions. The stronger the **headwind**, the shorter will be the **Take-Off Distance Required**, as shown in *Figure 2.7*.

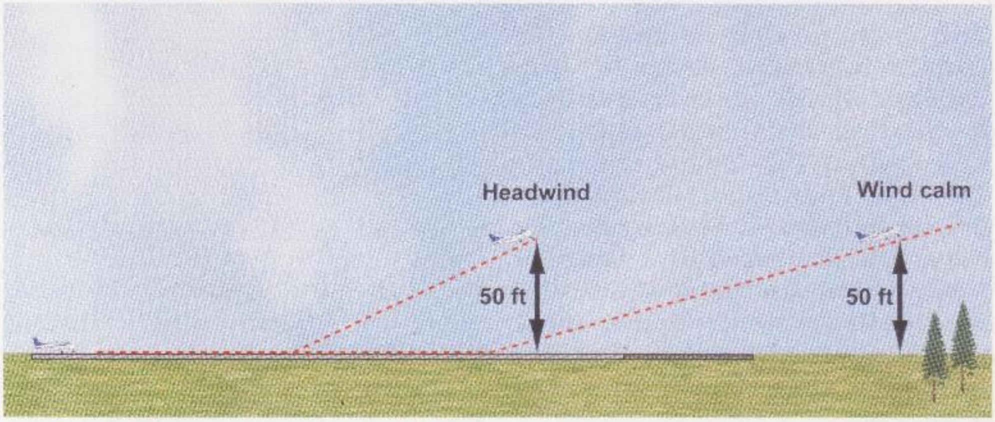


Figure 2.7 Headwinds reduce ground speed for a given indicated air speed and increase initial climb angle, decreasing Take-Off Distance Required.

When calculating **Take-Off Distance Required** in a **headwind**, the UK CAA recommends that, as a **safety factor, only 50% of the observed headwind component strength be used** in the calculation, in order to take into account changes in wind strength and direction. Some take-off performance graphs may have this **safety-factor** already built in. It is the pilot's responsibility to confirm whether that is the case or not.

Tailwinds.

If an aircraft were to take off with a **tailwind** of, say, 5 knots, the aircraft would have to accelerate to 5 knots ground speed before its airspeed began to register. At 5 knots groundspeed, with a 5 knot **tailwind**, the aircraft's airspeed would be zero. Airspeed is the critical factor in generating lift force, **so with a tailwind the aircraft will evidently have to accelerate to a groundspeed which is greater than the take-off airspeed, thus making the ground run longer.**

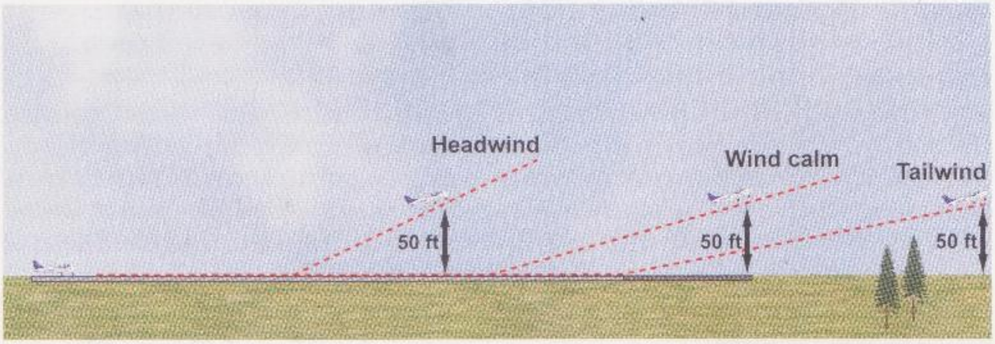


Figure 2.8 Tailwinds increase the ground speed for a given indicated air speed and reduce the initial climb angle. Take-Off Distance Required is, thus, greater in a tailwind.

Likewise, after lift-off, the aircraft's groundspeed will remain 5 knots above its airspeed, and, as an aircraft's achievable angle of climb performance is relative to the air in which the aircraft is flying and not to the ground, with a **tailwind** the aircraft's gradient of climb will be shallower with respect to the ground. **The aircraft's obstacle clearance performance will, thus, be degraded in a tail wind** and the horizontal distance required for the aircraft to reach the 50 feet screen height will be greater. **Take-Off Distance Required, then, will be greater in a tailwind.** *(See Figure 2.8.)*

Even a light **tailwind** will increase the **Take-Off Distance Required** very significantly, and obstacle clearance may be degraded to such an extent that a safe take-off may not be able to be carried out. **For a 5 knot tailwind, Take-Off Distance Required is increased by about 25% (increased by a factor of 1.25). In a 10 knot tailwind Take-Off Distance Required increases by about 155% (increased by a factor of 1.55).**

When calculating **Take-Off Distance Required in a tailwind**, it is recommended that that, as a **safety factor, 150% of the observed tailwind component strength be used** in the calculation in order to take into account changes in wind strength and direction.

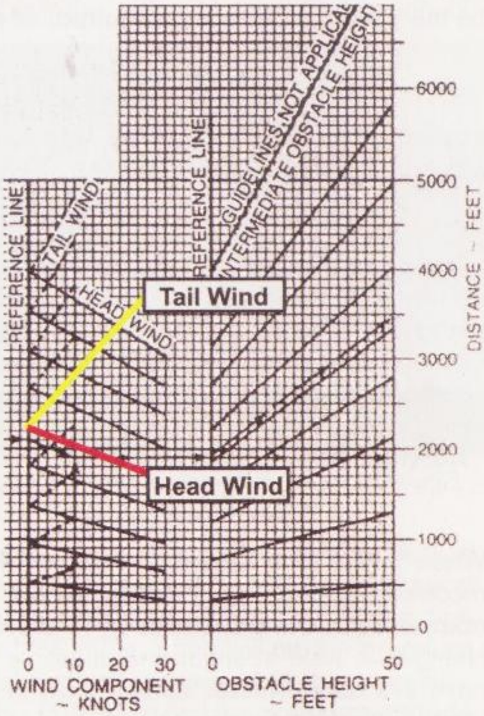


Figure 2.9 Most performance graphs include 50% / 150% wind safety factors.

Crosswinds.

The wind rarely blows down the runway centre-line, so very frequently a given wind will have a **crosswind component** as well as a **headwind/tailwind component**. When entering **headwind** into any take-off calculation, pilots must ensure that they make an accurate assessment of the wind speed and direction and use **the component of the wind which acts along the centre line of the runway, <u>against</u> the direction of take-off**. For example, a **crosswind** blowing at **90°** to the runway centre-line will give an aircraft **no beneficial headwind component** at all, whereas it may well cause the pilot difficulties of controllability during the take-off run because of the tendency of an aircraft to weathercock into wind and for the into-wind wing to lift.

Calculating Headwind Component.

Pilots can calculate **headwind components** for **any given wind direction and strength**, using a **flight navigation computer**. The CD-ROM in the **Navigation & Radio Aids** volume of this series teaches you how to do that. As a rough guide to assessing **headwind components**, however, pilots may use the diagram at *Figure 2.10.*

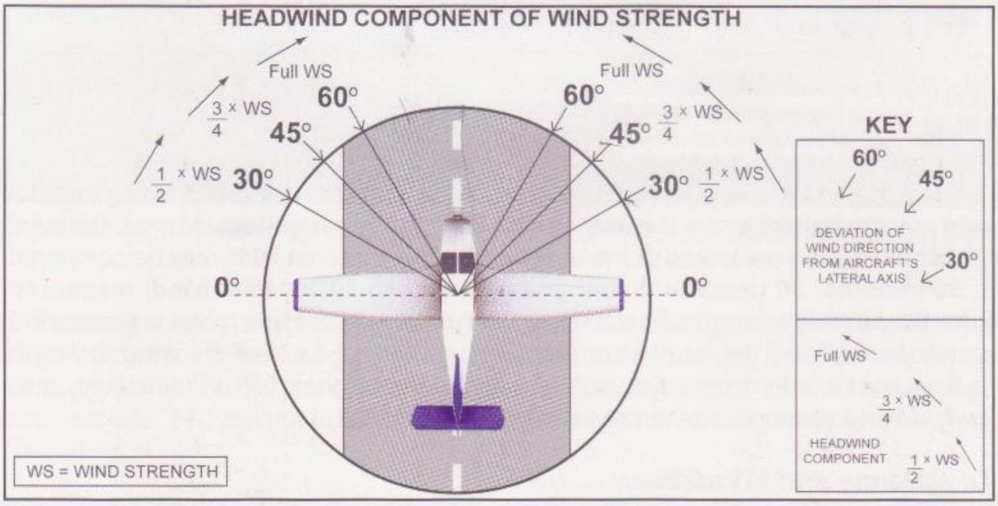


Figure 2.10 The "Clock" System of estimating Headwing Component. Angles are measured from the aircraft's lateral axis.

Notice that **wind angles** are measured with respect to the aircraft's **lateral axis** or with respect to **a line cutting the runway centre line at 90°**. The system illustrated may be memorized by comparing the factors of **headwind component** to the division of an hour of time. **30°** may be compared to **30 minutes**; **30 minutes** is **half an hour**, and so **30° of crosswind, measured from the aircraft's lateral axis**, gives a **headwind component** of **half the wind strength**. Similarly, **45°** gives **¾ of the wind strength** as the **headwind component**, and any angle greater than **60°** will effectively give the **full wind strength** as the **headwind component**. This system is not 100% accurate, mathematically, but it is very close to that, and may be used to estimate **headwind components** with a fair degree of accuracy if you do not have a computer or calculator with you.

Tailwind components in a **crosswind** may be estimated in the same manner.

Calculating Crosswind Component.

Pilots can calculate the **crosswind component** of **any given wind direction and strength** using **a flight navigation computer** or they may reasonably accurately assess the **crosswind component** using the diagram at *Figure 2.11*.

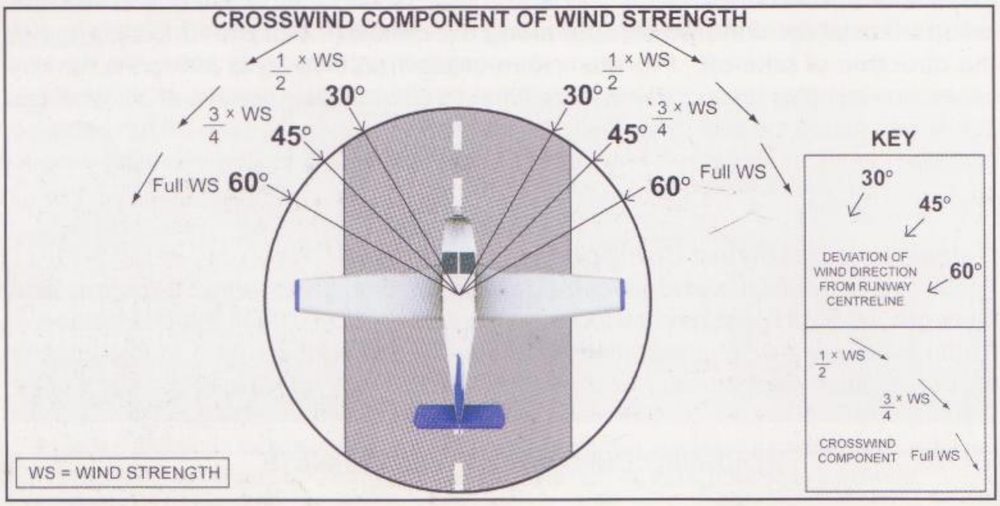


Figure 2.11 The "Clock" System of estimating Crosswind Component. Angles are measured from the aircraft's longitudinal axis.

Notice that, here, **wind angles** are measured with respect to the **aircraft's longitudinal axis** or with respect to the **runway centre line**. As you have just learned, the wind directions may be compared to the division of an hour of time. **30°** may be compared to **30 minutes**; **30 minutes** is **half an hour**, and so **30° of headwind, measured from the aircraft's longitudinal axis or the runway centre line**, gives a **crosswind component of half the wind strength**. Similarly, **45°** gives **¾ of the wind strength** as the **crosswind component**, and any angle greater than **60°** will effectively give the **full wind strength** as the **crosswind component**.

Turbulence and Windshear.

Turbulence and **windshear** will also adversely affect take-off performance.

Firstly, from a practical piloting point of view, in **turbulent conditions** it is often advisable, during the take-off run, to hold the aircraft on the ground for a slightly longer period of time to provide a better margin above the stall. This will also increase controllability after lift-off, but the penalty is that it will increase the take-off run, too, as well as the overall **Take-Off Distance Required**.

The possibility of **turbulence** and **windshear** must be taken into consideration when working out take-off distances. **Windshear** is a change in wind velocity (speed and/ or direction) over a very short distance. The presence of **windshear** can cause sudden fluctuations in airspeed. Hangars, buildings and areas of trees all influence the direction of the wind near them. In **turbulent conditions, windshear** and **gusts** may be significant in the lee of obstructions. The vertical components of this type of turbulence will affect climb angle and rate of climb, either beneficially or adversely. The great danger of the presence of **turbulence** and **windshear** is that the effects are **unpredictable**.

Runway Slope.

Runway Slope affects take-off distance because, if **slope** is present, a component of the aircraft's weight will act along the runway, down the **slope**.

If an aircraft takes off on a runway which **slopes** upwards, a component of the aircraft's weight will act **against** the direction of motion of the aircraft, reducing the net thrust force developed at the propeller, decreasing acceleration and increasing the take-off run. Obviously the **Take-Off Distance Required** (to read the 50 feet screen height) will also be increased.

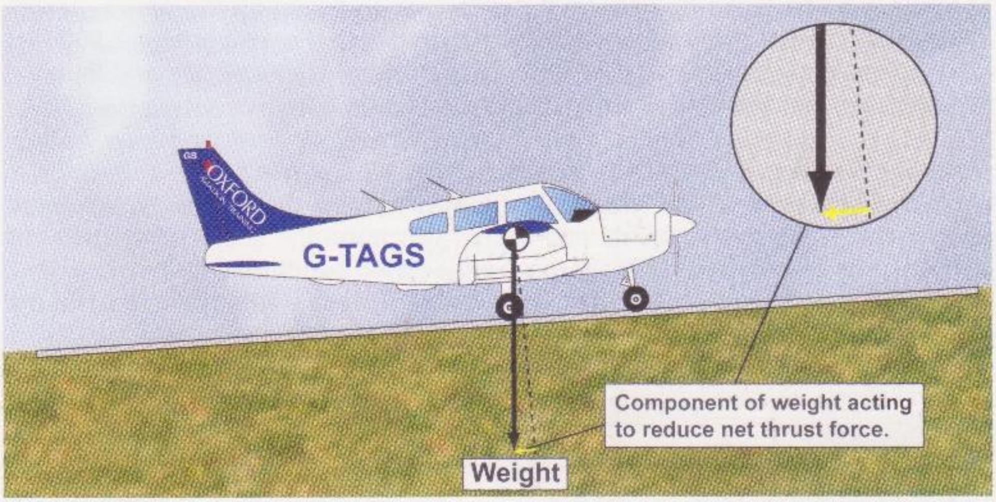


Figure 2.12 Upslope reduces acceleration owing to a component of weight acting backwards against thrust. This increases the Take-Off Distance Required.

Conversely, if an aircraft takes off on a **downwards sloping runway**, a component of the aircraft's weight will act in the direction of take-off, thereby adding to the thrust force developed by the propeller. **Taking off on a down-slope, then, will increase acceleration, reduce the take-off run and decrease the overall Take-Off Distance Required.**

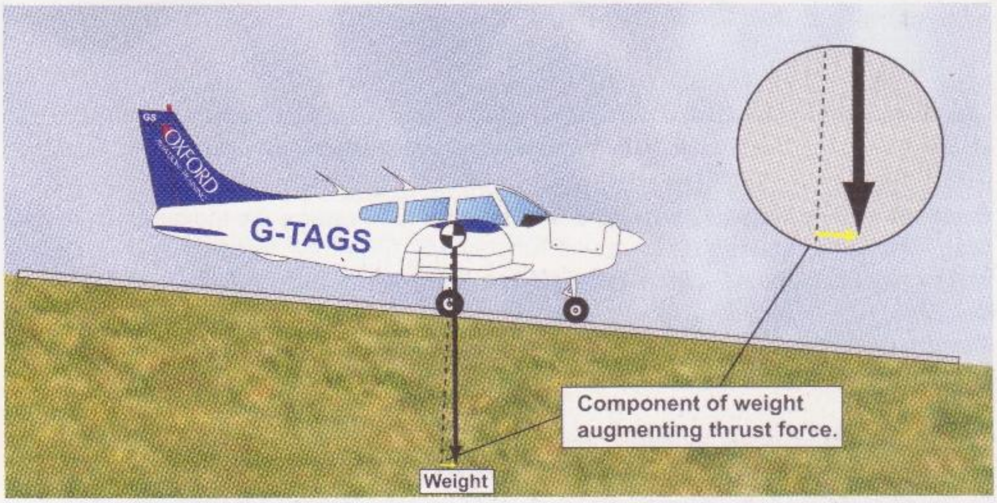


Figure 2.13 Downslope increases acceleration owing to a component of weight acting forwards to augment propeller thrust force. This reduces Take-Off Distance Required.

For every **1%** of up-slope the **take off distance** is increased by **5%**, or a factor of **1.05**.

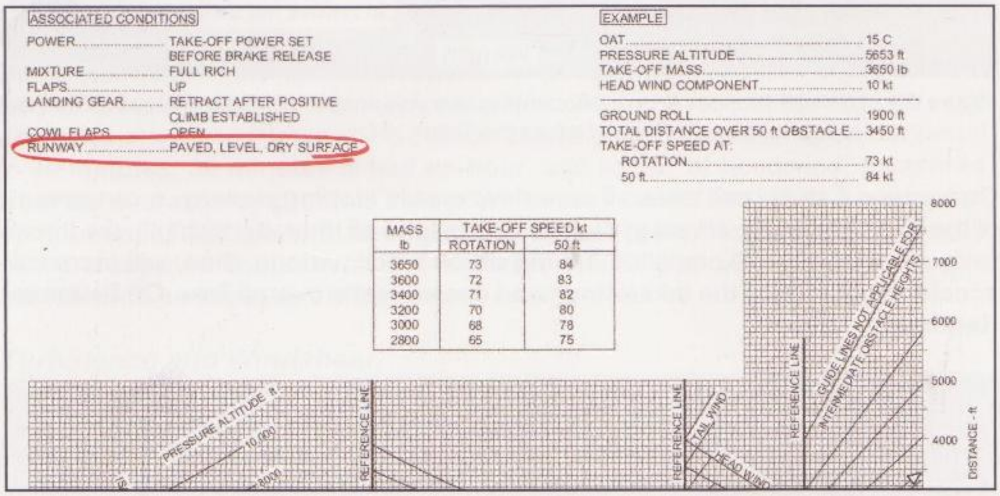
No factor is applied for the advantage of a downwards-sloping runway for take-off. A down-slope should be regarded as a bonus when taking off.

Calculating Runway Slope.

The **gradient of a slope** can be calculated if certain information is available. If a pilot knows the difference in height between the two ends of a runway, the **gradient of slope** may be found by dividing the difference in height by the runway length (taking care to work in the same units of measurement). For example, a **2 500 feet (760-metre)** long runway which is **50 feet (15 metres)** higher at one end than the other has a **slope gradient** of approximately **0.02**, or a **2%**.

Runway Surface.

Most **take-off performance graphs and tables** assume that certain **"associated conditions"** apply to the airfield and aircraft which are the subjet of the **take-off performance calculations.** One of those **associated conditions** is, invariably, that the aircraft is operating from a **level, paved, dry surface**. This is the case for the section of graph that we illustrate in *Figure 2.14*. If the **runway surface** conditions differ from these assumptions, allowance must be made for that difference, in take-off calculations.


ASSOCIATED CONDITIONS

POWER........................ TAKE-OFF POWER SET BEFORE BRAKE RELEASE
MIXTURE..................... FULL RICH
FLAPS.......................... UP
LANDING GEAR.......... RETRACT AFTER POSITIVE CLIMB ESTABLISHED
COWL FLAPS............... OPEN
RUNWAY...................... PAVED, LEVEL, DRY SURFACE

EXAMPLE

OAT.. 15 C
PRESSURE ALTITUDE.................................. 5653 ft
TAKE-OFF MASS.. 3650 lb
HEAD WIND COMPONENT........................... 10 kt

GROUND ROLL.. 1900 ft
TOTAL DISTANCE OVER 50 ft OBSTACLE.... 3450 ft
TAKE-OFF SPEED AT:
ROTATION... 73 kt
50 ft.. 84 kt

MASS lb	TAKE-OFF SPEED kt	
	ROTATION	50 ft
3650	73	84
3600	72	83
3400	71	82
3200	70	80
3000	68	78
2800	65	75

Figure 2.14 Performance graph assumptions.

Even on a hard, paved runway, a wet surface will cause an increase in wheel drag. An aircraft taking off on a wet runway will, therefore, accelerate less rapidly leading to an increase in the **take-off run** and in the overall **Take-Off Distance Required**. Any puddles of water on the runway would have a very significant retarding effect on an aircraft's acceleration. **Taking off through standing water should be avoided.**

Of course, many small airfields have grass strips. Even **dry grass** will **increase wheel drag** compared to a take-off on a paved or asphalt runway, again leading to an increase in the **take-off run** and overall **Take-Off Distance Required**.

Dry grass can increase Take-Off Distance Required by up to 15% compared to a paved runway. If **dry grass** is as long as **8 inches (20 cm), Take-Off Distance**

Required is increased by 20%. Long, wet grass will cause a much greater increase in the take-off run, depending on the length and wetness of the grass and the weight and wheel size of the aircraft.

Soft ground or snow will cause an even greater increase in **Take-Off Distance Required**.

Summary of Correction Factors.

The following table at *Figure 2.15*, taken from **UK CAA Safety Sense Leaflet No 7, 'General Aviation Aircraft Performance'**, summarises the **correction factors** that you have learned so far, and which should be applied to **take-off calculations** in order to allow for conditions which depart from the **associeted conditions** assumed by **take-off performance graphs**. Note that when more than one **correction factor** applies, each new factor involves a further **multiplication**. The table at *Figure 2.15* also includes **correction factors** to be applied to **landing calculations**, as well as **overall safety factors** to account for the fact that graphs contain **unfactored data**.

	TAKE-OFF		LANDING	
CONDITION	INCREASE IN TAKE -OFF DISTANCE TO HEIGHT 50 FEET	FACTOR	INCREASE IN LANDING DISTANCE FROM 50 FEET	FACTOR
A 10% increase in aeroplane weight, e.g. another passenger	20%	1.20	10%	1.10
An increase of 1,000 ft in aerodrome elevation	10%	1.10	5%	1.05
An increase of 10°C in ambient temperature	10%	1.10	5%	1.05
Dry grass* - Up to 20 cm (8 in) (on firm soil)	20%	1.20	15%$^{+}$	1.15
Wet grass* - Up to 20 cm (8 in) (on firm soil)	30%	1.3	35%$^{+}$	1.35
			Very short grass may be slippery, distances may increase by up to 60%	
Wet paved surface	-	-	15%	1.15
A 2% slope*	Uphill 10%	1.10	Downhill 10%	1.10
A tailwind component of 10% of lift-off speed	20%	1.20	20%	1.20
Soft ground or snow*	25% or more	1.25 +	25%$^{+}$ or more	1.25 +
NOW USE ADDITIONAL SAFETY FACTORS (if data is unfactored)		**1.33**		**1.43**

Notes: 1. * Effect on Ground Run/ Roll will be greater.

2. $^{+}$For a few types of aeroplane e. g. those without brakes, grass surfaces may decrease the landing roll. However, to be on the safe side, assume the INCREASE shown until you are thoroughly conversant with the aeroplane type.

3. Any deviation from normal operating techniques is likely to result in an increased distance.

Figure 2.15 Factors to be applied to account for surfaces which are not hard, dry or level. When more than one factor is applied, each new factor involves a new multiplication.

Flap Setting.

As you learnt in the **Principles of Flight** section of this volume, **deployment of flap reduces the stalling speed** and, as a corollary, will also enable an aircraft **to lift off at a lower indicated airspeed**. This can mean a shorter ground run.

Compared to a flapless take-off, use of the manufacturer's recommended take-off flap setting will shorten the Take-Off Run Required but reduce the initial angle of climb, and may increase Take-Off Distance Required.

Care must be taken, however, to use the manufacturer's recommended **take-off flap setting** because **deployment of flap always increases drag as well as lift**, and so use of inappropriately large **flap** settings may actually increase the **ground run** to lift-off. The manufacturer's recommended **take-off flap setting** will always be a small setting. For instance, **recommended take-off flap setting for the Cessna 152 is 10°**.

But even when the recommended **flap** setting is used, the **lift/drag ratio** will be degraded, and there will be a corresponding **reduction in the angle and rate of climb**. Consequently, even though use of **take-off flap** will shorten the **ground run**, the distance to the **50 feet screen height**, that is **the Take-Off Distance Required, may not be decreased**. *(See Figure 2.16.)*

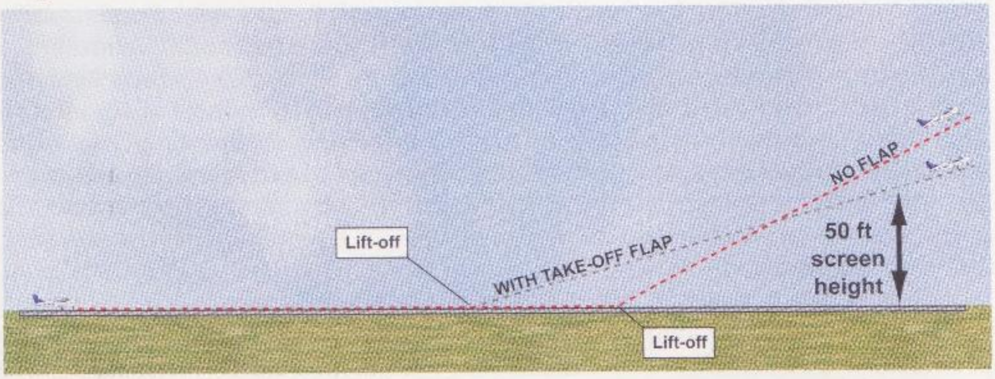


Figure 2.16 Take-off flap will reduce take-off run but may increase overall Take-Off Distance Required.

The actual effect of using **take-off flap** will depend on several factors such as the **flap setting** itself, engine power and propeller thrust. As we have mentioned, if **flap** is used on take-off it should always be with the setting recommended in the **Pilot's Operating Handbook (POH)**, but you must never forget to check any supplement included in the **POH**. Depending on runway surface conditions, runway length and prevailing meteorological conditions, a light aircraft may reach the **50 feet screen height** earlier by taking off without deploying **flap**.

Wing Contamination.

The presence of **insects**, **ice, rain drops** and **snow** on the wings of an aircraft, especially at the leading-edge, can have a significantly adverse effect on the generation of lift. Laminar flow aerofoils are particularly badly affected by **wing contamination**. All **contamination**, but especially **ice** and **snow,** will also increase an aircraft's **weight**. Consequently, take-off speed will be higher and **Take-Off Distance Required longer with contaminated wings**.

Figure 2.17 Wing contamination will degrade an aerofoil's lift-generating properties and increase Take-Off Distance Required. Ice and snow will also significantly increase weight.

Tyre Pressure and Wheel Contamination.

The **take-off run** will be longer if the aircraft's **tyre pressures** are below the recommended level. **Accumulated mud and/or grass** around wheel axles will also increase **rolling resistance** and lengthen the take-off run. Wheels fitted with spats may experience significant rolling resistance if the spats are packed with **mud, grass** or **slush.**

ENGINE FAILURE AFTER TAKE-OFF.

Though modern engines are very reliable, engines may **fail** or suffer from **loss of power** at any time. **The pilot must always be especially aware for the possibility of total or partial loss of power during the take-off run and initial climb.**

TAKE-OFF DECISION POINT.

A prudent pilot should know the point during the take-off run where the aircraft can be safely brought to a halt in the event of insufficient acceleration, engine failure, or such malfunctions as the loss of the Airspeed Indicator.

TAKE-OFF DISTANCE GRAPHS AND TABLES.

Take-Off Distances Required can be calculated by referring to either **tables** or **graphs**. In the following pages, we will cover **take-off calculations** using a representative **take-off distance graph** (*Figure 2.18*) typical of those available for most light aircraft.

Note that the **take-off performance data** contained in this type of graph are **unfactored**. Therefore, the **take-off performance** obtained from the graph will be expressed in **gross performance figures**, which assume that both the aircraft and engine are new, and that the aircraft is being flown in ideal conditions by a highly experienced pilot. Consequently, when a **Take-Off Distance Required** has been calculated from the **graph**, it is prudent to apply the recommended **overall safety factor** of **1.33** in order obtain **net take-off performance figures** which take into account any degradation in performance in an older aircraft being flown by an inexperienced pilot, in less than ideal conditions.

ASSOCIATED CONDITIONS

POWER........................ TAKE-OFF POWER SET
BEFORE BRAKE RELEASE
MIXTURE...................... FULL RICH
FLAPS.......................... UP
LANDING GEAR........... RETRACT AFTER POSITIVE
CLIMB ESTABLISHED
COWL FLAPS............... OPEN
RUNWAY.......................PAVED, LEVEL, DRY SURFACE

EXAMPLE

OAT.. 15 C
PRESSURE ALTITUDE..................................... 5653 ft
TAKE-OFF MASS...3650 lb
HEAD WIND COMPONENT............................ 10 kt

GROUND ROLL... 1900 ft
TOTAL DISTANCE OVER 50 ft OBSTACLE.... 3450 ft
TAKE-OFF SPEED AT:
ROTATION...73 kt
50 ft... 84 kt

MASS lb	TAKE-OFF SPEED kt	
	ROTATION	50 ft
3650	73	84
3600	72	83
3400	71	82
3200	70	80
3000	68	78
2800	65	75

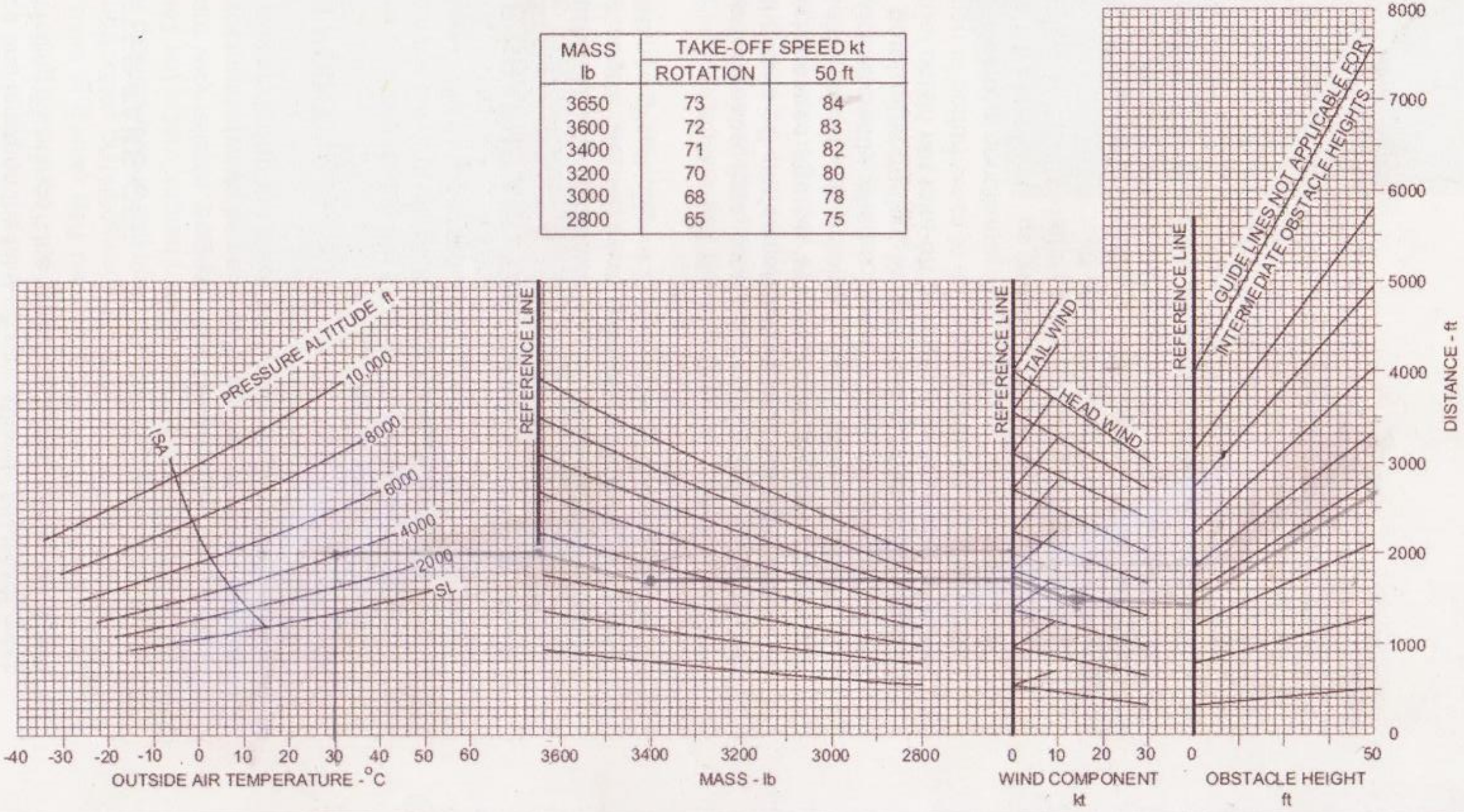
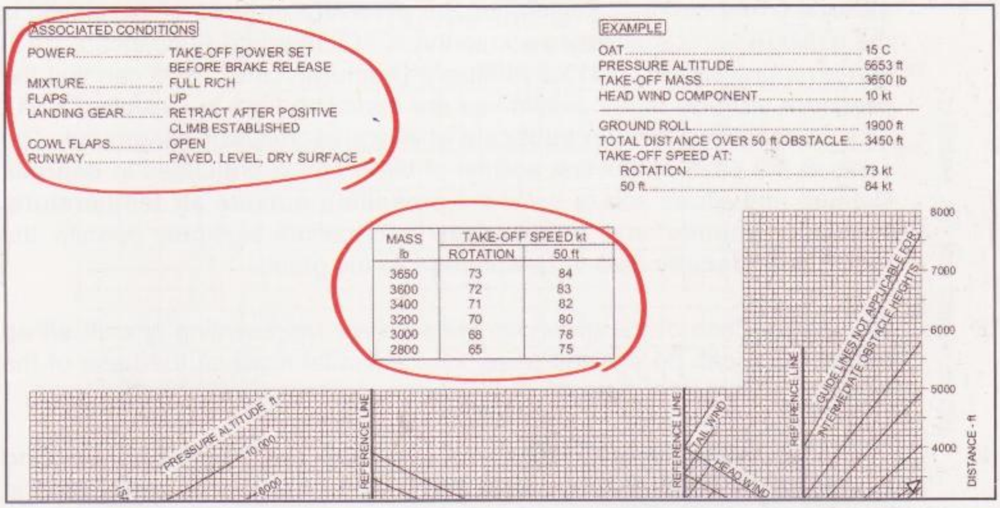


Figure 2.18 A typical take-off distance graph for a light aircraft.

Information Given at the Top of the Take-Off Distance Graph.

Before beginning any calculation of **Take-Off Distance Required** for prevailing runway and meteorological conditions and aircraft mass, do not fail to note the conditions assumed by the data in the **take-off distance graph**, as listed under the title **"Associated Conditions",** usually positioned at the top of the graph. (*See Figure 2.19.)*



ASSOCIATED CONDITIONS

POWER.................... TAKE-OFF POWER SET BEFORE BRAKE RELEASE
MIXTURE.................... FULL RICH
FLAPS.................... UP
LANDING GEAR.......... RETRACT AFTER POSITIVE CLIMB ESTABLISHED
COWL FLAPS.............. OPEN
RUNWAY.................... PAVED, LEVEL, DRY SURFACE

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ROTATION.................... 73 kt
50 ft.................... 84 kt

MASS lb	TAKE-OFF SPEED kt	
	ROTATION	50 ft
3650	73	84
3600	72	83
3400	71	82
3200	70	80
3000	68	78
2800	65	75

Figure 2.19 Associated Conditions and Take-Off Speeds assumed by the Take-Off Performance Graph.

You will see, immediately, that the graph assumes that **take-off (full) power will be applied before brakes-release, mixture will be fully rich, no flap will be deployed, landing gear will be retracted** after a positive rate of climb is established, and that the **runway is level and has a paved, dry surface.**

If there is any difference between the assumed and actual conditions for your aircraft type and runway conditions, **correction factors**, including the types already discussed, must be applied. These **correction factors** are summarised in the table at *Figure 2.15.* For instance, if the runway has a **dry grass surface** and a **2% up-hill slope**, any **Take-Off Distance Required** extracted from the graph would have to be multiplied by a factor of **1.2** and then again by **1.1** (Remember, all **correction factors** applied must be multiplied together.)

You will note that the information on the graph at *Figure 2.19* also includes details of **rotation speeds** and **take-off safety speeds** (speeds to be achieved at the **screen height of 50 feet**) for several different values of **take-off mass**. These speeds must be adhered to during the actual take-off, because they are the speeds which have been assumed in the construction the graph.

In the top right hand corner of the graph, you will notice that an **example calculation** has been carried out. Never make the mistake of using this example calculation to apply to your own aircraft. Always carry out the calculation using the figures for <u>your</u> aircraft and for the conditions prevailing at the airfield at the time of your planned take-off.

Using the Take-Off Distance Graph Itself.

Now let us take a closer look at the **Take-Off Distance Graph**, itself. The graph in *Figure 2.18* is divided into four vertical sections each of which has a different scale at its base.

1 The section at the extreme left contains curves representing the **pressure altitude** of the airfield. Remember, the **pressure altitude** of the airfield is the airfield's vertical distance above the ICAO Standard Atmosphere (IAS) sea-level pressure of **1 013.2 millibars (hectopascals)**. You can find the **pressure altitude** of the airfield you are operating from by selecting **1 013** on your aircraft's **altimeter subscale** while you aircraft is on the ground. The scale at the base of this first section of the graph is graduated in **degrees Celsius** and allows you to enter the **prevailing outside air temperature**. **Pressure altitude** and **temperature** information together, permits the required **air density** data to be entered into the graph.

2 The next section of the graph contains curves representing aircraft **all-up mass** which can be entered using the horizontal scale at the base of the section, graduated in **pounds (lb)**.

3 The next section contains lines representing **headwind and tailwind components** against the scale at the base of the section, graduated in **knots**. You should note that in some graphs the **50% headwind factor** and **150% tailwind factor** may have already been applied. But you should check the Performance section of the aircraft's **Flight Manual** or **Pilot's Operating Handbook** to confirm this fact.

4 The next section of the graph allows you to enter the height in feet of any obstacles in the initial climb-out path.

5 Finally, the **vertical scale at the extreme right of the graph** enables you to read off the **Take-Off Distance Required** in feet, **assuming that the associated conditions prevail which are listed at the top of the graph.**

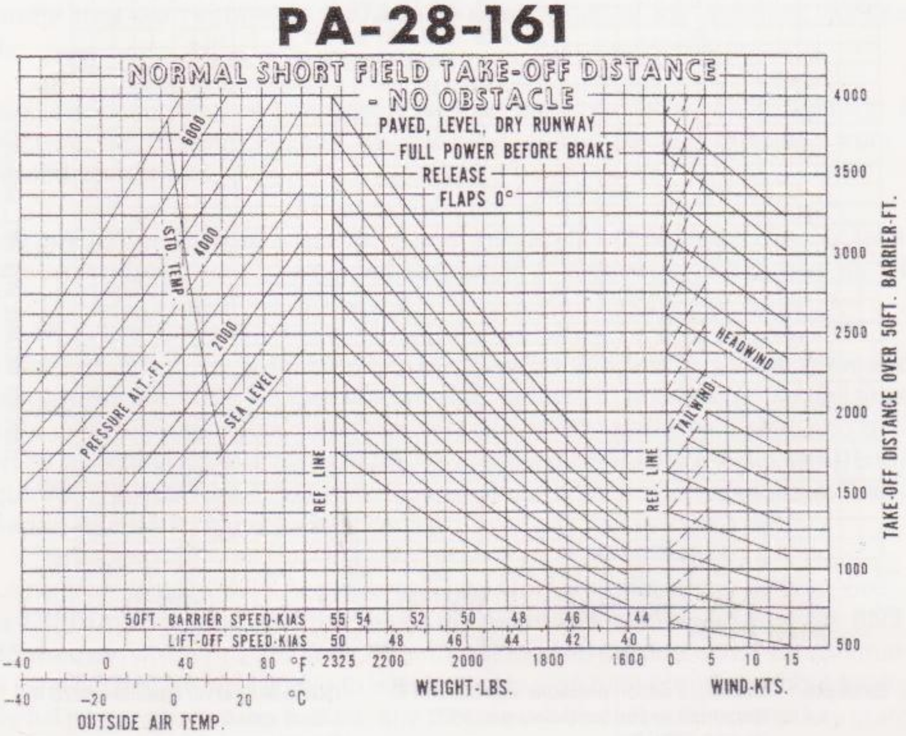
When the **Take-Off Distances Required** has been read from the graph, **correction factors** will need to be applied, if relevant. And, of course, the UK CAA recommended **overall safety factor of 1.33 should be applied**.

Example Calculation.

We will carry out our own **example calculation**, using the graph at *Figure 2.20* which refers to a **PA-28-161**. The information in this **Take-Off Distance Required** graph is formatted slightly differently to the graph at *Figure 2.18*, and contains no obstacle section, but it is typical of the type of graph you might find in an aircraft's **Flight Manual** or **Pilot's Operating Handbook**.

Let us assume that we wish to take off from an airfield with a grass strip, **1 025 metres** long, aligned **05/23** on a day when the outside air temperature is **12° Celsius**. Having prepared our aircraft for take-off, we calculate its all-up mass as **2 250 lb**. We observe the wind as blowing from about **270° Magnetic** at **15 knots**. The airfield **QNH** is **1 003.** By setting **1 013** on the aircraft's **altimeter subscale,** we note that at our **airfield elevation of 250 feet**, the **pressure altitude is 550 feet**.

The runway-in-use is **23** so, from the observable wind, we calculate that the **headwind component** is about **10 knots**.



Example: Departure airport pressure altitude: 550 ft
Departure airport temperatures 12ºC
Weight: 2250 lbs
Wind: 10 kts headwind

Distance over 50 ft barrier: 1375 ft
Lift-off speed: 48
Barrier speed: 53

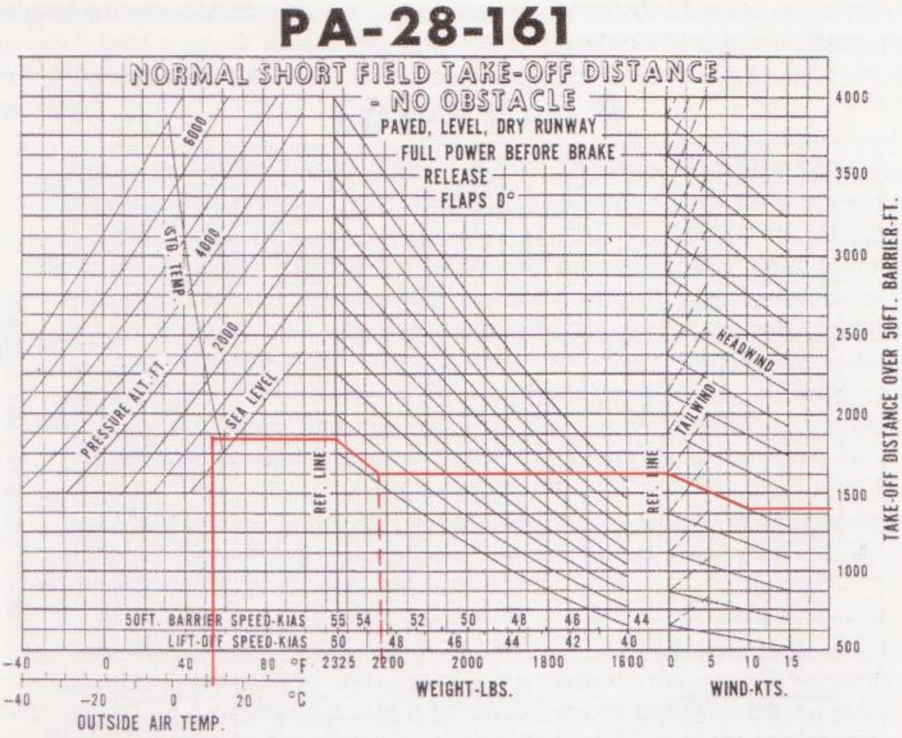
Figure 2.20 Short field take-off distance graph for a PA-28-161 Warrior.

We now have enough information to calculate the **take-off distance we require**. We note from the **associated conditions** on the **Take-Off Distance Required** graph that the **runway is assumed to be paved, level and dry,** and that it is further assumed that **full power is applied before brake-release** and that **no take-off flap is used**. Our runway is level, but it is a grass runway.

The runway that we will be using grass is short and the ground is dry. We note, therefore, that we must apply a **correction factor** to allow for the grass surface, after we have extracted the **Take-Off Distance Required** from the graph.

We will take a decision and the use of flaps depending on the overall **Take-Off Distance Required** and the **Take-Off Distance Available**.

We now begin our calculation, as indicated at *Figure 2.21, overleaf*. On the graph, our working is shown by the red lines.



Example: Departure airport pressure altitude: 550 ft
Departure airport temperatures 12ºC
Weight: 2250 lbs
Wind: 10 kts headwind

Distance over 50 ft barrier: 1375 ft
Lift-off speed: 48
Barrier speed: 53

Figure 2.21 Calculation of Take-Off Distance Required.

On the left-hand side of the graph, we locate the horizontal **temperature scale** at the foot of the graph and draw a vertical line from the **12° C** mark until the line meets a point among the **pressure altitude lines** corresponding to **550 feet**, the **pressure altitude** of our airfield. There is no **550 feet line**, so we have to interpolate, choosing a suitable point between the **sea-level** and **1 000 feet** lines.

We then draw a horizontal line from the **550 feet** point to the next **vertical reference line** which marks the beginning of the **weight/lift-off speed/screen height safely speed section** of the graph. From that **reference line**, we follow the slope of the nearest **weight-line** down to a point which corresponds to our calculated **take-off weight of 2 250 lbs**, read from the horizontal scale at the foot of the graph.

We note, reading vertically downwards to the **lift-off speed/screen height safely speed scales**, that our **lift-off speed** at **2 250lb** will be just over **48 knots**, and that our **screen height safety speed** should be **53 knots**.

Drawing, now, a further horizontal line towards the **vertical reference line** which marks the beginning of the **wind section of the graph**, we extend our line downwards parallel to the nearest **headwind line** to a point which corresponds to **10 knots** on the horizontal scale at the foot of the graph. In this example our line coincides with a chart drawn headwind line. This will not always happen.

From that point we conclude the graph part of our calculation by drawing a horizontal line to meet the **vertical scale** at the extreme right-hand side of the graph which gives the **Take-Off Distance Required**. We read from that scale that the **take-off distance that we require is 1 375 feet**, provided all of the assumed conditions apply.

Finally, we complete the calculation for our particular take-off by applying any **correction factors** which must be applied to allow for any deviation from the **assumed conditions**.

These **correction factors** are summarised in the table at *Figure 2.15*. Our take-off strip is **short dry grass**, so we need to multiply **1 375 feet** by **1.2** to give us **1 650 feet**.

The last action that we need to take is to multiply **1 650 feet** by the **recommended overall safety factor of 1.33 for the take-off**, in order to account for the fact that the graph's data assumes ideal conditions and a new and perfectly maintained aircraft flown by an expert pilot. This concluding calculation gives us a **Take-Off Distance Required** of **2 195 feet**. This is the distance we must compare with the **Take-Off Distance Available** at our airfield.

We note from the **UK AIP, Aerodrome Data Section**, that at our airfield, both the **Take-Off Run Available**, and the **Take-Off Distance Available** for Runway **05/23** is **1 025 metres**, which is **3 362 feet**. We, therefore, feel confident that we can make a safe take-off, that we will be able to initiate the take-off run normally, without having to apply full power against the brakes, and that we will be well within our safety margins by taking off without any flap deployed.

If we had found that the **Take-Off Distance Required** exceeded the **Take-Off Distance Available**, we would have to reduce weight by taking on less fuel or off-loading baggage and/or passengers. If we still wished to fly we would then need to carry out a new calculation for **Take-Off Distance Required (TODR),** at the revised weight, and compare the new **TODR** with the **Take-Off Distance Available**.

TAKE-OFF DISTANCE TABLES.

Sometimes, the data a pilot requires for calculating **Take-Off Distance Required** is given in tabular form. One such table is shown in *Figure 2.22*. The interpretation of these tables is straightforward.

Weight (Kgs)	Takeoff Speed		Press Alt Ft	0°C (32°F) Metres		10°C (40°F) Metres		20°C (68°F) Metres		30°C (86°F) Metres		40°C (104°F) Metres	
	KIAS	(MPH)											
	LIFT OFF	Clear 50ft		GND RUN	50 FT	GND RUN	50 FT	GND RUN	50 FT	GND RUN	50 FT	GND RUN	50 FT
998	56	63	SL	230	419	255	464	282	512	311	564	341	618
	(64)	(73)	2000	273	495	304	549	336	606	370	667	407	732
			4000	326	587	362	651	401	719	442	791	485	868
			6000	391	698	434	774	479	854	529	940	581	1031
			8000	469	832	520	922	575	1018	634	1120	697	1229
907	53	60	SL	183	336	203	372	224	411	247	452	272	496
	(61)	(69)	2000	218	397	241	440	267	486	294	535	323	587
			4000	260	471	288	522	319	576	351	635	386	696
			6000	311	560	345	621	382	685	420	754	462	828
			8000	373	668	414	740	458	817	504	899	554	983
816	50	57	SL	142	263	158	292	174	322	192	355	211	389
	(58)	(66)	2000	169	312	187	345	207	381	229	419	251	460
			4000	202	369	221	409	247	452	273	497	300	546
			6000	241	439	268	486	296	537	326	591	359	649
			8000	290	523	321	580	355	640	392	704	430	773

Figure 2.22 Take-off performance information presented in tabular format.

Representative PPL - type questions to test your theoretical knowledge of Take-off.

1. If the density of the atmosphere is reduced, the take-off distance required will be:

[✓ a.] increased
b. decreased
c. unaffected
d. reduced with a wind

2. What effect will a higher aircraft mass have on the rotate speed and take off safety speed?

a. It will decrease both speeds
b. It will increase rotate speed and decrease take off safety speed
[✓ c.] It will increase both speeds
d. It will decrease rotate speed and increase take off safety speed

3. That part of a runway surface which is used for normal operations during take off, excluding any clearway or stopway, is referred to as:

[✓ a.] the Take-Off Run Available (TORA)
b. the Accelerate-Stop Distance Available (ASDA)
c. the Take-Off Distance Available (TODA)
d. the Emergency Distance Available (EMDA)

4. Complete the following statement as accurately as possible using one of the options a), b), c) or d).

If the density of the air increases the effect will be:

a. to increase the take-off distance required
b. to increase the take-off run
[✓ c.] to decrease the take-off distance required
d. to decrease the indicated airspeed at lift-off

5. Complete the following statement as accurately as possible using one of the options, a), b), c) or d).

The main reason for taking off into wind is to:

a. increase the take-off distance required
b. decrease the take-off distance available
c. increase the ground speed of the aircraft at lift-off
[✓ d.] decrease the ground speed of the aircraft at lift-off and to decrease the Take-Off Distance Required

6. Complete the following statement as accurately as possible using one of the following options: a), b), c) or d).

During take-off, the use of the manufacturer's recommended take-off flap setting:

a. compared to zero flap, will increase the length of the take-off run and obstacle clearance performance
b. compared to zero flap, will decrease the take-off run required but reduce obstacle clearance performance
[✓ c.] compared to zero flap, will increase the indicated airspeed at which the aircraft can lift-off
d. compared to zero flap, will ensure a steeper angle of climb after lift-off

7. Complete the following statement accurately using one of the options: a), b), c) or d).

When the density of the atmosphere is relatively low, the resulting reduction in:

a. thrust and drag has no apparent effect on the take-off distance required
b. both lift and engine power will require a longer take-off distance
c. drag will permit the use of greater flap angles
[✓ d.] drag offsets the loss of engine power giving improved acceleration

8. The horizontal distance covered during take-off, from brakes-release to the 50 feet screen height, and which includes any stopway or clearway, is referred to as:

a. the Take-Off Run Available (TORA)
b. the Accelerate-Stop Distance Available (ASDA)
[✓ c.] the Take-Off Distance Available (TODA)
d. the Emergency Distance Available (EMDA)

9. That part of a take-off strip which includes the Take-Off Run Available and the stopway, is referred to as:

a. the Take-Off Run Available (TORA)
b. the clearway
c. the Take-Off Distance Available (TODA)
[✓ d.] the Accelerate-Stop Distance Available (ASDA) or Emergency Distance Available (EDA)

10. What name is given to the distance which comprises Take-Off Run Available (TORA) and any clearway?

a. Emergency Distance Available (EMDA)
b. Take-Off Distance Required (TODA)
c. Accelerate-Stop Distance Available (ASDA)
[✓ d.] Take-Off Distance Available (TODA)

11. A 15 knot wind at 60° off the runway heading gives a headwind component of approximately:

[✓ a.] 8 knots
b. 14 knots
c. 12 knots
d. 3 knots

12. A 15 knot wind at 60° off the runway heading gives a crosswind component of approximately:

a. 8 knots
[✓ b.] 14 knots
c. 12 knots
d. 3 knots

Question	1	2	3	4	5	6	7	8	9	10	11	12
Answer												

The answers to these questions can be found at the end of this book.

CHAPTER 3

CLIMB

INTRODUCTION.

An aircraft's ability to achieve a satisfactory **angle and rate of climb** is an important aspect of its overall performance. It is obviously efficient to be able to **climb rapidly** to the pilot's chosen cruising altitude, but it is also desirable that an aircraft should be able to **climb steeply** in order to achieve safe **obstacle clearance performance** as well as to keep noise pollution to a minimum. We will begin by examining **angle of climb**.

ANGLE OF CLIMB.

Figure 3.1 depicts an aircraft in un-accelerated straight and level flight. **Lift** balances **weight** and **thrust** balances **drag**, so all four forces are in **equilibrium**. Airspeed and altitude are constant.

Figure 3.1 Straight and level flight with the four principal flight forces in equilibrium.

If the pilot now eases back on the control column, without increasing thrust, the disposition of forces will be as shown in *Figure 3.2*.

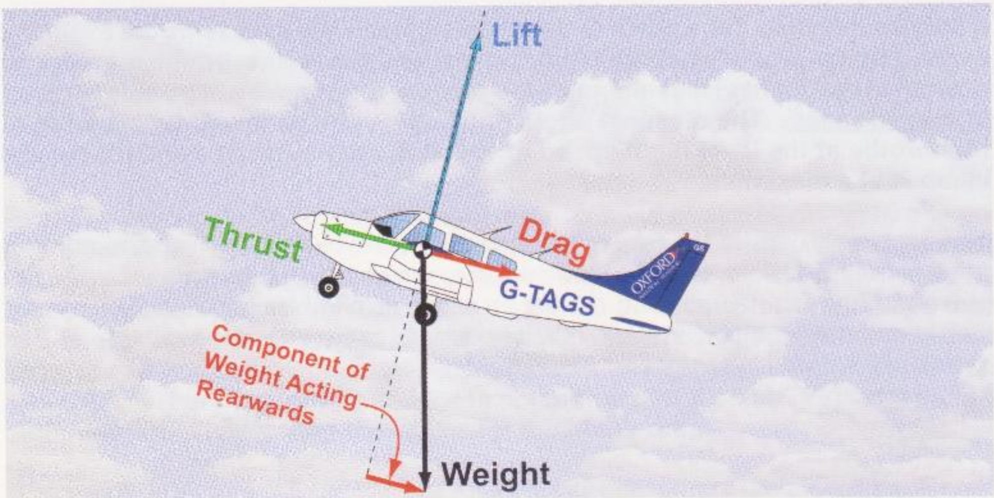


Figure 3.2 If the pilot attempts to climb without increasing thrust, the aerodynamic drag plus the component of the aircraft's weight acting rearwards are now greater than thrust. The aircraft will, therefore, lose speed.

Figure 3.2 shows that the aircraft will begin to climb, but **a component of the aircraft's weight now acts rearwards** along the longitudinal axis in the same direction as the **aerodynamic drag**. This component is called **weight apparent drag**. The rearward acting forces are now, consequently, greater than the forward acting thrust force. The end result, depending on the pitch altitude selected by the pilot, would be either that the aircraft continues to climb at a lower airspeed, or the aircraft may stall.

In order to maintain his **original speed in the climb**, therefore, the pilot opens the throttle to increase the thrust developed at the propeller and so balance the **rearwards acting weight component** of the aircraft (**the weight apparent drag**). The **extra thrust** that the pilot has applied is **excess thrust** that the engine has available over and above the thrust required to maintain level flight **at the same speed**. (*See Figure 3.3.*)

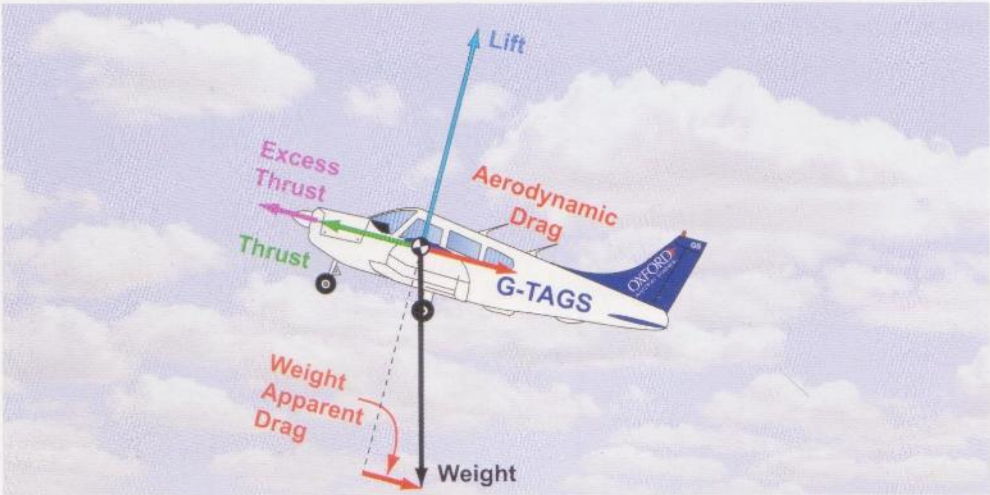


Figure 3.3 Forces in a steady climb showing excess thrust balancing weight apparent drag.

You have learnt in **Principles of Flight** that in order to maintain level flight, the thrust required from the propeller must exactly counteract **aerodynamic drag**. In level flight, then, any **extra thrust** which is available from the engine-propeller combination can be used to climb the aircraft, if the pilot wishes.

The greater the amount of excess thrust available, the greater can be the angle of climb.

It follows then that, for a given airspeed, the greater the excess thrust available in the engine-propeller combination, over and above the thrust required to maintain level flight at that airspeed, the steeper the aircraft will be able to climb <u>at that airspeed</u>. The steepest angle of climb will be achieved by climbing at full throttle at the level flight speed at which the extra thrust available for the climb is at a maximum.

This principle is depicted by *Figure 3.4* which shows two aircraft, each at its **maximum angle of climb**; (Note, though, that the force arrows are not drawn to scale.) The aircraft on the left has attained a steeper **angle of climb** because, for its **speed**, weight and configuration, in the climb, it had more **excess thrust available at that speed** when it was in straight and level flight.

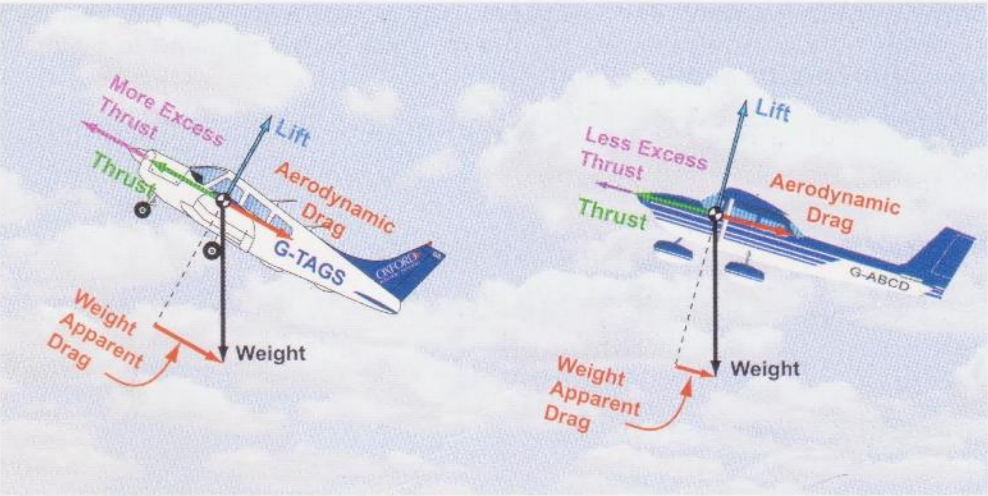


Figure 3.4 The steepest angle of climb will be achieved by climbing at full throttle at the level-flight speed at which the excess thrust available is a maximum.

There are several factors then which affect how much **extra thrust** is **available** for the climb, over and above the thrust required for level flight. The speed factor has already been mentioned, and we discuss speed in more detail, below. Other factors which affect **angle of climb** are **aircraft weight, aircraft configuration** (e.g. deployment of flaps and undercarriage), **air density** and, as far as the **angle of climb relative to the ground** is concerned, the strength of **headwind** component. These latter factors will mentioned latter in this chapter.

Speed and Best Achievable Angle of Climb.

Let us look at some final points about the relationship between **speed** and **angle of climb**.

As we have seen the **angle of climb** at a given **speed** is a function of the **excess thrust available** from the engine-propeller combination over and above the **thrust required to fly straight and level at that speed**. There will of course be only one level flight speed at which the **excess thrust**, still able to be developed by the propeller, is at a **maximum**. This will be the aircraft's **best angle of climb speed**, known as $\mathbf{V_X}$.

Jet-powered aircraft will achieve their **best angle of climb** at a speed where drag is minimum. (Jet fighters capable of producing more thrust than they weigh, such as the Harrier, can, of course, climb vertically, and actually accelerate in the vertical climb.)

But, as you learnt in **Principles of Flight**, in the case of an aircraft driven by a **fixed-pitch propeller**, the amount of **thrust produced decreases with airspeed** because propeller-blade angle of attack also decreases with airspeed. An aircraft with a **fixed-pitch propeller**, therefore, produces its **maximum thrust** at a **lower airspeed than the speed for minimum drag**. By the time such an aircraft has reached minimum drag speed, thrust has decreased considerably, even though engine power has increased. **Therefore, the speed for maximum angle of climb ($\mathbf{V_X}$) for a simple light aircraft is lower than the speed for minimum drag**.

The graph at *Figure 3.5* depicts the relationship (for a representative light aircraft) between the **speed in level flight** and two other parameters: the **thrust required to maintain level flight at that speed** and the **total thrust available from the**

propeller at that speed. The **thrust required** curve is taken from the total drag curve for the aircraft because, as you already know, **thrust required to maintain level flight must be equal to drag**.

V_X is the speed to fly for the best angle of climb. V_X for a Cessna 152 is about 65 knots.

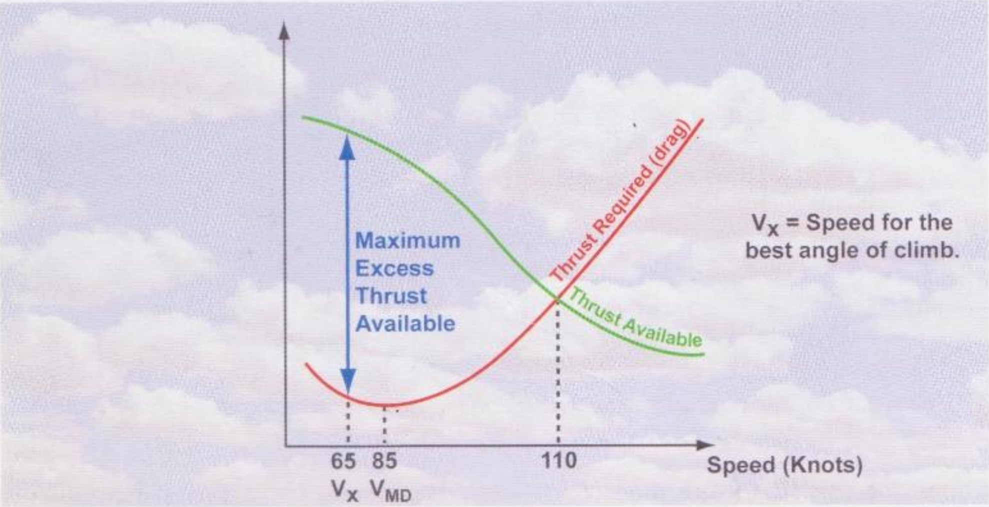


Figure 3.5 Climb angle or gradient is dependent on Excess Thrust Available. Maximum excess thrust available will give maximum angle or gradient of climb. V_X is defined as the speed for best angle or gradient of climb.

Examining the graph, we see that the **maximum amount of excess thrust available for the climb** is found where the distance between the thrust available and the thrust required curves is the greatest, The corresponding speed on the graph's horizontal axis is the speed, V_X at which the **greatest angle of climb is achieved when full throttle is applied**. V_X, then, is the speed to fly for the **best angle of climb**.

In a light aircraft such as the **Cessna 152**, V_X will be about **65 knots**.

At any other speed than V_X, you can see that the **excess thrust available** reduces; so for any other speed than V_X the angle of climb will also reduce.

Forces in the Climb.

In a **steady climb**, at **constant angle of climb** and **constant speed**, the forces of **thrust**, **drag**, **lift** and **weight** are in **equilibrium**, just as they are in level flight. However, in the climb, the **weight and aerodynamic drag** of the aircraft are balanced by **a combination of lift and thrust**. (*See Figure 3.6.*) An interesting phenomenon that you should note is that, because, in a steady climb, the **total thrust** is greater than **aerodynamic drag, the lift force, itself, is less than the aircraft's weight**.

For a light aircraft, at typical light aircraft **angles of climb**, the **lift** will be only a little less than the **weight**. And, of course, as the climb is initiated with the nose of the aircraft raised to the climbing attitude as full power is applied, the **lift** force will momentarily increase. **But as soon as the aircraft is established in the climb, lift reduces to a little below the value of weight**.

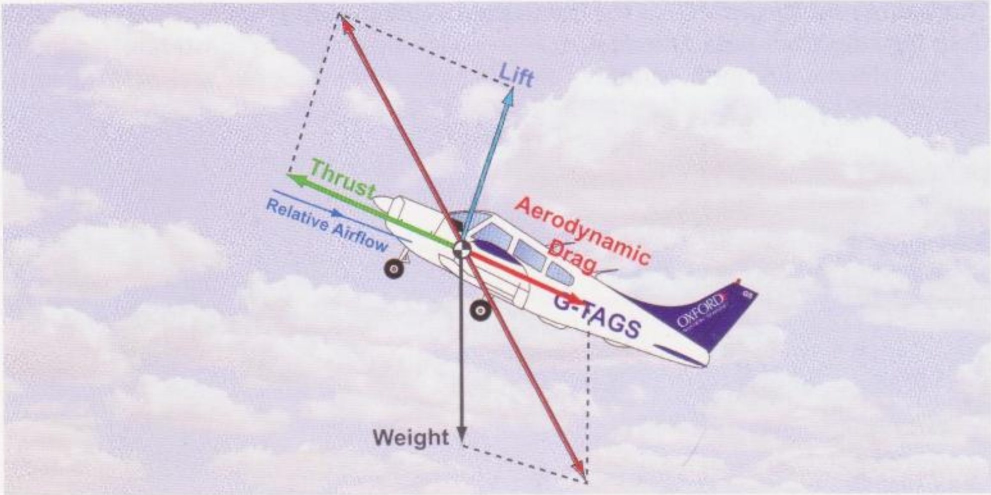


Figure 3.6 Equilibrium in a steady climb, at constant speed. Total thrust is greater than aerodynamic drag, and lift is less than weight.

The lift generated by an aircraft in a steady climb, at constant airspeed and power setting will be less than the aircraft's weight.

As the **angle of climb** steepens, the more the **lift** force reduces with respect to **weight**. (For a Harrier jet fighter **in a vertical climb**, it is **thrust** alone which balances both the aircraft's **weight** and **aerodynamic drag**, the **lift** force playing no role at all.)

Other Factors Affecting Angle of Climb.

Weight.

The greater an aircraft's **all–up weight**, the greater the **lift** required to maintain level flight at any speed. The **lift formula, Lift = $C_L \frac{1}{2} \rho v^2 S$**, teaches us that for a given airspeed and at constant density, the increase in **lift** required to support a heavier aircraft can only be obtained by increasing **C_L**. Unless flap is lowered, which may not be practical or safe, **C_L** can be increased only by increasing **angle of attack**. An increase in **angle of attack** will increase **induced drag**, and so, at any given speed, **more thrust is required to maintain level flight than for a lighter aircraft**. Consequently, there will be less **excess thrust available** in level flight for the aircraft to **climb**. The **angle of climb** achievable at any speed will, thus, reduce. It follows that, **when an aircraft is heavily loaded, the best angle of climb achievable will be less steep than the best angle of climb for a more lightly loaded aircraft**.

For any given **climb angle**, an increase in **weight** will also increase the **rearwards acting weight component** (i.e. the **weight apparent drag**), requiring increased **"excess" thrust** to balance it. Therefore, for a given value of **maximum excess thrust available** from the propeller, which is already reduced for a heavier aircraft, **the best climb angle achievable will be further reduced compared to a lighter aircraft**.

Increasing the aircraft's all-up weight will reduce the best angle of climb.

Figure 3.7, overleaf, shows that the overall effect of increasing **weight** is that the **thrust required curve** moves up and to the right, whereas the **thrust available curve** remains unchanged. The graph confirms, then, that, at any given straight and level flight speed, the **excess thrust available for the climb reduces**, and that the best achievable **angle of climb** at that speed will be shallower than for a lighter aircraft. The graph for the heavier aircraft also shows that the speed at which **maximum excess thrust** is available, increases compared to a lighter aircraft.

Consequently, the speed for the best angle of climb is higher for a heavy aircraft than for a lightly-loaded aircraft.

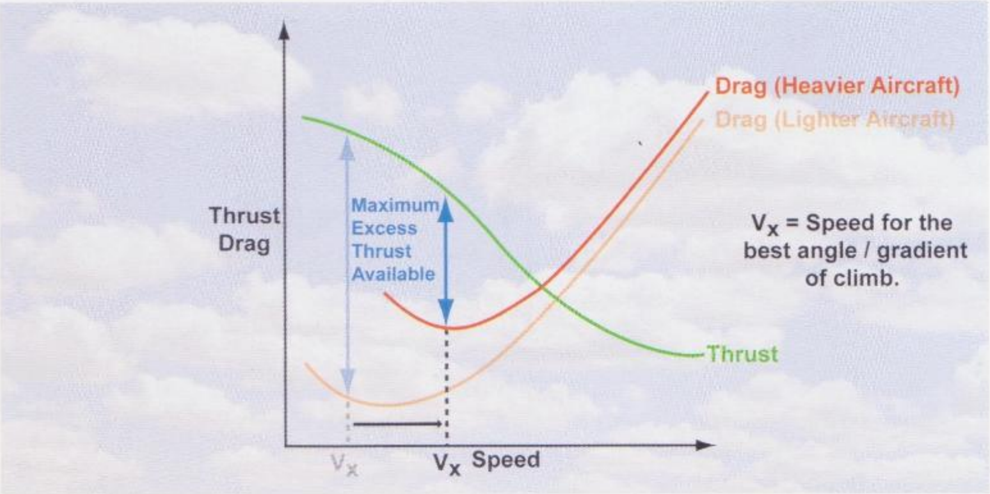


Figure 3.7 At increased aircraft weight, the thrust required curve moves up and to the right. The thrust available curve remains unchanged. For all speeds, excess thrust available for the climb reduces. ***V_X****, the speed for the best angle of climb, increases.*

To summarise, then, **a heavier aircraft will have a shallower best angle of climb than a more lightly loaded aircraft, and the speed at which the reduced best angle of climb is achieved is higher.**

Aircraft Configuration.

The angle of climb is also affected by the **configuration** of the aircraft. By **configuration**, we mean whether **flaps** and **undercarriage** are extended or not.

Figure 3.8 shows a representative light aircraft in the climb, with flaps and undercarriage retracted.

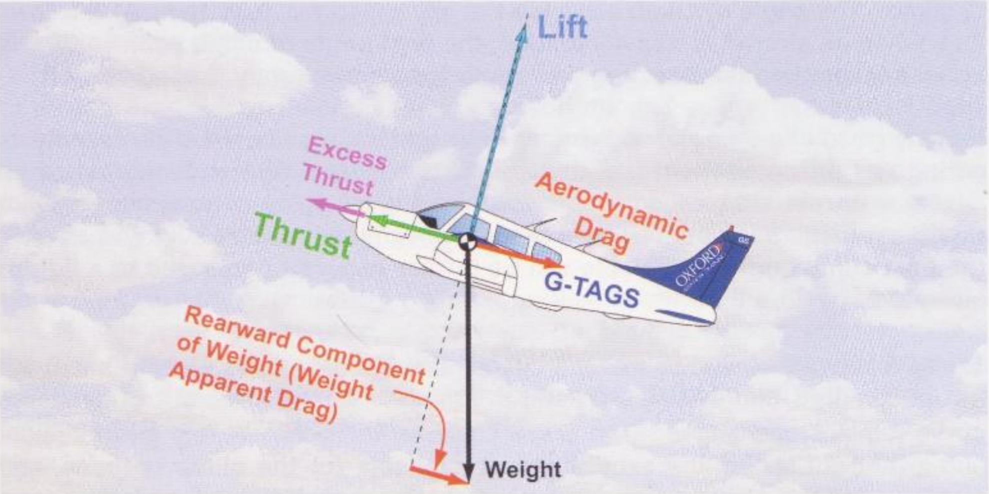


Figure 3.8 A aircraft in the climb, with undercarriage and flaps retracted.

If the undercarriage and flaps are extended, the **parasite drag** of the aircraft and, thus, its **total drag**, at any given speed will increase. Consequently, at any given speed, there is a reduction in **excess thrust available** from the propeller at that speed, and the best achievable **angle of climb** at that speed will also be reduced (*See Figure 3.10.*)

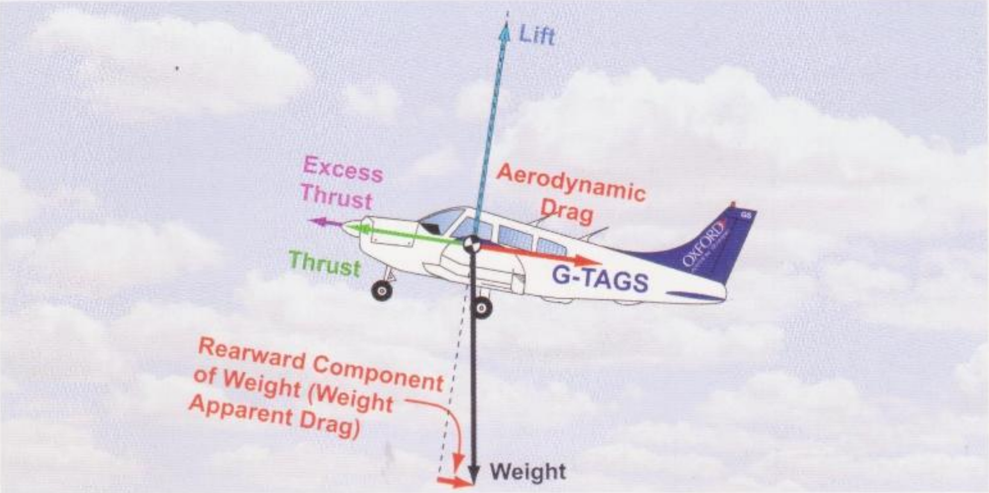


Figure 3.9 An aircraft in the climb with flaps and undercarriage extended.

If we look again at the graph for **thrust available** against **thrust required**, for **flaps and undercarriage extended**, we see that the **thrust required curve** which is based on the **drag curve**, has moved upwards, and to the left. The consequence of this change is although the excess thrust available has deceased, the speed at which **maximum excess thrust** is **available** for the climb, V_X, has also decreased.

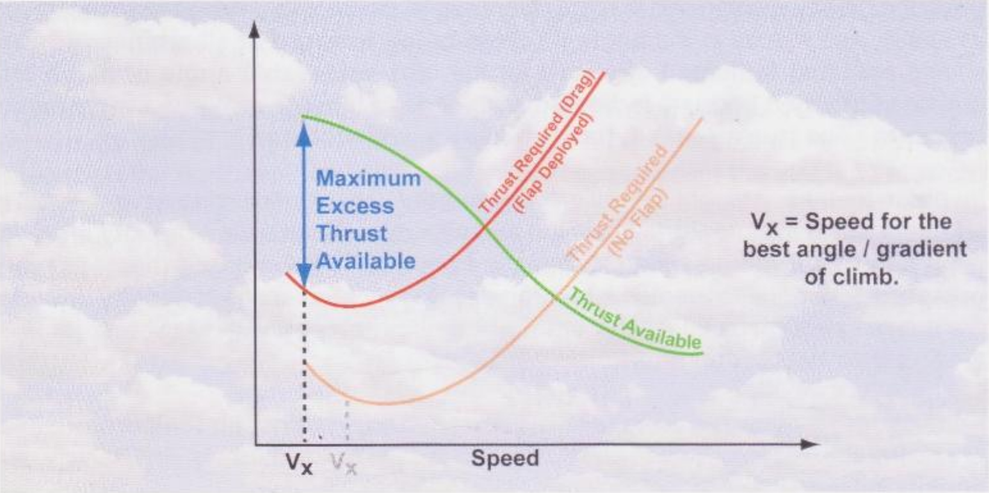


Figure 3.10 When parasite drag is increased, the thrust required curve moves upwards, best climb angle is reduced, and V_X *is lower.*

With the undercarriage and/or flaps extended, V_X is lower and the best achievable **climb angle** is shallower. A pilot might conclude, therefore, that, on take-off, it would be prudent not to deploy **flaps** so that the climb angle is as steep as possible. However, **flaps** do have a beneficial effect on take-off performance in the sense that they reduce the lift-off speed and the length of the take-off run. Consequently, **flaps** are often used for take-off, but are retracted in stages as soon as it is safe to do so, in order to increase the **angle of climb** as soon as possible.

The **Pilot's Operating Manual** should be consulted for flap retraction speeds.

Density.

As you have already learnt in the chapter on **Take-Off**, both **propeller thrust** and **engine power** are affected by the **density of the air** in which an aircraft flies. A decrease in **air density** will reduce **propeller thrust** available.

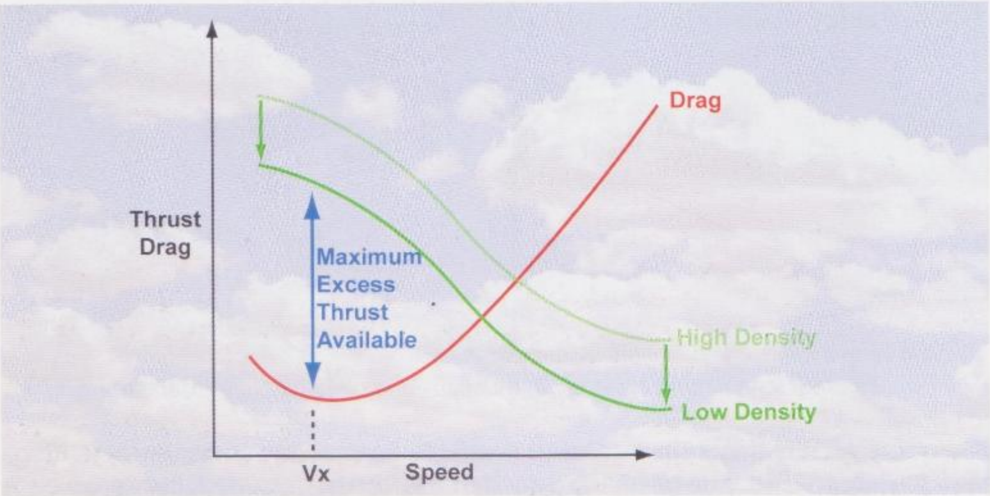


Figure 3.11 A decrease in air density will reduce propeller thrust, and reduce the excess thrust available..

From the graph, you can see that the **decrease in air density**, reduces excess thrust available, and results in the **angle of climb being reduced at all airspeeds**. You should note that **indicated airspeed** for the best **achievable angle of climb** will remain unchanged because **indicated airspeed** is a function of $\frac{1}{2}\rho v^2$, the **dynamic pressure**. The **true airspeed, for V_X however, will increase**.

In order to take into consideration **air density** when calculating your aircraft's performance, a pilot needs to know the aircraft's **density altitude**. **Density altitude** is **pressure altitude** (i.e. vertical distance from the **1013.2 millibar (hectopascal) pressure** datum line) corrected for **air temperature**. Calculations of **density altitude** are easy to perform using a standard **flight navigation computer**. (See **Volume 3** of this series **Navigation and Radio Aids**.)

Normally, however, when using **take-off performance graphs**, **air temperature** and **pressure altitude** information is entered into the graphs separately. In this way, **air density** is taken into account.

A headwind increases the angle of climb with respect to the ground; a tailwind reduces it.

Wind Speed and Direction.

Up until now in this Chapter, we have been considering **angle of climb** with respect to the air in which the aircraft is flying. But any aircraft's **angle of climb with respect to the ground** is also affected by **wind speed and direction**, namely, the **headwind** and **tailwind component**. **Climb angle** with respect to the ground will steepen when flying into a **headwind** and be more shallow with **tailwind**. This topic has already been covered in Chapter 2: **Take-Off**. (*See Figure 3.12.*)

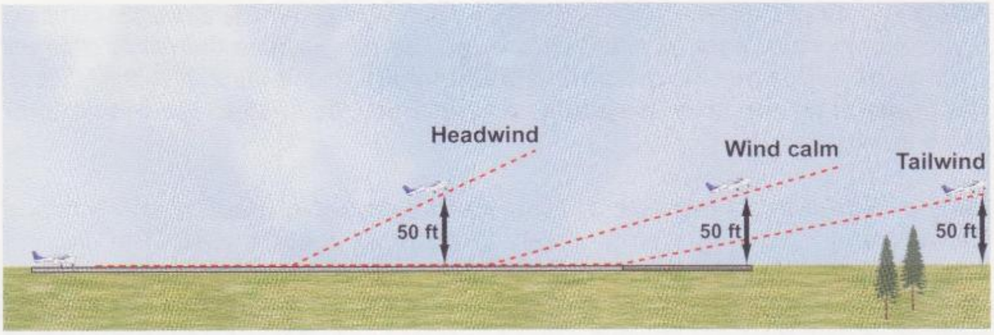


Figure 3.12 Relative to the ground, headwinds increase climb angle and tailwinds decrease climb angle.

The best rate of climb will cause the aircraft to gain the maximum height in the least amount of time.

RATE OF CLIMB.

Achieving the best possible **angle of climb** is of great importance when considering an aircraft's **obstacle clearance performance**. But, often, following take-off, a pilot's principal concern is to climb to the **cruising altitude** as **rapidly** as possible. If this is so, then the pilot is more concerned with achieving the best **rate of climb**, rather than the best **angle of climb**.

There is an important difference between **rate of climb** and **angle of climb**. The **rate** at which an aircraft gains height depends both on the **angle of (or gradient) of his flight path** and on its **forward speed along that path**. As you may imagine, an aircraft may climb slowly at a fairly steep angle or at high speed at a fairly shallow angle. For any given aircraft, however, there is **one combination of speed and angle of climb**, in other words of **speed along a climbing flight path**, which will permit the aircraft to increase its height by the greatest amount in a given amount of time. This will be the aircraft's best **rate of climb**.

Figure 3.13 attempts to depict the concept of **best rate of climb**. The vertical axis represents gain of height in feet, and the horizontal axis represents airspeed. The speeds on the horizontal axis, below each aircraft, represent the airspeed at which that aircraft is flying. The aircraft on the middle sloping line, climbing at 75 knots, has made the greatest gain of height even though the aircraft on the left is climbing at a steeper angle, at a lower speed, and the aircraft on the right is climbing at a higher

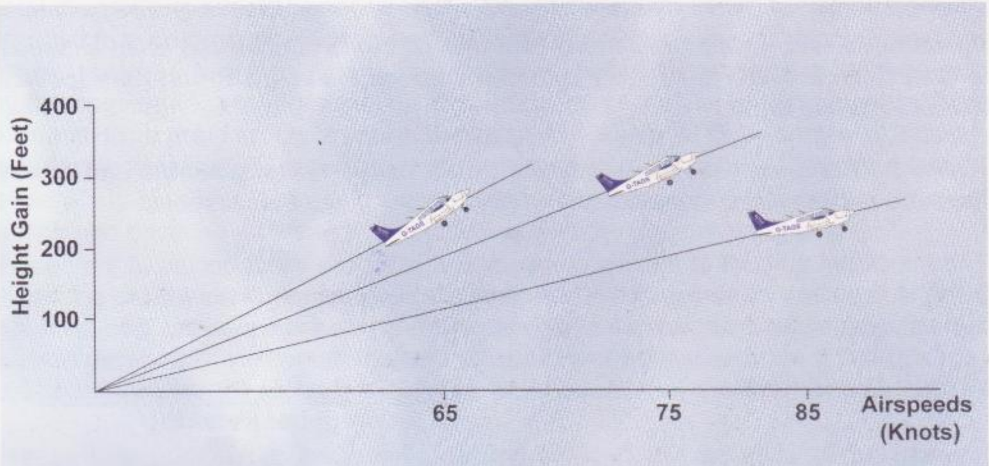


Figure 3.13 Climb performance at different speeds.

airspeed, but at a shallower angle. The speed at which the middle aircraft is climbing represents the **best rate of climb of speed**. We can assume that all aircraft are climbing **at full power**, so the **pitch attitude** of the middle aircraft is the attitude which, **at full power**, gives the **angle of attack** required to attain the **best rate of climb speed**.

Rate of Climb is a Function of Excess Power Available.

We have learnt that **angle of climb** is a function of **excess thrust**. The diagram which illustrates the concept of **angle of climb** is a force diagram, which resolves forwards and rearwards acting forces. (*See Figure 3.4.*) However, **rate of climb** is a question of both **thrust** to achieve a given **gradient of climb** and **speed along that gradient**. **Rate of climb**, then, is a function of **excess thrust multiplied by velocity**. In other words, **rate of climb** is a function of **excess horsepower.** You may recall from your **Physics** lessons that **power is the rate at which work is done**.

Work = Force × Distance

$$\text{Power} = \frac{\text{Work}}{\text{Time Taken}}$$

$$\text{Power} = \frac{\text{Force} \times \text{Distance}}{\text{Time Taken}}$$

Power = Force × Speed

And, as force produced by a propeller is known as thrust,

Power = thrust × speed

To lift an aircraft weighing **2000lbs** to **4000ft** requires **2000 × 4000 = 8 000 000 ft-lbs of work**. For a **2000lb** aircraft to climb to **4000ft** in **8 minutes** would require work to be done at the rate of **1 000 000 foot-lb/min**. Now **33 000 ft-lbs/min** is defined as **One Horse Power**; so the power required to lift a **2000lb** aircraft to **4000ft** in **8 mins** is $\frac{1\,000\,000}{33\,000}$. **30.3 Horse Power**, approximately.

To summarise, then, the aircraft's **maximum rate of climb** is achieved at a **gradient** that is **slightly less steep** than that giving its **maximum angle of climb**, but at **slightly higher airspeed**.

As we have said, an aircraft's **maximum rate of climb** is achieved at an airspeed in level flight, at which there is a **maximum amount of excess thrust horsepower** available for the climb.

Figure 3.14 is a representative graph of **thrust horsepower available** and **thrust horsepower required** to maintain level flight at any given true airspeed.

The maximum amount of excess power available for the climb occurs at the speed at which the distance between the two curves is the greatest. If we wish to calculate the achievable vertical speed of an aircraft, we may use the equation:

$$\text{Vertical Speed (feet/min)} = \frac{33\,000 \times \text{Excess Power Available}}{\text{Weight of aircraft}}$$

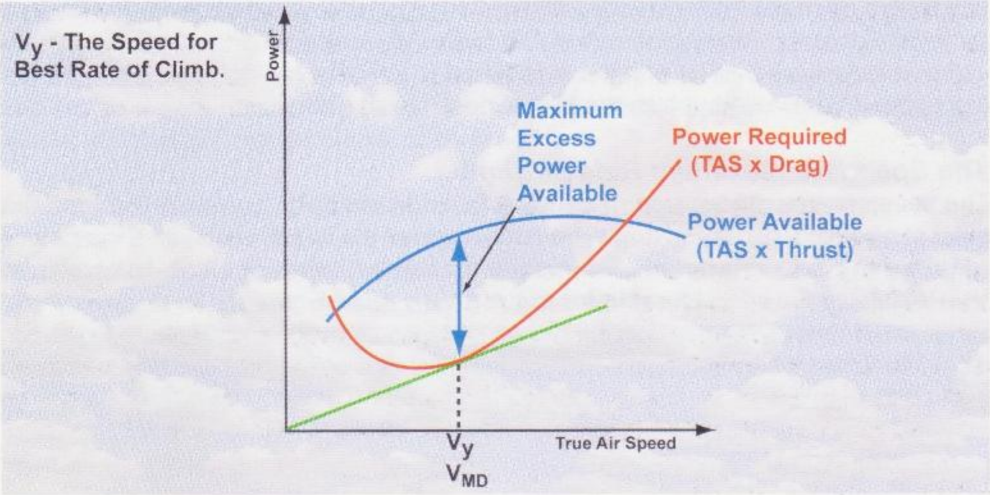


Figure 3.14 The speed for maximum rate of climb is the speed at which there is the maximum excess of power available over power required for level flight at that speed. This speed is known as V_Y.

The speed for maximum rate of climb is the speed at which there is the maximum excess of power available over power required for level flight at that speed. This speed is known as V_Y.

For instance, in the case we have just considered of the aircraft weighing **2000lbs** climbing to **4000ft** in **8 minutes**, which required an excess thrust horsepower of **30.3 HP**, the equation may be written as:

$$\textbf{Vertical Speed (ft/min)} = \frac{33\,000 \times 30.3}{2000} = 500 \text{ ft/min}$$

Which is what we would expect as **4000 ft** is reached in **8 minutes**.

The Power Available and Power Required Curve.

The method of deriving the **power available curve** in the graph at *Figure 3.14* requires a knowledge of power output of the internal combustion engine which goes beyond the scope of this book. The power **available curve** is basically an expression of power available after the power losses arising from the inefficiency of the propeller have been deducted from engine power output.

The **power required curve** is derived from the **total drag curve** for the aircraft. Total drag at any aircraft speed is multiplied by the speed, itself, to give the power required to overcome drag and to maintain level flight. You may ask yourself why the **power required graph** in *Figure 3.14* indicates that high power must be delivered by the engine-propeller combination at low speeds as well as at high speeds. The explanation is that, at low speeds, the aircraft is flying at high angles of attack, resulting in high values of **induced drag** despite the low speed. At high speeds, angle of attack is small, but, of course, **parasite drag** is very high because airspeed is high and because **parasite drag** increases with the square of the airspeed.

When the **power available curve** is above the **power required curve**, level flight is possible, and, as we have seen, at the speed where the vertical distance between the two curves is the greatest, the **rate of climb will be a maximum if full throttle is applied and a pitch attitude selected to maintain that speed**.

The outside portions of the graph, beyond the two intersections of the **power available** and **power required curves**, indicate speeds at which level flight is impossible because, at those speeds, whether high or low, more power is required for level flight than the engine can deliver. The two intersections of the two power curves also reveal that full throttle is required to achieve not only the highest level flight speed attainable but also the lowest possible level flight speed.

The Speed for Maximum Rate of Climb.

The speed for **maximum rate of climb** is found by dropping a vertical line from the point at which a straight line drawn from the origin of the two axes touches the **power required curve** at a **tangent**. **The speed for the best rate of climb is known as V_Y. V_Y** is also the speed for **minimum drag V_{MD}**. *(See Figure 3.15).*

V_Y is the speed at which to fly to obtain the best rate of climb. V_Y for the PA-28 Warrior, up to 5000 feet, is 75 knots indicated air speed.

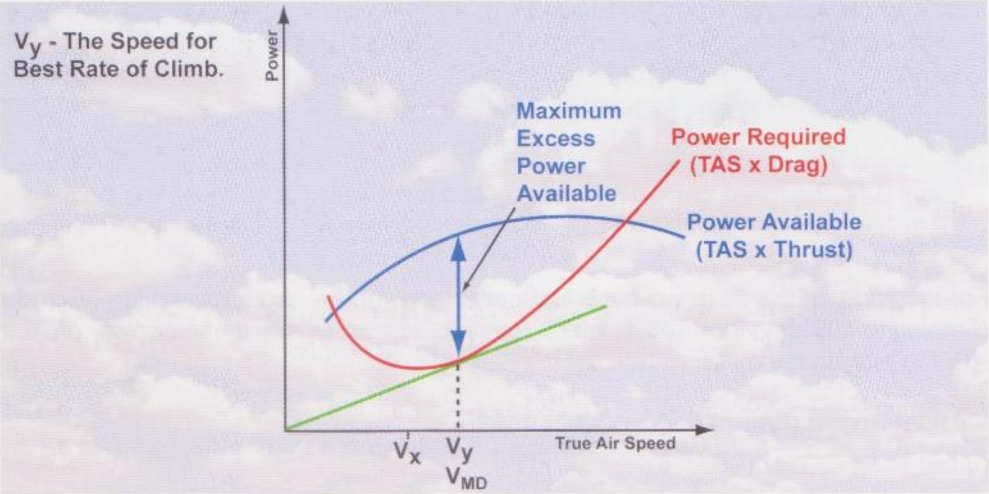


Figure 3.15 The best rate of climb speed, V_Y, is also the speed for minimum drag, V_{MD}.

You should note that because **thrust** and **power** are not the same thing, the airspeed at which **maximum excess thrust** is available (**V_X**) is not the same as the airspeed where **maximum excess thrust horsepower** is available (V_Y). Remember that **thrust from a fixed-pitch propeller is maximum at full throttle with the aircraft stationary**. By the time **V_{MD}** is reached, **propeller thrust** will have begun to decrease, so **maximum excess thrust** available occurs at a lower airspeed than **V_{MD}**. **V_X** for the **PA28-161 Warrior** is **65 knots**. **V_Y** for the **PA28-161 Warrior** is **75 knots**.

The manufacturer's recommended best rate of climb speed is often slightly higher than V_Y so that the airflow over the engine is sufficient for effective cooling.

V_Y, then, is the speed to fly when seeking to achieve the **maximum height gain in the shortest possible time**. Nevertheless, some Pilot's Operating Manuals may give a speed slightly higher than V_Y as an aircraft's **best rate of climb speed** because a slightly higher speed ensures a more satisfactory cooling effect on the engine at the high power settings and relatively low speeds used in the climb. If a pilot sees that cylinder head temperature and engine-oil temperature are approaching their upper limits in the climb, he should increase speed.

Factors Affecting Rate of Climb.

Aircraft Weight.

The higher an aircraft's all-up weight (mass) the lower the rate of climb.

As you have already learnt, the greater an aircraft's **all–up weight**, the greater the **lift** required to maintain level flight at any speed. At a given speed, unless flap is lowered (and we will assume here that it is not), **lift** can be increased only by increasing **angle of attack**. An increase in **angle of attack** will increase **induced drag**, and so, at any given speed, **more thrust is required to maintain level flight than for a lighter**

aircraft. If more **thrust** is required to maintain a given speed then more **power** is required, too, leaving less **excess power** available to achieve a desired **rate of climb**. This situation holds for all speeds; **consequently, an increase in weight will cause a decrease in the maximum rate of climb**. Conversely, a decrease in weight will improve **rate of climb**, at all speeds.

Also, as we have seen in the diagrams illustrating angle of climb, a climb at any angle with a heavier aircraft will lead to an increase in the weight component acting rearwards (the so-called **weight-apparent drag**). As the **maximum rate of climb** is achieved at a given combination of speed of climb and angle of climb, **weight apparent drag** will always be a factor. **An increase in weight apparent drag leaves less power available for the climb, again decreasing rate of climb at all speeds**.

The following equation for **rate of climb** that you met earlier in this chapter:

$$\text{Rate of climb in feet per minute} = \frac{33000 \times \text{Excess Power Available}}{\text{Weight}}$$

clearly shows that **an increase in weight decreases rate of climb**. The calculation that we made earlier to illustrate the use of this equation involved a **2000 lb** aircraft with an **excess of power available** of **30.3 Horsepower**, climbing **4000 feet** in **8 minutes**, at a rate of climb of **500 feet per minute**. If we increased the aircraft's weight to **2 300 lb**. the equation shows us that rate of climb will decrease. Substituting the new figures into the equation, we obtain:

$$\text{Rate of climb in feet per minute} = \frac{33000 \times 30.3}{2\,300} = 435 \text{ feet per minute}$$

At higher aircraft weights, then, the power required (drag × speed) for level flight is greater, for any airspeed. Minimum **drag**, and **power** required to balance that **drag**, is higher at the **greater weight**, and, in fact, **as weight increases**, the **power required curve** moves up and to the right, as depicted in *Figure 3.16*.

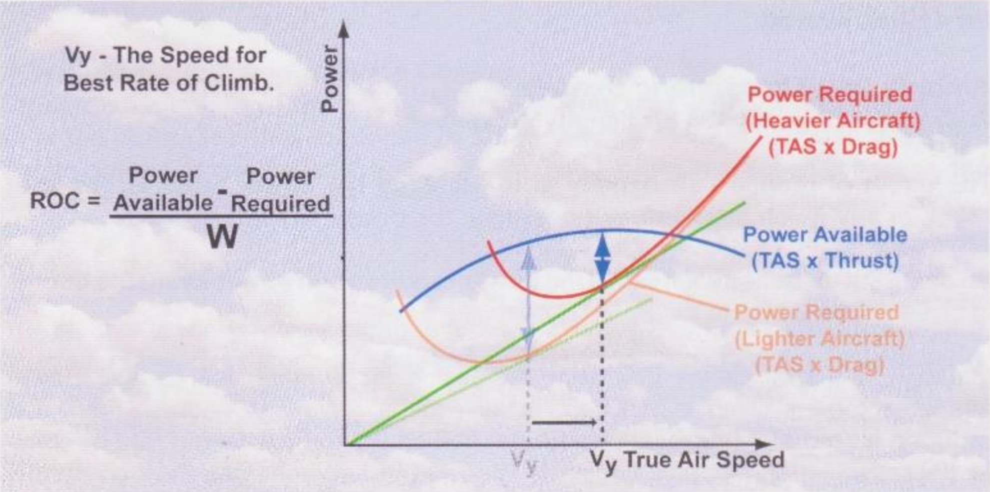


Figure 3.16 An increase in weight moves the power required curve up and to the right. Excess power available, and, thus, rate of climb reduce at all speeds.

The graph for the higher weight illustrates clearly that there is less excess power available for the climb, at any speed; so the maximum rate of climb decreases and V_Y, the speed for the best achievable rate of climb at the higher weight, increases.

Aircraft Configuration.

Let us now consider **the effect of flap on the rate of climb**. We have already seen in our treatment of angle of climb, that **deployment of flap increases drag at any speed** and, therefore, will reduce the amount, excess thrust and **excess power** available for the climb, at all speeds. Consequently, when flaps are deployed, the **power required curve**, which as you have learnt is derived for the **total drag curve**, will move upwards and to the left. (*See Figure 3.17.)*

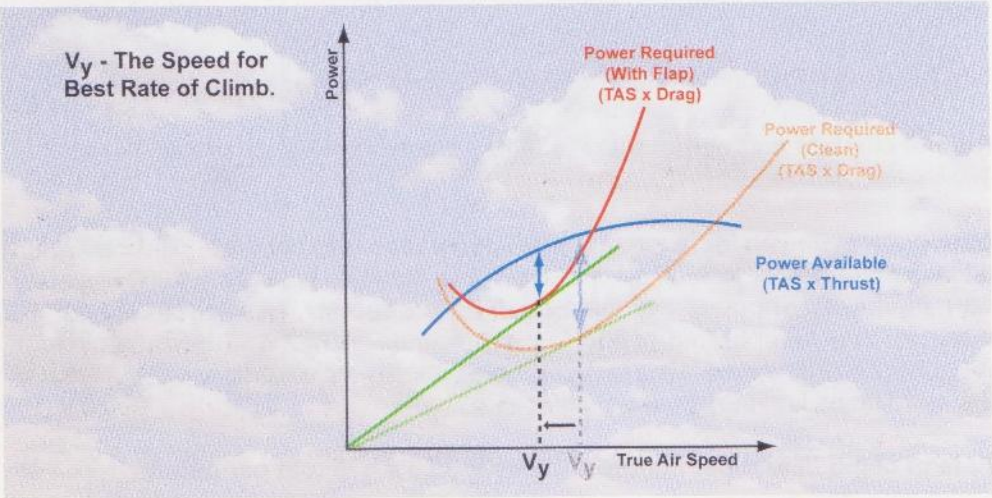


Figure 3.17 The extension of flap and/or undercarriage leads to an increase in parasite drag, causing the power required curve to move up and to the left.

With flap deployed, an aircraft's rate of climb and angle of climb will be reduced.

The graph clearly illustrates that the maximum excess power available, and, thus, maximum achievable rate of climb, decreases with flaps lowered. Furthermore, V_Y, the speed for the best <u>achievable</u> rate of climb is lower than for a clean aircraft.

Altitude and Atmospheric Density.

With increasing altitude, air density decreases.

The effect of reduced air density is to <u>increase</u> the power required for level flight, at any given airspeed, but <u>decrease</u> the power available.

So, reducing **air density** will cause the **power required** and **power available curves** to close up, as shown in *Figure 3.18, opposite.*

Figure 3.18 shows clearly that, with decreasing **air density**, the **excess power available** for the climb is reduced, at all speeds. We can deduce, then, that **reduced air density (increasing altitude) will cause the maximum rate of climb to decrease.** If an aircraft's engine is fitted with a turbo-charger, the decrease in climb performance with altitude can be delayed, but most light training aircraft are not turbo-charged.

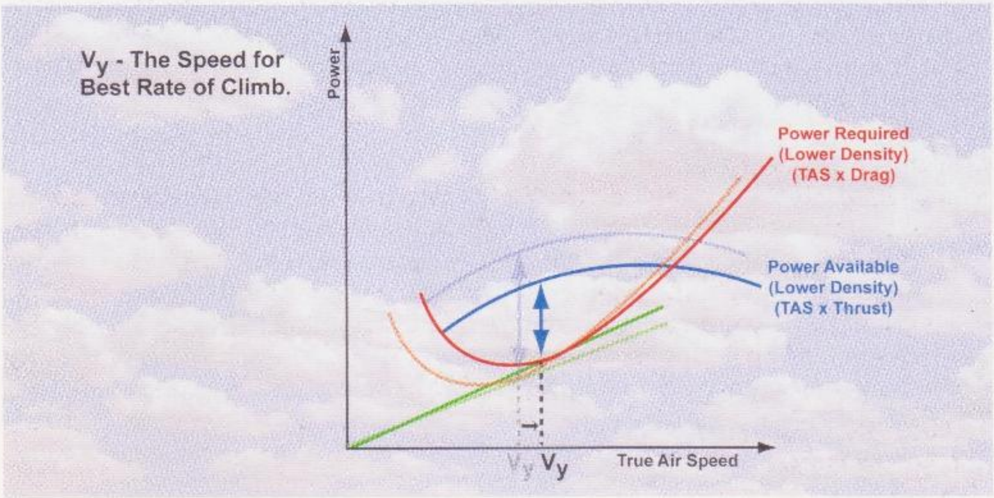


Figure 3.18 A reduction in density reduces the power available and increases the power required, therefore decreasing the Excess Power Available and the Rate of Climb. The Airspeed V_Y *for the best achievable Rate of Climb is higher.*

You can also see from the graph that **speed for the best achievable rate of climb is higher at the lower density**. However, it is important to grasp that the speeds used in the **power available/power required graphs** are **true airspeeds**, whereas the speed that the pilot reads from his **ASI** is **indicated airspeed**. **At lower air densities, the indicated airspeed for best rate of climb, which is, itself, a function of the air density element of dynamic pressure (dynamic pressure = ½ ρv^2), will decrease.**

The indicated airspeed for the best achievable rate of climb will decrease with increasing altitude, but the true airspeed increases.

As an aircraft climbs, therefore, the pilot who strives to maintain the **best rate of climb** perceives that he must fly at constantly reducing indicated airspeeds in order to optimise performance. **In practice, though, a single recommended climbing speed is used within specific height bands**. For example the **best rate of climb** for the **PA28-161 Warrior's** is obtained at **75 kts** up to **5000 ft**, at **70 knots** up to its operating ceiling of **10 000 ft**, and then at **65 knots** to its service ceiling of about **15 000 feet**.

Absolute Ceiling and Service Ceiling.

Closer examination of the power curves reveals that, with increasing altitude (it is the corresponding reduction in air density, of course, which is decisive), the minimum possible true airspeed for level flight increases whereas the maximum level flight speed decreases. Eventually, then, an altitude is reached where there is only one possible speed for level flight. At this altitude excess power is nil, and therefore the rate of climb is zero. (*See Figure 3.19, overleaf.*)

The altitude at which **rate of climb** reduces to zero is the aircraft's **absolute ceiling**. If an aircraft were to reach its **absolute ceiling**, it could carry out no manoeuvres. This fact, and because it would take a very long time for the aircraft to struggle up to its **absolute ceiling**, makes the **absolute ceiling** fairly meaningless for practical purposes. Therefore, in the **Pilot's Operating Handbook**, it is usual to see the aircraft's **service ceiling** referred to. An aircraft's **service ceiling** is the altitude at which the aircraft's **maximum rate of climb** reduces to **100 feet per minute**. The **service ceiling** for the **PA28-161 Warrior** is around **15 000 feet**.

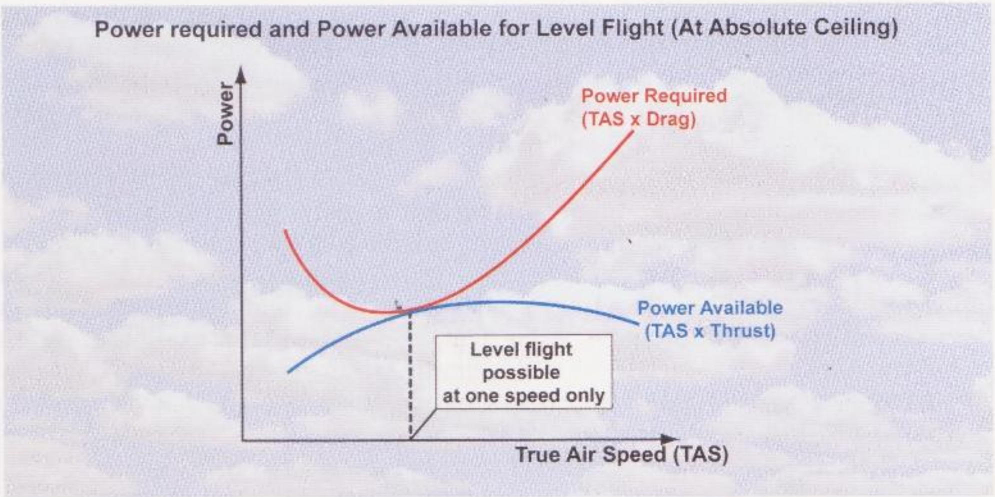


Figure 3.19 Eventually , an altitude is reached where there is only one possible speed for level flight and where the rate of climb has reduced to zero. This altitude is the aircraft's absolute ceiling.

There is, of course, no necessity for the pilot always to climb the aircraft at the **best rate of climb speed** or the **best angle of climb speed**. There may be no operational or flight safety reason for a pilot to gain altitude as quickly as possible. A pilot may choose, for instance, to climb en route after having set the heading for the first leg of a cross country flight. This type of climb is often called a **cruise climb**. In the **cruise climb**, the nose of the aircraft will be lower than for **best angle or rate of climb**, giving the pilot a better view ahead. For the Warrior the recommended **cruise climb speed** is **90 knots**, with full power selected.

CALCULATING AN AIRCRAFT'S CLIMB PERFORMANCE.

The calculations of the actual **climb performance** that a pilot can expect on a given day, flying from a known airfield, are carried out using the **performance tables or graphs** in the **Pilot's Operating Handbook (POH)** for the aircraft to be flown. Using the information from the **POH**, a pilot may calculate such values as expected **rate of climb**, **fuel consumed in the climb** to a given height or cruising altitude, and **horizontal distance covered** in the climb.

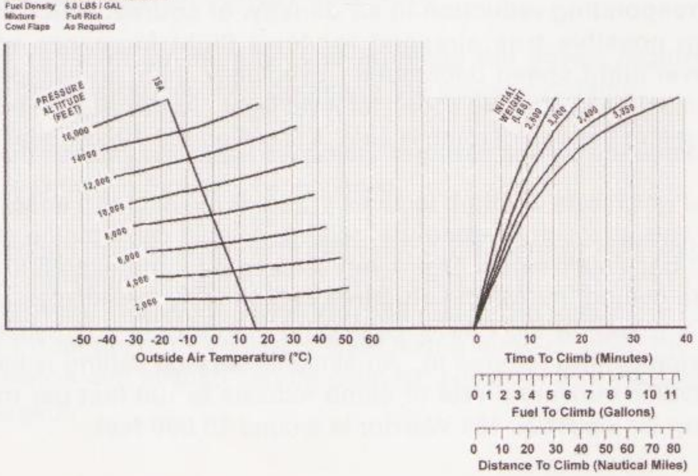


Figure 3.20 A representative climb performance graph.

In the example overleaf, we are going to calculate the values that we have just mentioned using a representative **climb performance graph** of the type represented in *Figure 3.20*. Note that the **time to height** gives us an **average rate of climb**, while the **horizontal distance covered** would enable us, if we wished, to calculate the **mean angle of climb**.

Note, too, that no wind information can be entered into the graph. Therefore, any estimation of angle of climb would have to assume zero wind, and be adjusted to allow for prevailing wind conditions.

As with most **performance graphs**, the **climb graph** assumes that atmospheric conditions are those of the **ICAO Standard Atmosphere (ISA)**. Furthermore, the **climb graph** is **unfactored**. You will recall that the term **unfactored** means that the graph makes no allowance for varying degrees of pilot proficiency or for any mechanical or aerodynamic deterioration of the aircraft. The climb graph also assumes that the climb will be made at **full throttle**, with **mixture fully rich**.

The method used to calculate the desired performance figures from the **climb graph** is first to consider standard values for the **cruise altitude** to which we wish to climb. So the first variables to consider are the **cruise pressure altitude** and the **outside air temperature** at the **cruising altitude**. We are, thus, effectively considering the **density altitude** to which we wish to climb. These considerations give us the **air density** conditions at the required altitude.

In following this graphical method, the assumption is that the aircraft is climbing from sea-level; (**ISA sea-level conditions prevailing**, of course.). Consequently, it is necessary to amend the performance figures extracted from the graph in the case of a climb begun from an airfield situated at a level other than **ISA sea-level**. This is done by subtracting from the first set of figures, values for the altitude of the airfield from which the aircraft took off.

Example of a Climb Calculation using a Climb Performance Graph.

We will assume that we wish to take-off from an airfield whose **pressure altitude** we have already calculated to be **4 000 feet**; (i.e. **4 000 feet** above the **1013.2 millibars** (hectopascals) pressure datum). Our aircraft's **all-up weight** is to be **3 650 lb** and the **outside air temperature** is **20° Celsius**. We wish to climb to **Flight Level 100** where the **temperature** is forecast to be **0° Celsius**. We immediately realize that we do not have to calculate a **pressure altitude** for a **Flight Level**. **All Flight Levels are measured from the Standard Pressure Setting**. So, **Flight Level 100** is **10 000 feet** above the **1013.2 millibars** (hectopascals) pressure datum.

We wish to calculate **how long** it will take us to climb to **FL 100**, **how much fuel we will use** and what **horizontal distance we will cover in the climb**. We will begin by entering the values for the conditions prevailing at **Flight Level 100**, the level to which we wish to climb. The process we are using is illustrated on the **climb performance graph** at *Figure 3.21, opposite*.

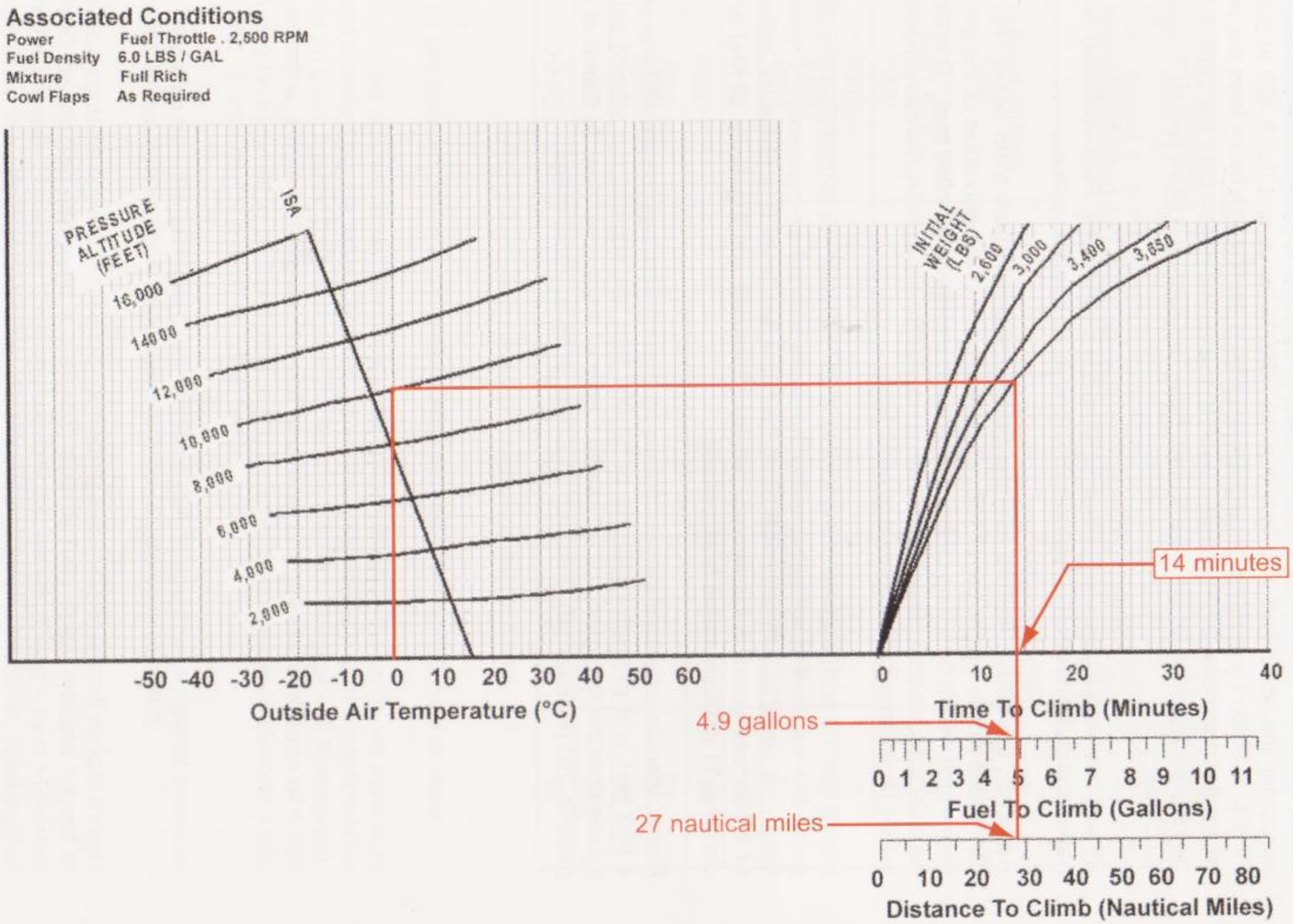


Figure 3.21 Time taken, fuel used and distance covered from sea level to a pressure altitude of 10 000 feet (Flight Level 100).

Locating the **temperature** forecast for **Flight Level 100**, **0° Celsius**, we draw a line vertically upwards until we meet the curve of the **10 000 feet pressure altitude**. From that point, we draw a horizontal line across to meet the curve for our aircraft's **weight** of **3650 lb**. We are fortunate to have on the graph a curve for that precise value, but if our aircraft had weighed, say, 3 500 lbs, we would have ended our horizontal line about half way between the 3650 lb curve and the 3 400 lb curve. Finally, in Stage One of our calculation, we drop a vertical line down from the point where the horizontal line meets the **3650 lb curve** and note where the vertical line intersects the scales for **Time To Climb**, **Fuel To Climb** and **(Horizontal) Distance To Climb**.

As you see from *Figure 3.21*, **Time To Climb** is **14 minutes**, **Fuel To Climb** is **4.9 gallons** and **(Horizontal) Distance To Climb** is **27 nautical miles**.

However, the above figures assume that we wish to climb from sea-level (i.e. ISA sea-level) to Flight Level 100. But we know that the **elevation** of the airfield from which we will be taking off lies at a **pressure altitude of 4 000 feet**. Therefore, we must subtract from the values already extracted from the graph, the corresponding values for a climb from **sea-level** to **4000 feet**.

Noting that the **temperature** at the airfield is **20° Celsius**, we extract from the climb graph the values that we need, using the same method as previously. From the Graph we see that a hypothetical climb from **ISA sea-level** to a **pressure altitude of 4 000 feet** would, in our aircraft, require **5 minutes** and **2 gallons of fuel** while covering **11 nautical miles horizontally**.

Finally, then, in order to obtain our figures for a climb from a **pressure altitude of 4 000 feet** to a **pressure altitude of 10 000 feet**, we subtract the second set of figures from the first, giving us a **Time To Climb of 9 minutes**, **Fuel To Climb of 2.9 gallons** and **(Horizontal) Distance To Climb of 16 nautical miles**.

Example of a Climb Calculation using a Climb Performance Table.

You may find that the climb performance figures pertaining to your aircraft are available only in **tabular form**, though **tables** are more commonly found in examination papers than in **Pilot's Operating Handbooks**. A representative table containing flight performance figures is depicted overleaf in *Figure 3.21*.

FUEL, TIME and DISTANCE TO CLIMB

Associated Conditions
Weight: 2440 Lbs, **Flaps:** 0°, **Full Throttle**
Mixture leaned as per maker's instructions
79 Knots, indicated airspeed. No Wind

FOR TRAINING PURPOSES ONLY

Pressure Altitude Feet	ISA Temp °C	From Sea Level Time in Minutes	Fuel used Gallons	Distance
Sea Level	15	0	0	0
1000	13	2	0.4	2
2000	11	4	0.7	5
3000	9	6	1.5	8
4000	7	8	1.8	11
5000	5	10	2.0	14
6000	3	13	2.5	17
7000	1	16	3	21
8000	-1	19	4	27
9000	-3	24	5	34
10 000	-5	30	6	42

Figure 3.21 Climb performance figures in tabular format.

Let us see how we derive climb performance information from this type of **table**.

First of all we notice that we cannot enter any information into the **table**, we must read figures directly from the **table**. We may, however, **interpolate** (i.e. make estimations based on given figures) for pressure altitudes which do not coincide with those given. For example, **a time to height from ISA sea-level to a pressure altitude of 4 500 feet** may be deduced to be **9 minutes**; (lying between 8 minutes for a climb to 4 000 feet and 10 minutes for a climb to 5 000 feet).

We note also that the table`contains standard **ISA** temperatures against pressure altitudes, so we cannot allow for temperature deviations from standard.

The table contains several associated conditions, assuming an aircraft **weight** (mass) of **2440 lbs**, **no flap deployed**, a climb with **throttle fully open**, **mixture leaned in accordance with the maker's recommendations**, **no wind**, and a **best indicated airspeed for the climb of 79 knots**. We take note of these conditions, knowing that we have to make allowance for any variation from the conditions stipulated.

So, let us assume that we wish to estimate **how long** it would take us to climb from an airfield lying at a **pressure altitude** of **1000 feet**, on a given day, to a **pressure**

altitude of **6 000 feet**. We wish to know, too, **how much fuel** we will consume in the climb and what **horizontal distance** we would cover, assuming no wind.
Firstly, we can read directly from the chart the figures for a climb to **6 000 feet** from **sea-level**. **Time** would be **13 minutes**, **fuel consumed** would be **2.5 gallons, and horizontal distance covered** would be **17 miles**.

But we are taking off from an airfield lying at a pressure altitude of 1000 feet. Therefore, we must <u>subtract</u> the figures for a hypothetical climb from sea-level to 1000 feet from the above figures for the climb from sea-level to 6 000 feet. From the graph, we see that **time to height**, **fuel consumed** and **horizontal distance covered** for the **hypothetical climb from sea-level to 1000 feet** are **2 minutes**, **0.4 gallons** and **2 miles**, respectively. Consequently, we **<u>subtract</u>** these figures from the earlier figures to obtain the required information for a climb from the airfield to a **pressure altitude** of **6 000 feet**. We calculate, then, that **the climb we are planning will take 11 minutes, consume 2.1 gallons of fuel and cover a horizontal distance of 15 miles assuming zero wind.**

Figure 3.22 illustrates another type of table you may come across.

<u>CLIMB PERFORMANCE</u>

Associated Conditions
Gross Weight: 2440 Lbs, **Full Throttle**
Lean Mixture per maker's instructions. 79 KIAS

FOR TRAINING PURPOSES ONLY

	Rate of Climb - Feet per Minute Outside Air Temperature - °C				
	-20°	-10°	0°	10°	20°
Sea Level	850	790	730	670	610
2000	730	670	610	560	500
4000	620	550	490	430	370
6000	490	430	360	310	250
8000	370	300	250	190	150
10 000	250	180	150	70	20

Figure 3.22 Climb performance figures in tabular format.

This type of table enables you to calculate **rate of climb** at various **pressure altitudes** and **outside air temperatures**. Having noted all the associated conditions, especially the recommended indicated airspeed for the climb, let us assume that we need to find the **rate of climb at 3000 feet**, if the **outside air temperature is +10° C**. Remember, the altitudes in the table are pressure altitudes. Examining the table, we see that in the **+10° C** column (notated simply as **10° C**) we find **rates of climb** of **560 feet per minute at 2 000 feet** and **430 feet per minute, at 4 000 feet**. It seems logical, then, that in order to estimate the **rate of climb at 3 000 feet**, we should take the **mean value of the rates of climb at 2 000 feet and 4 000 feet**, because the **rate of climb at 3 000 feet** will be between the two rates of climb given by the table. That difference is **130 feet per minute**. Half of that difference is **65 feet per minute**. We know that **the rate of climb that we are looking for lies between 560 feet per minute and 430 feet per minute.** We can, therefore, **add 65 feet per**

minute to the lower value or subtract it from the higher value. Either way, we arrive at **495 feet per minute**, which seems to be a sensible answer.

Conclusion.

Do not underestimate the importance of knowing what your aircraft's **climb performance** will be in a given set of circumstances. **It is the angle of climb which is the critical parameter for flight safety**, especially when combined with take-off considerations at an airfield surrounded by obstacles which must be cleared on the climb-out.

If you are to take-off from an upward-sloping wet grass strip, on a hot day, at a high airfield, at near your aircraft's maximum weight (mass), and with obstacles in your climb-out path, **it is vital that you have an accurate idea of what will be the take-off run required and your initial angle of climb**. Getting your performance figures wrong in such circumstances could lead to catastrophe.

Representative PPL - type questions to test your theoretical knowledge of the Climb.

1. From the table shown, extract the rate of climb for an aircraft operating at 5 000 feet with an outside air temperature of 0° C.

CLIMB PERFORMANCE

Associated Conditions
Gross Weight: 2440 Lbs, **Full Throttle**
Lean Mixture per maker's instructions. 79 KIAS

FOR TRAINING PURPOSES ONLY

	Rate of Climb - Feet per Minute Outside Air Temperature - °C				
	-20°	-10°	0°	10°	20°
Sea Level	850	790	730	670	610
2000	730	670	610	560	500
4000	620	550	490	430	370
6000	490	430	360	310	250
8000	370	300	250	190	150
10 000	250	180	150	70	20

Figure 3.23 Climb performance figures in tabular format.

a. 555 feet per minute
b. 425 feet per minute
c. 490 feet per minute
d. 295 feet per minute

2. To gain the greatest amount of height in the shortest time, an aircraft should be flown at:

a. 60 knots
[✓ b.] the best rate of climb speed (V_Y)
c. the best angle of climb speed (V_X)
d. at the speed for maximum endurance

3. The indicated air speed for the best rate of climb when climbing to an aircraft's service ceiling will tend to:

a. decrease then increase
b. remain the same
c. increase
[✓ d.] decrease

4. What is the reason for increasing the speed in a prolonged climb?

a. to maintain the best rate of climb
b. to reduce the noise of the aircraft in sensitive areas
[✓ c.] to increase the flow of air through the engine and keep it cool
d. to maintain the best angle of climb

5. The best rate of climb is achieved:

   a. when flying at the speed for maximum excess thrust available
   b. when climbing into wind
   c. when flying at $\mathbf{V_X}$
   d. when flying at the for maximum excess power available.

6. Climbing at $\mathbf{V_X}$ will achieve:

   a. the best time to height
   b. the greatest increase in altitude in a given time
   c. the maximum angle of climb
   d. the maximum horizontal distance for a given vertical distance

7. One effect of climbing an aircraft with flap selected would be:

   a. an improved climb performance
   b. a decreased co-efficient of drag
   c. a decreased co-efficient of lift
   d. a reduced rate and angle of climb

8. Increasing the mass (and, therefore, the weight) of an aircraft will:

   a. decrease the rate and angle of climb
   b. increase the rate and angle of climb
   c. increase the rate of climb and decrease the angle of climb
   d. decrease the rate of climb and increase the angle of climb

9. Climbing at $\mathbf{V_Y}$ will achieve:

   a. the maximum angle of climb
   b. the greatest increase in altitude in a given period of time
   c. the maximum increase in height in the shortest horizontal distance
   d. the best obstacle clearance performance

10. An aircraft cruising at a pressure altitude 2 000 feet is cleared to climb to a pressure altitude 8 000 feet. Using the table, calculate the time taken in minutes, the fuel used in gallons and the horizontal distance flown in the climb, assuming zero wind.

FUEL, TIME and DISTANCE TO CLIMB

Associated Conditions
Weight: 2440 Lbs, **Flaps:** 0°, **Full Throttle**
Mixture leaned as per maker's instructions
79 Knots, indicated airspeed. No Wind

FOR TRAINING PURPOSES ONLY

Pressure Altitude Feet	ISA Temp °C	From Sea Level		
		Time in Minutes	Fuel used Gallons	Distance
Sea Level	15	0	0	0
1000	13	2	0.4	2
2000	11	4	0.7	5
3000	9	6	1.5	8
4000	7	8	1.8	11
5000	5	10	2.0	14
6000	3	13	2.5	17
7000	1	16	3	21
8000	-1	19	4	27
9000	-3	24	5	34
10 000	-5	30	6	42

Figure 3.24 Climb performance figures in tabular format.

a. 19 minutes, 4 gallons, 27 miles
b. 23 minutes, 4.07 gallons, 32 miles
c. 15 minutes, 3.3 gallons, 22 miles
d. 4 minutes, 0.7 gallons, 5 miles

11. The lift produced by the wing of an aircraft in a steady climb maintaining a constant indicated airspeed will be:

a. less than weight
b. greater than weight
c. equal to weight
d. independent of weight

12. How will an aircraft's maximum rate of climb be affected by selecting take-off flap?

    a. The maximum rate of climb will increase
    b. The maximum rate of climb will not be affected
    c. The maximum rate of climb will remain the same provided that the pilot chooses an appropriate power setting
    d. The maximum rate of climb will decrease

13. What effect will a decreasing headwind component have on the best achievable angle of climb.

    a. The angle of climb will decrease
    b. The angle of climb will steepen
    c. The angle of climb will remain constant at all values of headwind component.
    d. The angle of climb is independent of the value of headwind component.

Question	1	2	3	4	5	6	7	8	9	10	11	12
Answer												

Question	13
Answer	

The answers to these questions can be found at the end of this book.

CHAPTER 4
EN-ROUTE PERFORMANCE

INTRODUCTION.

This chapter deals with the performance of an aircraft in the **en-route phase** of flight. The **en-route phase** of flight includes **climb to cruising altitude**, the **cruise** itself, and the **initial descent**. Chapter 3 covered the **climb** in detail, so, in this chapter, we will deal with the **cruise** and the **initial descent**. We begin with the **cruise**.

Cruise performance is generally measured in terms of an aircraft's **range**, **fuel consumption** and **endurance**. But, first of all, we will consider the forces acting on an aircraft in the **cruise**, assuming **straight and level flight, at constant speed**.

FORCES ACTING ON AN AIRCRAFT IN THE CRUISE.

You learnt in **Chapter 9** of the **Principles of Flight** section of this volume, that, for an aircraft to be in **steady**, **straight flight**, **all forces acting on the aircraft, and any turning moments to which the aircraft is subjected, must balance one another**. In other words, for **steady**, **straight flight**, **the forces, and moments** acting on the aircraft must be in a state of **equilibrium**.

Chapter 9 explained that because of the disposition of the principal flight forces of **thrust**, **drag**, **lift** and **weight**, and the movement of their lines of action during flight, the **turning moments** produced by the **thrust-drag force couple** and the **lift-weight force couple** are very rarely in balance. For instance, in *Figure 4.1, below,* both the **thrust-drag** and **lift-weight couples** reinforce each other to give a **nose-down pitching moment.** Consequently, in this case, a downwards-acting force must be generated by the **tailplane** or **stabilator** to achieve **equilibrium**. (*See Figure 4.1.*)

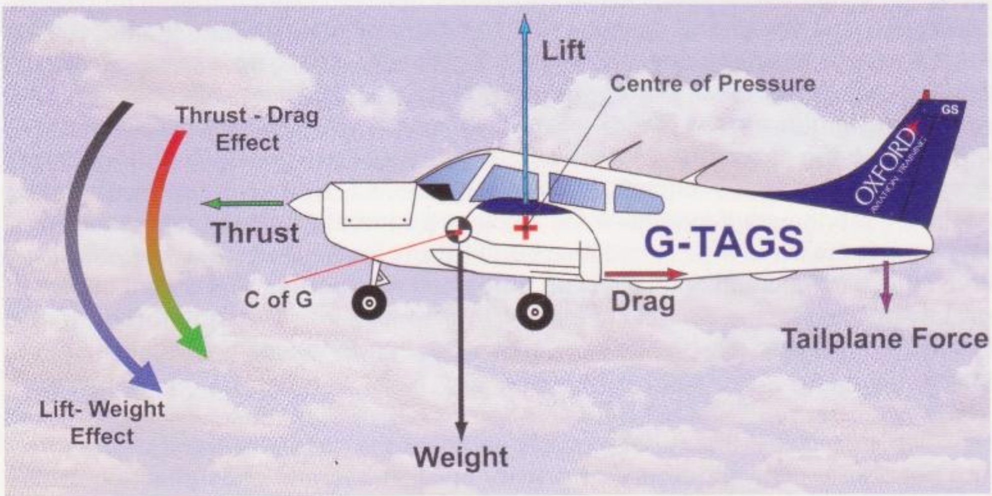


Figure 4.1 A tailplane force is required to balance the Thrust-Drag and Lift-Weight Couples.

The magnitude and direction of the **tailplane force** is under the control of the pilot through his manipulation of the control column in the fore and aft directions. The fact that the pilot has control over the **tailplane force** means that **equilibrium** may be maintained for all conditions of straight and steady flight, and, by trimming the aircraft correctly, the pilot can put the aircraft in **equilibrium** and fly it without having to apply any force to the control column.

Straight and level flight at constant speed, the flight condition for the cruise, is a special case of steady straight flight where altitude is maintained constant. So, in the cruise, all the forces acting on the aircraft will be in equilibrium. In straight and level flight at constant speed, **thrust** will be balanced by **drag**, and the **upwards acting forces** will be balanced by the **downwards acting forces**. The **tailplane force** may act upwards or downwards depending on aircraft type and flight condition, so the **upwards acting forces** may comprise **lift plus the tailplane force** or **lift minus the tailplane force** (as in the case in *Figure 4.1*) and the **downwards acting forces** may comprise **weight plus the tailplane force** (as in the case in *Figure 4.1*) or **weight minus the tailplane force**.

Any **tailplane force** which increases the total drag acting on the aircraft will have an adverse effect on performance. A **tailplane downforce**, because it acts in the same direction as **weight**, also adds to the aircraft's effective **weight** and requires the wings to produce extra **lift**, thus increasing **induced drag**. A decrease in **tailplane downforce**, on the other hand, will lead to a reduction in the **lift** force required to balance it, resulting in a corresponding reduction in **induced drag**.

Any tailplane force required to maintain an aircraft in equilibrium will generate increased drag. A tailplane down-force will also increase an aircraft's effective weight. Any tailplane force, then, will reduce range and endurance.

But, as we have already learned, **any increase in drag requires more power and thrust to be generated to maintain level flight at any speed**. Consequently, any amount **of tailplane force**, acting either upwards or downwards, required to maintain an aircraft in **equilibrium**, will affect **range**, **endurance** and **rate of fuel consumption**. **An increase in tailplane force will always reduce range and endurance, and increase rate of fuel consumption**.

As you learnt elsewhere, in **Volume 5** on **Aeroplanes and Mass & Balance**, the position of the **centre of gravity** of the aircraft, along the aircraft's longitudinal axis, will affect the amount of **tailplane force** required to maintain **equilibrium** at any speed, because, since the aircraft rotates about its **centre of gravity** when it manoeuvres, the tailplane's **moment arm** changes in length with changing **centre of gravity** position. The position of the **centre of gravity** will, therefore, affect an aircraft's **range** and **endurance**. The exact effect of **centre of gravity** position depends on aircraft type, especially whether an aircraft is low or high wing. But, generally speaking, for the type of aircraft depicted in *Figure 4.1,* a forward **centre of gravity** position even though it lengthens the tailplane's **moment arm** will mean that more **tailplane force** is required to maintain **equilibrium**, leading to greater **induced drag** and, thus, a more detrimental effect on **range** and **endurance**. A rearward **centre of gravity** position on the aircraft in *Figure 4.1* will require less **tailplane force**, leading to reduced **induced drag** and fewer consequent performance degradations in the **cruise**.

However, despite the theory, for practical purposes the general aviation pilot is rarely in a position to consider **centre of gravity** position in terms of its effect on **cruise performance**. **The pilot's main concern is that the centre of gravity of the aircraft remains within its prescribed fore and aft limits, for the duration of any planned flight**.

PERFORMANCE AND POWER CONSIDERATIONS IN THE CRUISE.

As we have discussed, the essential condition for straight and level flight at constant airspeed is that the forces acting on the aircraft should be in **equilibrium**. Among other things, for straight and level flight at constant airspeed, the **total drag** generated by the aircraft must be balanced by an **equal and opposite thrust** from the propeller-engine combination. As we learnt in the chapter on **climb**, we may consider **drag** being balanced by either the **thrust** force produced by the propeller, or by the **power available** from the propeller-engine combination. In terms of aircraft **en-route performance**, it is the power requirements that we need to consider.

The **power required** to overcome the **drag** generated by an aircraft at any **true airspeed** is found by multiplying the drag force by the true airspeed. The rationale behind this method of calculating **power required** was covered in the chapter on **climb**, but basically, because **power is defined as work done per unit time**, **power** may be calculated as follows:

Work Done = Force × Distance

$$\text{Power} = \frac{\text{Work Done}}{\text{Time}}$$

$$\text{Power} = \frac{\text{Force} \times \text{Distance}}{\text{Time}}$$

$$\frac{\text{Distance}}{\text{Time}} = \text{Speed}$$

Therefore, **Power = Force × Speed**

The standard unit of **power**, in science, is the **watt**, in other words, the **Joule per second**. These units are obtained by multiplying **force in Newtons** by **speed in metres per second**. But in aviation, we still talk about **power** in terms of **Horsepower**. **One Horsepower** is developed when **33 000 pounds (lb) are raised through one foot in one minute**, or if **550 lb are raised through one foot in one second**. If the **drag**, measured in **lb**, produced by an aircraft flying at a given **airspeed** is multiplied by that **airspeed**, converted to **feet per minute**, and then divided by **33 000**, the number of **horsepower** required to balance that **drag** is found. The actual calculation is not important to us at this level of study, but that is the method used to calculate how much **horsepower** is required to keep an aircraft flying straight and level, at constant speed.

In order to calculate how much **thrust horsepower** can be delivered by an aircraft's propeller at any **airspeed**, we take the **thrust in lb** able to be produced by the propeller at that speed, multiply the **thrust** by the **speed** itself, in **feet per minute**, and then divide by **33 000**.

A graph of **power available** from the engine-propeller combination and **power required** for level flight, against **true airspeed**, can be established for any aircraft. A graph of this type, identical to the one you meet in **Chapter 3**, is depicted at *Figure 4.2*.

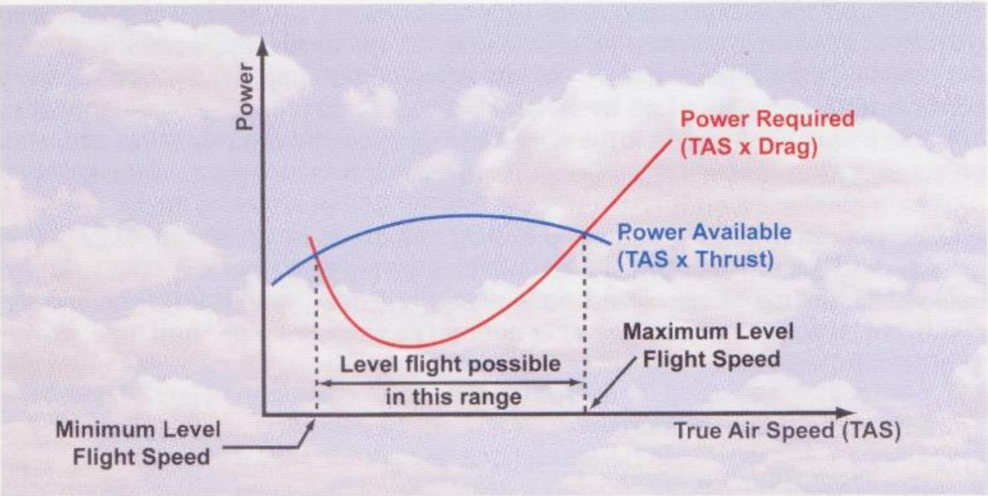


Figure 4.2 A graph of power required for level flight and power available from the propeller-engine combination, against true airspeed.

Any engine-propeller combination fitted to an aircraft can deliver a given maximum amount of **thrust horsepower** at given **airspeeds**. This information is given by the **power available curve** in *Figure 4.2*. Similarly, the **total drag** generated by the aircraft at the various speeds requires a **given amount of thrust horsepower** to overcome that **drag** in order for the aircraft to maintain straight and level flight. This information is given by the **power required curve** in *Figure 4.2*.

Both the lowest speed for level flight and the highest speed for level flight require full power.

Excess power available from the engine-propeller combination, over and above that required for level flight, can be used either to accelerate or climb the aircraft.

You will notice that the curves intersect each other in two places. An aircraft is able to maintain straight and level flight at speeds on the horizontal axis between the two intersections. In other words, **wherever the power available curve is above the power required curve, level flight can be maintained**. The speed corresponding to the intersection on the left is the slowest speed at which level flight is possible; the **power required** for level flight at that speed corresponds exactly to the **power available** from the engine-propeller combination. That **power** can only be delivered at **full throttle**. Consequently you can see that for an aircraft to fly level at the slowest possible speed, the pilot must open the throttle fully. If the aircraft is flown at a speed slower than the speed indicated, the aircraft will descend.

The right hand intersection of the two curves corresponds to the highest level flight speed attainable by the aircraft. Again the **power required** at that speed corresponds exactly to the power **available** and will require full throttle to deliver. If the pilot attempts to fly faster than this speed, the aircraft will descend.

Full power is required at the slowest speed for level flight because **low speed requires high angles of attack which generate high levels of induced drag** which must be balanced by the engine delivering **all the power it has available**. At the highest speed attainable, **angle of attack is very small, but, as the speed is high**, **parasite drag is high** which again requires **full power**.

At all speeds between the minimum and maximum level flight speeds, there is **power available** from the engine-propeller combination over and above the power required, and the aircraft is flying at less than full throttle. **This excess power available can be used either to accelerate the aircraft in level flight or to climb the aircraft**.

ENDURANCE.

An aircraft's endurance is a measure of its ability to remain airborne for a given maximum time. To remain airborne for as long as possible, the aircraft must **consume fuel at as low a rate as possible. Rate of fuel consumption** is a function **of power required**, and **fuel consumption** will be a minimum when the **power required** to maintain level flight is a minimum. **Minimum rate of fuel consumption, then, will be achieved at the speed for minimum power.** The **minimum power speed** is the speed that corresponds to the **lowest point on the power required graph**, and may be labelled as $\mathbf{V_{MP}}$. (*See Figure 4.3*) $\mathbf{V_{MP}}$ for the **PA28-161 Warrior** is about **65 knots**.

For a propeller driven aircraft the speed for maximum endurance is minimum power speed, $\mathbf{V_{MP}}$.

Increased weight decreases endurance.

Deployment of flaps decreases endurance.

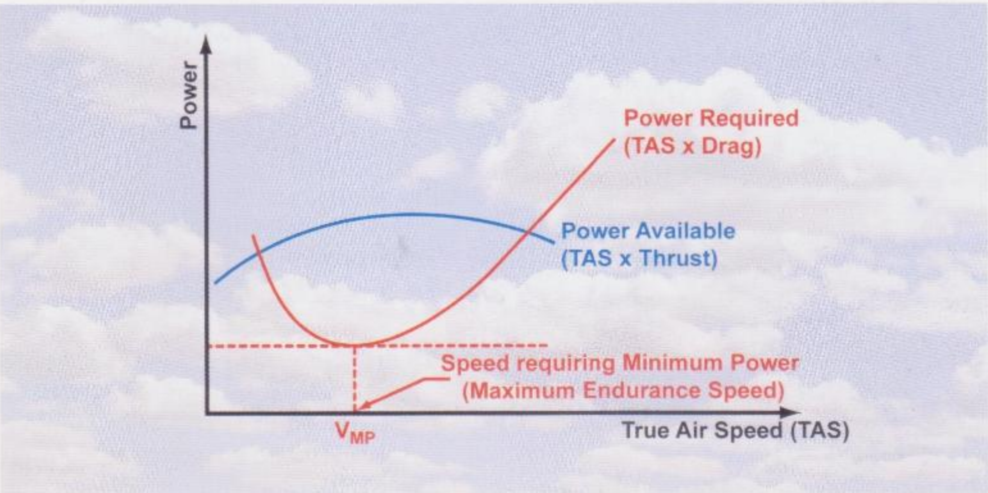


Figure 4.3 The level-flight speed which requires minimum power ($\mathbf{V_{MP}}$*) is the speed for maximum endurance.*

Any **increase in weight** or **deployment of flaps**, both of which will **increase drag** for any given level-flight speed, will require **more power to maintain level flight** and **decrease an aircraft's endurance (the amount of time that an aircraft can fly)**.

RANGE.

Most often, pilots are concerned to be able to cover the maximum distance for minimum fuel consumption. **The maximum distance an aircraft can fly for a given quantity of fuel consumed is called the aircraft's range.** Several factors, not the least being wind speed and direction, affect an aircraft's **range**. The first factor we will consider is engine power.

Power and Range.

The speed for maximum endurance is not the speed to use when we wish to fly as far as possible. In other words, maximum endurance speed is not the **speed for maximum range**. To achieve maximum distance on a given quantity of fuel, we must fly at a speed which gives us the best compromise between speed and fuel consumption. This speed is that at which the ratio between **speed achievable** and **power required** is the least. **In order to find the speed at which the power/speed ratio is most favourable, a line is drawn from the origin of the axes of the power available - power required graph to touch the power required curve at a tangent** (*see Figure 4.4*). A vertical line dropped from the tangent to the curve, to intersect the horizontal axis, allows us to read **the speed for maximum range** directly. If the gradient of the straight line were to meet the curve at any other point than the tangent (it would then, of course, cut the power required curve in two places), the line would be steeper and, therefore, the **power/airspeed** ratio would be less favourable.

Though it is beyond the scope of this book, it can be shown that the **speed for maximum range** for any propeller-driven aircraft is also the **speed for minimum drag**, often represented as V_{MD}. **Minimum drag** occurs at the **best lift/drag ratio** with the aircraft flying at an angle of attack of about 4°.

You will note that the speed for maximum range (minimum drag), V_{MD}, is a little higher than the speed for maximum endurance (minimum power), V_{MP}.

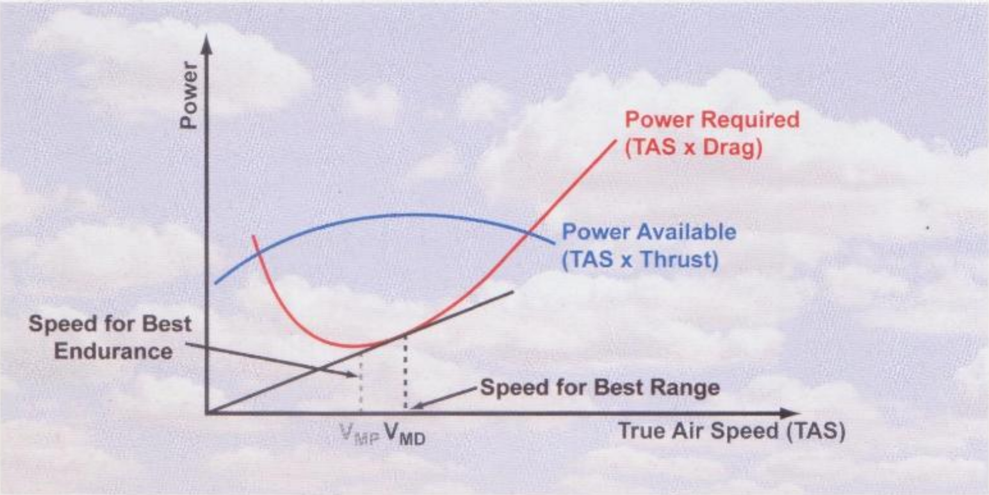


Figure 4.4 The speed at which the aircraft achieves the most advantageous compromise between speed and power required is the speed for maximum range. This is also the speed for minimum drag.

The speed for maximum range is minimum drag speed, V_{MD}.

FACTORS WHICH EFFECT FLYING FOR RANGE.

The key point about flying for **maximum range** in a propeller-driven aircraft is that the aircraft flies at the **speed for minimum drag**; that is, at the **speed and angle of attack for the most favourable lift/drag ratio**. This **angle of attack** is about **4°** in a typical general aviation aircraft, and, as we have seen, in the **PA28 Warrior**, the **speed for this angle of attack**, giving **best lift/drag ratio and maximum range**, is 75 kts. At this **speed and angle of attack**, the aircraft is flying at its most efficient, aerodynamically speaking.

There are **four principal factors** which affect an aircraft's **range** and **speed for maximum range: aircraft mass (weight), aircraft configuration, altitude** and **wind speed and direction**. By aircraft **configuration** we mean whether the **flaps** and/or **undercarriage** are deployed or not. We will examine these four factors, one by one.

Aircraft Weight.

As we have seen, in order to achieve **maximum range** the aircraft must fly at the **speed for minimum drag**. It must also, however, fly at **minimum load**. If greater **load** is carried, the **maximum achievable range** will decrease, while the **speed** at which **the lower maximum range** is achieved will increase.

Increasing an aircraft's **weight** means that the wings of the aircraft must generate extra **lift** to support the higher **weight**. Consequently, as an aircraft's **weight** increases the aircraft must fly faster to maintain any given **angle of attack**, or it must fly at a greater **angle of attack** for any given **airspeed**.

An increase in **lift** at any speed results in an increase in **induced drag** at that speed. **More power** will be required to overcome the **extra drag**, the greater power will **raise fuel consumption**, and so **the best power required/speed ratio will be less favourable** at a higher aircraft weight than at a lower weight. **Consequently, maximum range will be less at the higher weight**.

On the other hand, the **angle of attack** for the best **lift/weight ratio** remains unaffected by **weight** and will remain at about **4°**. As we have just stated, **a heavier aircraft must fly faster to maintain a given angle of attack**. Therefore, **the speed for maximum achievable range will increase**.

The effect of increasing **weight** just described means that the **power required curve** in our graph moves up and to the right. The **speed for maximum range** is, as before, given by dropping a vertical line from the tangent to the **power required curve** formed by a straight line drawn from the origin of the graph's axes, and reading the new **maximum range (minimum drag) speed, V_{MD}**, from the horizontal axis. (*See Figure 4.5.*)

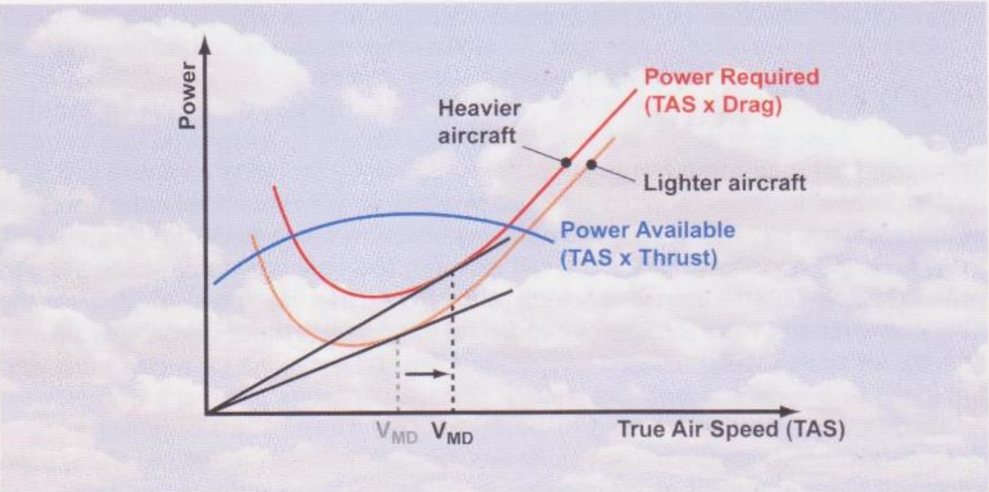


Figure 4.5 At higher weights, lift and drag increase and the power required to overcome the drag increases. The power required curve moves up and to the right. Maximum range decreases and the speed for best achievable maximum range increases.

Aircraft Configuration.

If **flaps** and/or **undercarriage** are deployed, there is a significant increase in **drag**. Considering **flaps** alone (most light aircraft having fixed undercarriages anyway), when they are lowered more **lift** and associated **drag** is generated at **lower speeds.**

Drag and **power required** are higher at all **speeds** because of the increase in the **coefficient of drag, C_D**, engendered by the change in the effective shape and camber of the wing cross section (aerofoil). Consequently, **the value of minimum drag will increase, and require increased power to balance that drag. Increased power means a higher rate of fuel consumption and a decrease in maximum range** compared to a more lightly loaded aircraft.

Selecting any angle of flap increases drag by a greater proportion than lift. Therefore, the best achievable lift/drag ratio will also be lower when flap is deployed.

The result of all the above considerations is that the **power required curve** moves upward and to the left, as shown in *Figure 4.6.*

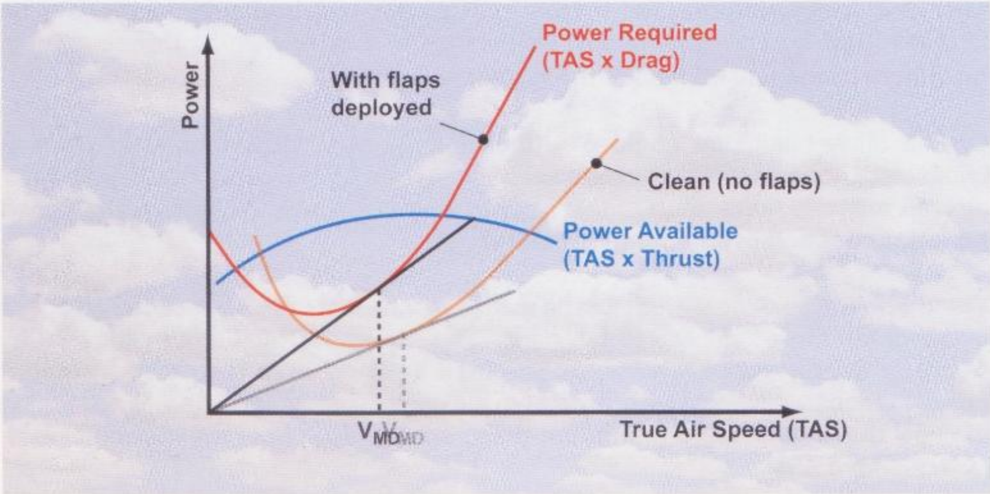


Figure 4.6 With flaps extended, drag and power required increase at all speeds. The power required curve moves up and to the right. Maximum range decreases and the speed for best achievable maximum range increases.

The **speed for maximum range** is, as before, given by dropping a vertical line from the tangent to the power required curve formed by a straight line drawn from the origin of the graph's axes, and reading the new **maximum range (minimum drag) speed, V_{MD}**, from the horizontal axis. You will see that the best attainable **power/speed ratio** is less favourable than for a "clean" aircraft, and that the speed which gives the best **power/speed ratio** (i.e. the speed for the **maximum attainable range**) is lower than for an aircraft with no **flap** deployed.

Altitude.

If we were considering the aircraft alone (i.e. its aerodynamic properties) and not the engine, we would get the same **maximum range** by flying at the same **indicated maximum range speed, (speed for best lift/drag ratio)** whatever **altitude** we flew at. **Indicated airspeed** is a function of **dynamic pressure** ($\frac{1}{2} \rho v^2$), and so is **drag**, so (still considering the aircraft only) as long as we flew at indicated **airspeed** for best **lift/drag ratio**, the **drag** would be the same. One might naturally think that the **power required** to overcome the **drag** at that **speed** would also be the same. However, the **power required** is not the same. **Power required is a function of true airspeed, not indicated airspeed**, and, as you know (see **Chapter 4** of **Principles of Flight**),

the higher an aircraft flies the greater is its true airspeed for a given indicated airspeed, and the greater the power required at that airspeed. Also, at the **higher altitude**, **air density is lower** which further **increases the power required** for level flight while **reducing the power available** from the engine.

In order to get the maximum range from an aircraft, both the aircraft and the engine must be operated to best advantage. It follows, then, that the correct **altitude** to fly is the **altitude** at which the **indicated minimum drag (maximum lift/drag ratio) airspeed** is also the **true airspeed** which permits the engine-propeller combination to operate at its most efficient. This reasoning explains why some **Pilot's Operating Handbooks** (but not all) give an **altitude** alongside the aircraft's **maximum range speed**. If the aircraft is flown at higher **altitudes** than the optimum **altitude**, more and more **power** will be required to achieve the speed **for minimum drag (best lift/drag ratio)**.

Reducing air density reduces an aircraft's overall performance.

Therefore, to maximize range at high **altitude** we must either reduce **speed**, meaning we are using the aircraft less efficiently, aerodynamically speaking, or open the throttle fully (or maybe enrichen the mixture), meaning that we are using the engine uneconomically.

Maximum range speed is the speed for the best lift/drag ratio, unless flying at high altitude when power considerations have to be taken into account.

Consequently, for all aircraft there is a best altitude at which to fly for range. That **altitude** is determined by the efficiency of the engine-propeller combination, not by the aerodynamic properties of the aircraft which would be equally as efficient at all altitudes.

In practice, for light, piston-engine powered aircraft with a fixed-pitch propeller and without a supercharger, which tend to operate at low altitudes, the best height for maximum range at those low altitudes is not very critical.

Wind considerations are usually far more critical to a light aircraft's best achievable range.

Effects of Wind on Range.

Wind of any **strength** and any **direction** will affect an aircraft's **range**.

When no **wind** is blowing; that is, when the **wind** is calm, an aircraft's **true airspeed** will be the same as its speed over the ground. Speed over the ground is known as **groundspeed**.

An aircraft flying with a the **wind** behind it, i.e. a **tailwind**, will have a higher **groundspeed** than an aircraft flying at the same **true airspeed** when no **wind** is blowing or if it is flying into a **headwind**. With a **tailwind**, the **speed of the wind** itself is added to the aircraft's **true airspeed** to give the aircraft's **groundspeed**. Consequently, with a **tailwind**, the aircraft is covering a greater distance for any given rate of fuel consumption, than if it were flying in calm conditions or against a **headwind**. **A tailwind, then, will increase an aircraft's range.**

An aircraft flying into a **headwind** will have a lower speed over the ground than an aircraft flying at the same **true airspeed** when the wind is calm, or if there is a **tailwind**. With a **headwind**, the **speed of the wind** itself is subtracted from the aircraft's **true airspeed** to give its **groundspeed**. Consequently, with a **headwind**, the aircraft is covering a smaller distance for any given rate of fuel consumption, than if it were flying in calm conditions or with a **tailwind**. **A headwind, then, will reduce an aircraft's range**.

When taking into consideration the effect of the **wind** on the fuel consumed over a given distance for a track that you have planned to fly on a cross-country route, you will very often find that the direction of the **wind** is such that it is blowing obliquely to your planned track, at a greater or lesser angle. A **crosswind** of this nature will mean that you will experience either a **headwind or tailwind component** when tracking along the ground. **Volume 3** of this series, **Navigation & Radio Aids**, teaches you how to take account of **crosswinds** to calculate your heading and **groundspeed**. **Wind strength and direction may change significantly over time and with altitude**. In flying cross-country, therefore, the pilot-navigator needs to be very aware of deviations in **wind strength and direction** from those forecast.

When flying into a headwind, the speed for maximum range will be a little higher than the speed derived from the power required – power available graph, and the speed given in the **Pilot's Operating Handbook**. The increased fuel consumption resulting from the higher power setting is compensated for by the fact that the higher speed will mean that less time is spent flying against the **headwind**, on the track concerned.

When flying with a tailwind, the speed for maximum range is lower than that given in the **Pilot's Operating Handbook**. The reduction in best range speed is lower so that the aircraft can benefit from the higher **groundspeed** and, at the same time, reduce fuel consumption. In a strong **tailwind**, the speed to choose for **maximum range** will probably be not far different from the speed for best endurance.

CRUISE PERFORMANCE GRAPHS.

In the **Pilot's Operating Handbook (POH)** for your aircraft, you will probably not find any theoretical treatment of flying the aircraft for **range** or **endurance**. The **POH** generally contains graphs of the type depicted in *Figures 4.7*, and *4.8*, allowing the pilot to carry out practical **range** and **endurance** calculations.

Endurance Graphs.

Figure 4.7 depicts a typical **endurance graph** for a light aircraft. The method of calculating **endurance** from the graph is similar to the method that you learnt in the previous chapter for extracting performance figures for the climb.

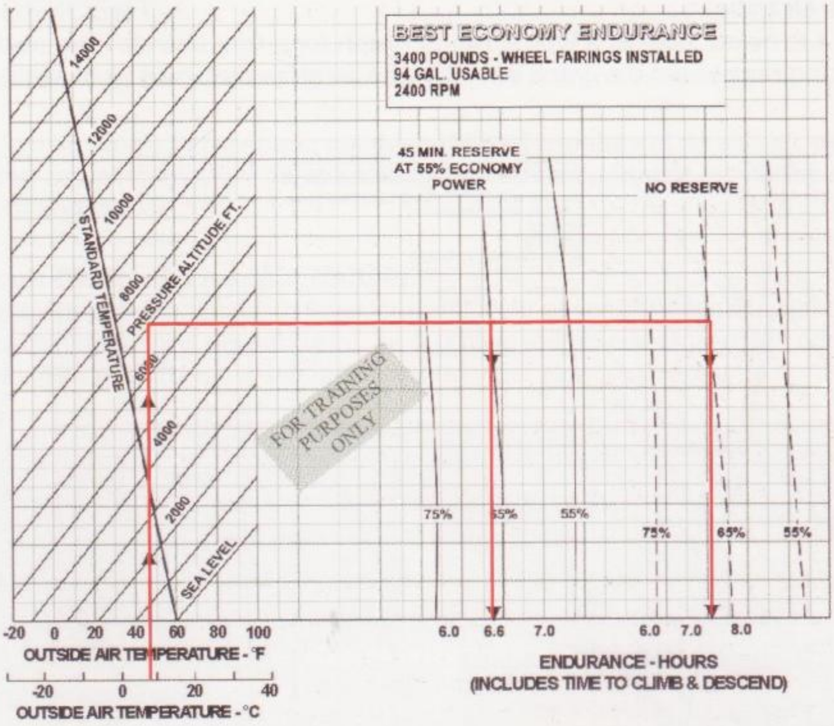


Figure 4.7 A Typical Endurance Graph for a light aircraft.

The red lines on the graph depict how **endurance** is extracted from the graph for a given set of atmospheric and aircraft parameters.

The example assumes that an aircraft is to cruise at a **pressure altitude of 7 000 feet** with an **outside air temperature of 7°C**. The power setting is assumed to be **2 400 revolutions per minute**, and the pilot wishes to have **45 minutes of reserve fuel** in his aircraft's tanks, at the end of the planned flight. Given these assumptions, *Figure 4.7* shows how the corresponding **endurance** is extracted from the graph. **Outside air temperature** and **pressure altitude** are entered at the left hand end of the graph by drawing a vertical line from the temperature scale to the curve representing the **pressure altitude**. A horizontal line is then drawn across to the curve representing **45 minutes reserve** (note that reserve figures assume the power setting to be **55% of maximum power**). A vertical line is dropped from this curve to cut the horizontal axis at a point which gives the aircraft's **endurance** in hours (**6.6 hours** in the example illustrated). The endurance given also takes into consideration the climb to height, and the descent.

Note that the example also shows that the **endurance with no reserves of fuel** would be approximately **7½ hours**.

Range Graphs.

Figure 4.8, below, depicts a typical **range graph** for a light aircraft. The method of calculating **range** from the graph is exactly the same as that used for the endurance graph.

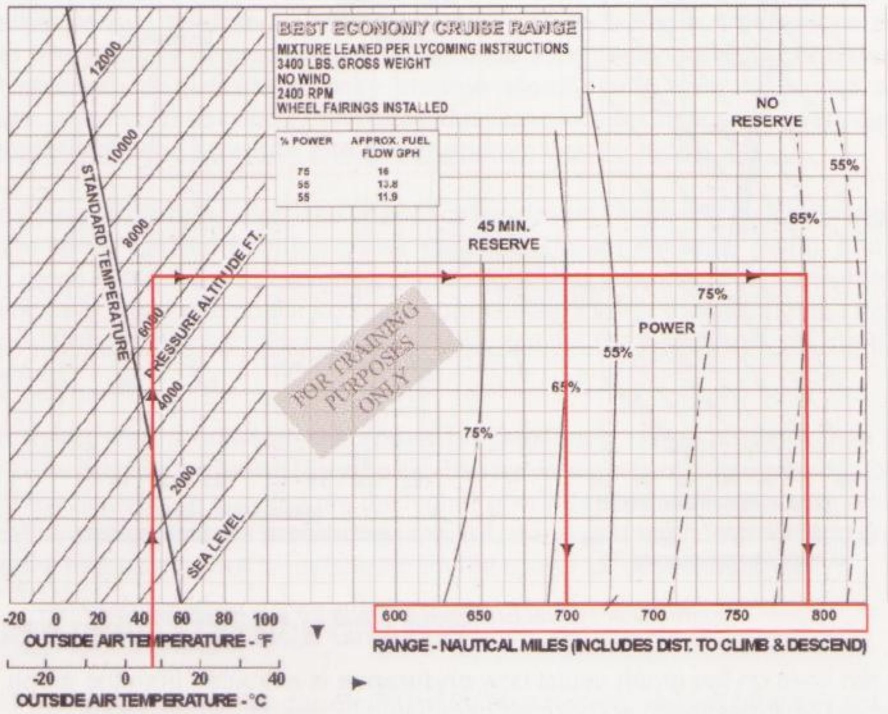


Figure 4.8 A typical range graph for a light aircraft.

The example assumes that an aircraft is to cruise at a **pressure altitude of 7 000 feet** with an **outside air temperature of 7°C** and **65% power** set.

You can see that, allowing for **45 minutes of reserve fuel**, the achievable range will be **700 nautical miles**, while, if **no reserve fuel** is assumed, the range will be **just over 780 nautical miles**.

When using **Cruise Performance Graphs**, be sure to follow the instructions in the **Pilot's Operating Handbook** carefully. Be sure, too, to take note of all the assumptions made in the calculations; the assumptions will most probably need to be taken into consideration to refine the figures extracted from the graphs.

THE DESCENT.

The descent may be regarded as the final part of the en-route of flight.

There are two ways of assessing the **descent performance** of an aircraft: **angle of descent**, sometimes called **descent range**, or **rate of descent**, sometimes called **descent endurance**.

Angle of Descent (Descent Range).

Figure 4.9 depicts an aircraft in level, cruising flight at constant speed, with the four principal flight forces in **equilibrium**. As you have learnt, one of the main conditions for level flight at constant speed is that **thrust** must balance **drag**.

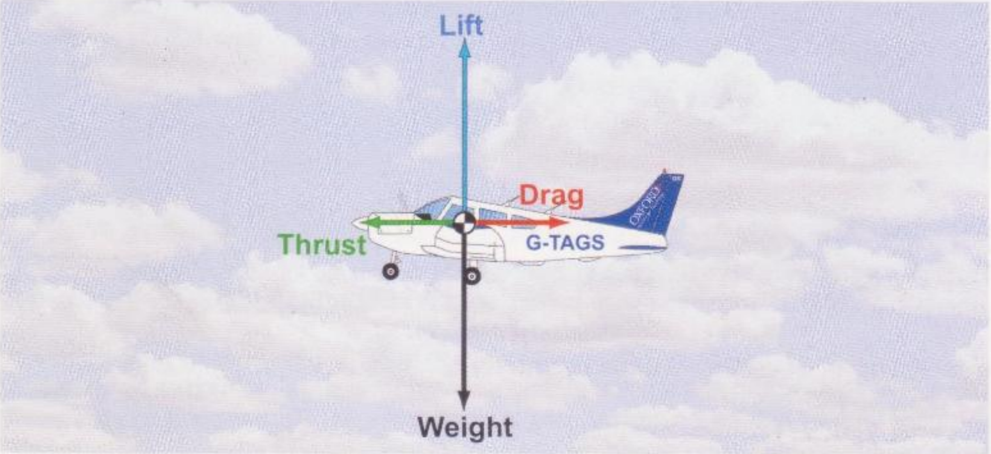


Figure 4.9 In straight and level flight at constant speed, the four principal flight forces are in equilibrium.

In order to initiate a **steady descent**, **thrust** is normally reduced by the pilot reducing power. **Drag** now exceeds **thrust**. In order to keep the flight forces in **equilibrium** and maintain **speed**, the nose of the aircraft must be lowered until the **forwards-acting component of the aircraft's weight** increases the forwards-acting forces to the point where the **aerodynamic drag** is again **balanced**. The aircraft is now descending at the same constant speed that it had in level flight, with all flight forces again in **equilibrium**.

Figure 4.10 A constant-speed descent, with all principal flight forces in equilibrium.

If the pilot closes the throttle further, propeller **thrust** is again reduced, and the aircraft's nose must be lowered even more so that the **forwards-acting component of weight** can maintain the flight forces in **equilibrium** and maintain **speed**. This action will further steepen the descent angle. **In fact, the greater the margin of drag force over the thrust force, the greater will be the descent angle**.

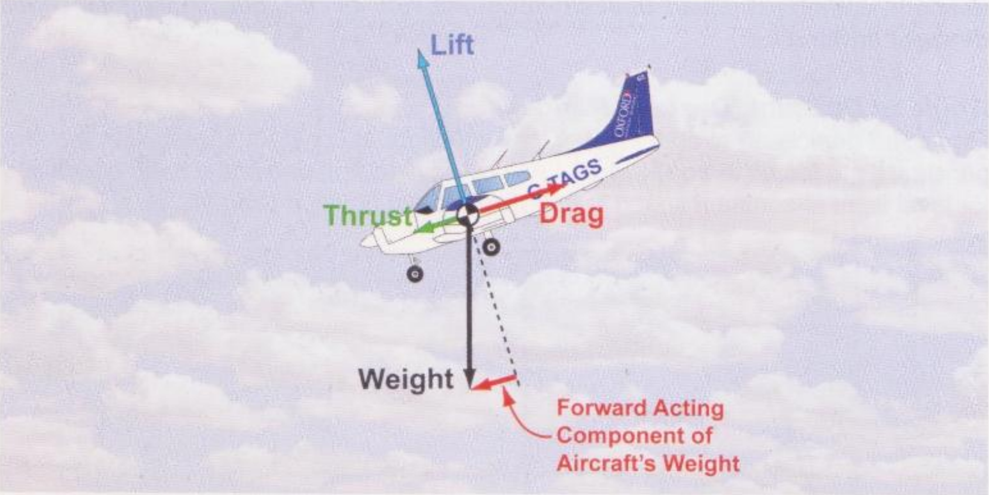


Figure 4.11 The more thrust is reduced, the greater must be the forward-acting component of weight in order to balance aerodynamic drag, and the steeper will be the descent required to maintain a given speed.

Obviously, to descend at a shallower descent angle while maintaining cruising speed, the pilot should reduce power by only a small amount. To descend more steeply while maintaining cruising speed, power should be reduced further.

Glide Angle.

Even though modern engines are extremely reliable, a pilot should always be prepared for an engine-failure. If an engine-failure should occur while on a cross-country flight, an important consideration for the pilot is that he should quickly identify a suitable field in which to land. In order to give himself the greatest chance of finding and reaching a suitable field, the pilot should aim to fly the aircraft at its best (shallowest) **glide angle**. By doing this, a greater distance will be covered, before the aircraft descends to ground level.

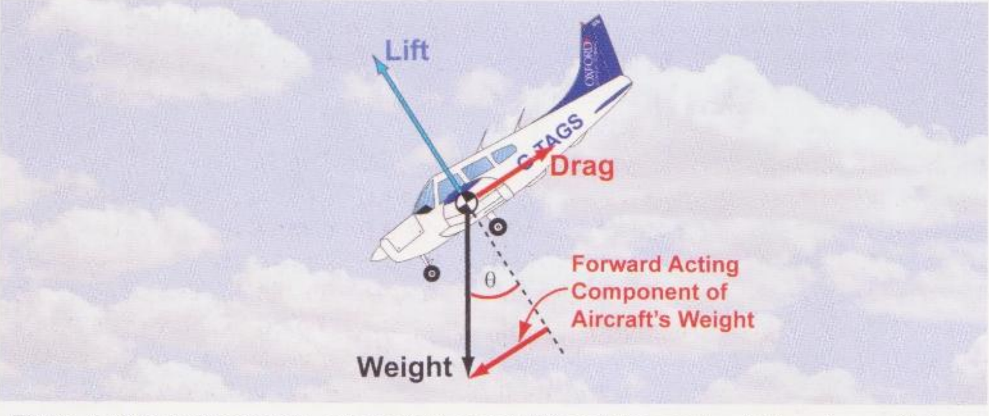


Figure 4.12 In a steady glide, at constant speed, lift and drag and weight are in equilibrium. The only propulsive force is the forward-acting component of the aircraft's weight.

When the engine fails, there is, of course, no thrust force produced by the propeller. So the only forces acting on an aircraft in the **glide**, following engine failure, are **lift**, **drag** and **weight**. **In a steady glide at constant speed, these three forces must be in equilibrium**. The **weight** of the aircraft is supported by the **resultant of the lift and drag** forces, and the only propulsive force acting on the aircraft is the **forwards-acting component of the weight force**. (*See Figure 4.12.*) **In a glide, at constant airspeed, this forwards-acting component of weight is equal and opposite to the aerodynamic drag.**

It is simple to prove mathematically that the angle θ between the **lift vector** and the **resultant of the lift and drag vectors** is equal to the **angle of glide** of the aircraft with respect to the ground, assuming zero wind.

The angle θ will be a minimum, and, therefore, the aircraft's glide angle shallowest (i.e. giving maximum range) when the ratio of lift to drag is highest.

Best glide performance is achieved by flying the aircraft at the speed for maximum lift/drag ratio.

Therefore an aircraft's best glide performance is achieved when it flies at the speed for the best lift/drag ratio.

Now, the **best lift/drag ratio** is achieved when **drag is a minimum** (lift having to remain constant). **So an aircraft's best angle of glide performance is achieved at the speed for minimum drag, V_{MD}**.

To achieve maximum gliding range the aircraft should be flown at minimum drag speed, ***V_{MD}****.*

On most light aircraft, the **speed for minimum drag** is achieved at an angle of attack of about **4°**. **V_{MD}** will be given in the **Pilot's Operating Handbook**. For the **PA28-161 Warrior**, **V_{MD}** is **75 knots**, giving a **maximum lift/drag ratio of 10:1** and a **best glide angle** of about **7°**.

In still air, then, from **3 000 feet** above ground level, a Warrior flying at its **best glide speed of 75 knots** would cover about **5 nautical miles**. You may remember that **V_{MD}** is also the speed for **maximum range in the cruise**, because at the **best lift/drag ratio** the wing is operating at its most efficient.

Factors Affecting Glide Angle.

Flaps.

Flaps increase drag at any speed. So lowering **flaps** will always degrade the **lift/drag ratio** and, thus, steepen the **glide angle**. **Flap**, then, must not be deployed when gliding for range, but deployment of **flap** is advantageous when the **glide** needs to be steepened, such as for the final approach to land.

Speed.

As we have just discussed, the **speed for minimum drag**, **V_{MD}**, in other words, the **speed for the best lift/drag ratio**, gives an aircraft its **best glide performance**. Flying faster than **V_{MD}** will steepen the glide angle. Flying slower than **V_{MD}** will also steepen the glide angle, because at speeds lower than **V_{MD}** the **lift/drag ratio** is less favourable. Therefore, when flying at **V_{MD}**, **never raise the nose to try to "stretch" the glide**. You will only steepen the **glide** by raising the nose and you may also cause the aircraft to stall. **Many accidents have been caused by attempting to "stretch" the glide**.

Flying at ***V_{MD}****, best lift/drag ratio, gives an aircraft its shallowest glide angle. Flying at any other speed will steepen the glide. Therefore, when at* ***V_{MD}****, never raise the nose to try to stretch the glide.*

Wind.

Wind has a significant effect on **glide angle and range**. *Figure 4.14* shows **descent angle** and **descent range** in conditions of **zero wind**, a **headwind** and a **tailwind**. In zero wind, given its **maximum lift/drag ratio** of **10:1**, a Warrior will glide approximately **5 nautical miles** from **3 000 feet** above ground level.

Angle of descent is measured relative to the volume of air in which the aircraft is flying. Consequently, **relative to the ground, a headwind steepens the glide angle** and **decreases gliding range**. In a **headwind the speed for best gliding range is increased slightly** to reduce the amount of time the aircraft remains exposed to the **headwind**. Conversely, **a tailwind will decrease the glide angle with respect to the ground and increase the gliding range. In a tailwind the speed for best glide is reduced slightly** to increase the aircraft's exposure to the beneficial effect of the **tailwind**.

Figure 4.13 Headwind increases glide angle and decreases range. Tailwind decreases glide angle and increases range. With its 10:1 lift/drag ratio, clean, a Warrior will glide about 5 nm from a height of 3 000 feet.

THE EFFECT OF AIRCRAFT WEIGHT ON GLIDE ANGLE.

Increasing an aircraft's weight has no effect on the glide angle. The **glide angle** is dependent only on the **lift/drag ratio** and is independent of **weight**. In a heavier aircraft (*see Figure 4.13*) there is an increase in both the **lift** and **drag** forces which act on the aircraft during the descent. But the **<u>ratio</u> of lift to drag**, and, hence, the **glide angle**, will remain the same. However, the increase in **lift** and **drag** required to balance a heavier aircraft's **weight** in the glide, can only be generated by an increase in **speed**. This higher **speed** is produced by the greater value of the **forwards-acting weight component**. **Thus, increased weight has no effect on an aircraft's best glide angle, but best glide is achieved at a higher speed.**

Increased weight has no effect on an aircraft's best glide angle, but that angle will be achieved at a higher speed.

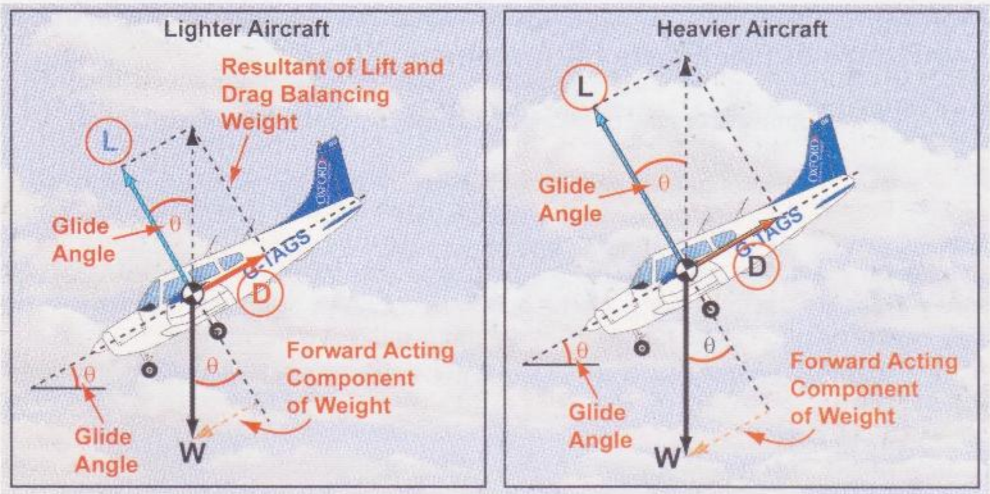


Figure 4.14 Weight has no effect on glide angle; glide angle depends on lift/drag ratio alone. However, a heavier aircraft will glide at a faster speed.

RATE OF DESCENT (DESCENT ENDURANCE).

The best way to consider **rate of descent** is to think of it as being the opposite to rate of climb.

You will recall that maximum rate of climb is achieved by flying at the speed at which the difference between the power required to maintain level flight and the thrust horsepower available from the engine-propeller combination is the greatest. At that speed, the maximum amount of excess power is available for climbing the aircraft, and flying at that speed with full power applied (full throttle for a fixed-pitch propeller) will give a pilot the maximum rate of climb.

The speed for best rate of climb, then, is the speed at which the difference between the power required for level flight and the power available from the engine is a maximum. This speed is known as **V_{MD}**. **V_{MP}**, for the **PA28-161 Warrior** is **65 knots**.

When an aircraft is descending at a given speed, it should be evident that more power is required at that speed for level flight than the engine is developing. The bigger the difference between the required power and the power the engine is developing, the greater is the rate of descent. Consequently, with the throttle closed, in order to keep this difference as small as possible we need to fly at the speed for minimum power. This speed is known as **V_{MP}**. Therefore, to maximise descent endurance (and achieve the maximum rate of descent) we must fly at **V_{MP}**.

You should note, however, that at any given descent airspeed, the desired rate of descent can be selected by the pilot by increasing or reducing power.

Note, too, that whereas wind has a significant effect on angle of descent, **wind has no effect on rate of descent**.

However, at a selected, constant airspeed in the descent, increasing and decreasing power will increase and decrease the angle of descent, respectively.

Representative PPL - type questions to test your theoretical knowledge of En - Route Performance.

1. If the centre of gravity of an aircraft is moved rearwards, the effect is:

a. a stronger lift/weight couple which requires a greater tail-plane to maintain the aircraft in equilibrium
b. an increased range and endurance
c. a reduced range and endurance
d. a greater tail-load

2. What speed must be flown to attain maximum cruise endurance?

a. V_Y
b. Maximum Speed
c. V_{MP}
d. V_{MD}

3. A wing contaminated by a small amount of ice will produce:

a. more weight and more lift
b. more drag, more weight and less lift
c. an increase in both lift and drag co-efficient
d. an increase in weight and decrease in drag

4. When gliding for maximum range an aircraft with a greater weight will:

a. have a reduced glide range
b. have a shallower glide angle
c. have a faster gliding speed but the same glide angle
d. have a faster gliding speed and a reduced gliding range

5. What speed, from *Figure 4.15*, should be flown for maximum range?

a. A
b. B
c. C
d. D

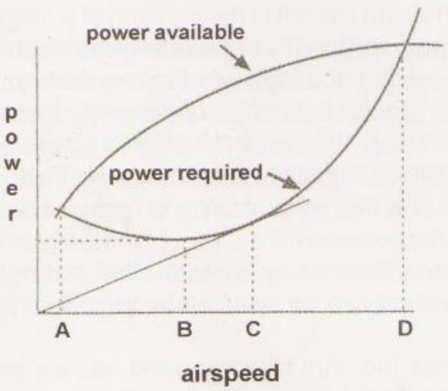


Figure 4.15 Power Curves for Q.5.

6. The glide range will be maximised by flying at:

a. a relatively high angle of attack such as 10°
b. a relatively low angle of attack such as 4° which will give the best lift/drag ratio
c. a negative angle of attack
d. a high descent angle

7. A pilot wishes to fly at a speed which will give him maximum range. He knows that he is flying in a tailwind. How will the speed selected by the pilot compare with the maximum range speed for still air quoted in the Flight Manual?

a. It will be decreased slightly
b. It will increased slightly
c. It will be the same as for still air
d. The speed will be greater by the value of the tailwind component

8. What is the effect of a headwind on the glide angle and gliding range with respect to the ground?

a. Glide angle and glide range will remain the same as in still air
b. Glide angle and glide range will increase
c. Glide angle and glide range will decrease
d. Glide angle will increase and glide range decrease

9. What is the maximum range speed for a piston engine aircraft?

a. $\mathbf{V_{MP}}$
b. $\mathbf{V_{MD}}$
c. At a lower speed than $\mathbf{V_{MP}}$
d. At a speed less than $\mathbf{V_{MD}}$

10. The true airspeed of an aircraft which maintains a constant indicated airspeed will:

a. increase as altitude increase
b. remain constant as altitude increases
c. decrease as altitude increases
d. act unpredictably, as true airspeed has no connection with indicated airspeed

11. Examine the graph in *Figure 4.16.* Which of the speeds indicated by A, B, C or D should be flown for maximum endurance?

a. A
b. B
c. C
d. D

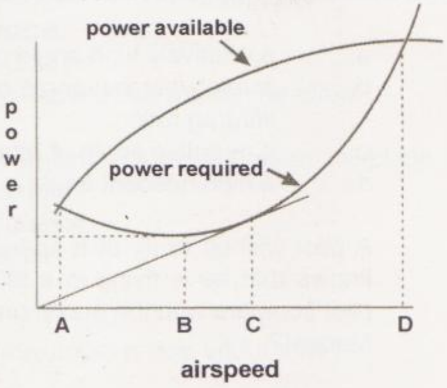


Figure 4.16 Power Curves for Q.11.

12. The Centre of Pressure of a given aircraft is aft of the aircraft's Centre of Gravity. During straight and level flight, any increase in the lift causing an imbalance in the equilibrium of forces is compensated for by:

a. an upward force generated by the tailplane
b. a downward force generated by the tailplane
c. an increase in thrust
d. a decrease in drag

13. Compared to gliding in still air, the effect of a tailwind will:

a. increase the glide range but have no effect on the rate of descent
b. decrease the glide angle and decrease the rate of descent
c. have no effect on the glide range or the rate of descent
d. increase the glide angle and increase the rate of descent

14. What would be the effect of an increase in temperature upon air density and aircraft performance?

a. Increased density and reduced aircraft performance
b. Increased density and increased aircraft performance
c. Reduced density and an increase in aircraft performance
d. Reduced density and reduced aircraft performance

15. In order to maximise glide range, the aircraft should be flown:

a. at a high angle of attack to achieve V_Y
b. at a low angle of attack to achieve V_{MP}
c. at a negative angle of attack to achieve V_X
d. at a low angle of attack to achieve V_{MD}

16. What speed must be flown to attain maximum cruise range?

a. V_X
b. Maximum speed
c. V_{MD}
d. V_{MP}

17. If weight is increased, the range of the aircraft will be:

a. reduced
b. unchanged
c. increased
d. increased unless lift can be reduced

18. An aircraft has a best lift/drag ratio of 9:1. What is the maximum distance it could glide from 4 000 ft above ground level, in zero wind conditions?

a. 6 nautical miles approximately
b. 7 nautical miles approximately
c. 18 nautical miles approximately
d. 9 nautical miles approximately

Question	1	2	3	4	5	6	7	8	9	10	11	12
Answer												

Question	13	14	15	16	17	18
Answer						

The answers to these questions can be found at the end of this book.

CHAPTER 5
LANDING

LANDING DISTANCE.

The **landing distance required** for an aircraft to touch down safely is measured from a point where the aircraft is **50 ft** above the threshold to the point at which the aircraft is bought to a full stop. (*See Figure 5.1.*)

The Landing Distance is measured from a point 50 feet above the threshold to the point in the landing run where the aircraft is brought to a full stop. At the screen height, the reference landing speed, V_{REF}, is assumed to be 1.3 times, V_{SO}.

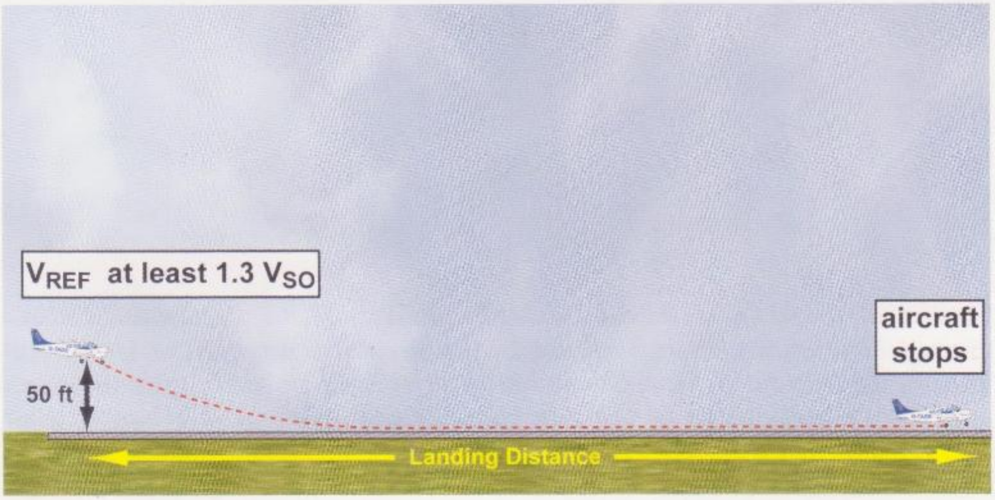


Figure 5.1 Landing Distance is measured from the 50 feet screen height to the point in the landing run where the aircraft is bought to a full stop.

The **50 feet** point is referred to as the **landing screen height** which is similar to the take off screen height. In the definition of **landing distance**, it is assumed that, at the **landing screen height**, the aircraft is flying at a reference speed, **V_{REF}**, of at least **1.3 times the aircraft's stalling speed**. **V_{REF}** gives the aircraft a **30%** margin of safety over its stalling speed, in the landing configuration. The stall speed in the landing configuration, with flaps lowered, is known as **V_{SO}**. So, if **V_{SO}** is **50 knots**, **V_{REF}** is **30%** greater than this; that is **65 knots**.

V_{REF} must be achieved, but excess speed on the approach will increase the landing distance required.

Pilots must be aware that although **V_{REF}** must be at least **1.3 × V_{SO}**, if the speed exceeded **V_{REF}** significantly, the **landing distance** would also be increased by a significant margin. It is very important that a pilot should determine the correct approach speed for the conditions, and fly that speed as accurately as possible.

The Landing Distance Available.

The **landing distance** that an aircraft **requires** must not exceed the **landing distance available**. The **landing distance available (LDA)** at an airfield is defined as being **the length of runway suitable for landing**, taking into account any obstacles in the approach path. Usually, the **LDA** is the distance from one threshold of the runway to the other. *(See Figure 5.2, overleaf.)*

In a typical landing, landing flaps will have been selected at a suitable point on the approach, and with an airspeed of at least **V_{REF}** at the **50 feet screen height**, the throttle will normally have been closed. By following this procedure, the **landing distance required** will be kept to a minimum. There are, however, several factors which affect **landing distance required**, which we will now go on to examine.

The Landing Distance Available is the length of runway suitable for landing, taking into account any obstacles in the approach path.

Figure 5.2 The Landing Distance Available (LDA) at an airfield is defined as being the length of runway suitable for landing.

FACTORS AFFECTING THE LANDING.

Aircraft Mass.

Increased aircraft mass means increased momentum, increased V_{REF} and increased landing distance.

Increased **mass** means that for any given true airspeed, the **momentum** of the aircraft will also be higher (**momentum = mass × velocity**). A body's **momentum** is often defined as a measure of how much **force** is required to stop the body moving. Therefore, **the higher an aircraft's momentum the greater the braking force required to bring the aircraft to rest.** As **braking force** is a function of the aircraft's brake assembly and is constant for any given set of runway conditions, **the greater the aircraft's mass, the longer will be the period of time during which the braking force must be applied and the longer will be the landing distance required**.

As you learnt in **Principles of Flight**, the greater the aircraft's **mass**, the greater will be its **weight**. You have also learnt that **the heavier an aircraft is, the higher will be its stall speed**. Therefore, as approach speed needs to be at least **1.3** times V_{SO}, a heavier aircraft will need to approach and touch down at a higher speed than a lighter aircraft. As we mentioned above, **momentum = mass × velocity**, so **the higher speed will impart greater momentum to the aircraft and increase the landing distance required**.

Of course, the heavier the aircraft, the greater will be the **load** acting on the undercarriage rolling assembly and the greater will be the **rolling resistance** once the aircraft is on the ground. However, this one beneficial effect on landing performance of increased **mass** or **weight** does not affect the aircraft anywhere near as much as its increased **momentum**.

A 10% increase in aircraft mass will increase Landing Distance Required by 10%.

The overall effect of increasing an aircraft's mass or weight, then, is to increase the landing distance required. As a rule of thumb, we may assume that the **landing distance required** increases by **10%** for every **10%** increase in the aircraft's **mass**. As a practical guide, for a light aircraft, a **10%** increase in **mass** equates approximately to carrying an extra passenger with luggage.

Reducing **mass** will, by counter argument, shorten the **landing distance required**.

Air Density.

As you have learned from the **lift equation** in **Principles of Flight**, **Lift = $C_L \frac{1}{2} \rho v^2 S$**, **lift** is directly proportional to **air density**, ρ. Thus, a decrease in **air density** will also decrease **lift**, and, for the reasons given below, lead to an increase in the **landing distance required**.

Air density, you will recall, decreases with increasing altitude and increasing temperature.

In lower air density, lift is reduced at any given value of true airspeed, v. Consequently, in order to maintain the **lift** necessary to support the aircraft in steady flight, whether that be straight and level flight or descending flight, such as on the approach to land, an aircraft will have to fly at a higher **true airspeed as air density** falls. Increased **speed** increases an aircraft's **momentum**, making it more difficult to stop, and, therefore, also increases, increasing the **landing distance required**.

You should be aware that it is particularly difficult for the pilot to detect conditions of low **air density**. **True airspeed**, **v**, must increase to maintain **lift** when **air density falls**; **indicated airspeed** is not affected by changing **air density**, being a measure of the **dynamic pressure**, $\frac{1}{2} \rho v^2$. As ρ falls, **v** increases so that the expression, $\frac{1}{2} \rho v^2$, remains constant, giving a constant **indicated airspeed**. Consequently, the pilot will get no clue from his **airspeed indicator** that **air density** is low.

In order, then, that a pilot may recognise that **air density** is low and, thus, be ready and prepared for longer **landing distances**, he needs to know what the **density altitude** is of the airfield from which he is operating. However, if he uses a **landing performance graph** to calculate the **landing distance required** for his aircraft, on a given day, he enters **pressure altitude** and **temperature** into the graph. As we learnt earlier in the chapter on **Take-Off**, these two factors used together will account for **air density**. But if a pilot has no access to **landing performance graphs** for his aircraft, he may calculate the **density altitude** of the airfield using a **flight navigation computer**. That calculation will tell the pilot whether or not **air density** is of a significantly high or low level. If **density altitude** is significantly different from the **pressure altitude** of the airfield, then the manufacturer's predicted **landing performance** will have to be modified.

For every 1 000 ft increase in altitude or 10ºC increase in temperature landing distance required will increase by approx 5%, or a factor of 1.05.

The drag equation, **Drag = $C_D \frac{1}{2} \rho v^2 S$**, might <u>suggest</u> that if **air density** is low, the drag force acting on the aircraft will also be lower. However, although, in conditions of low **air density**, the aircraft lands at a higher **true airspeed**, for the reasons explained above, the **indicated airspeed**, a function of $\frac{1}{2} \rho v^2$, will be the same whatever the density, because the reduction in ρ is compensated for by the increase in **v**. So, the **drag** force acting on the aircraft during the landing roll will also be the same. Only the higher **true airspeed** is critical; **so the longer landing run is the result solely of the increased momentum of the aircraft.**

High **humidity** also decreases **air density**. Therefore, **if you are operating from a hot, humid, high airfield, be aware of the effect of the prevailing conditions on your aircraft's performance.** For every **1 000 ft** increase in **altitude**, or **10°C** increase in **temperature**, **landing distance** will increase by approximately **5%**; that is, by a factor of **1.05**.

A headwind will decrease the landing distance required and a tailwind increase it. When applying wind to landing distance calculations, it is recommended that only 50% of a headwind should be assumed, but 150% of a tailwind.

Wind, Speed and Direction.

The speed and direction of the **wind** affects **landing distance required** because of the influence of **head and/or tailwind components**, on the ground speed of the aircraft. Just as for the take-off, it is essential that, when calculating **landing distance required**, the pilot calculates the strength of the **head and/or tailwind component** of the wind.

Headwinds will reduce the ground speed for any given indicated air speed and consequently reduce the landing distance required. Tailwinds, on the other hand, will increase ground speed for a given indicated air speed and increase the landing distance required.

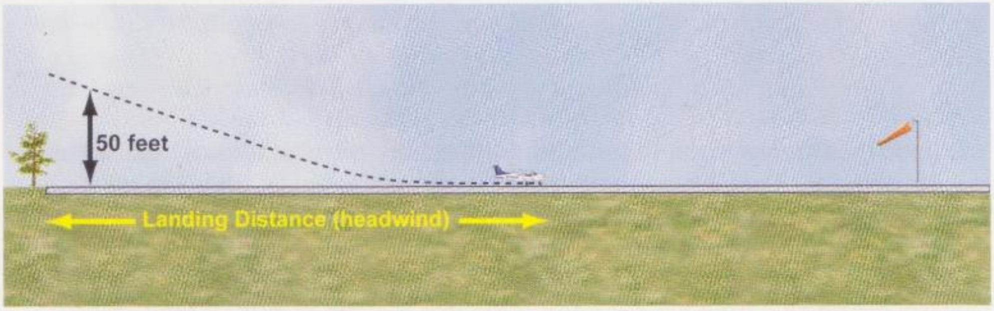


Figure 5.3a A landing with headwind.

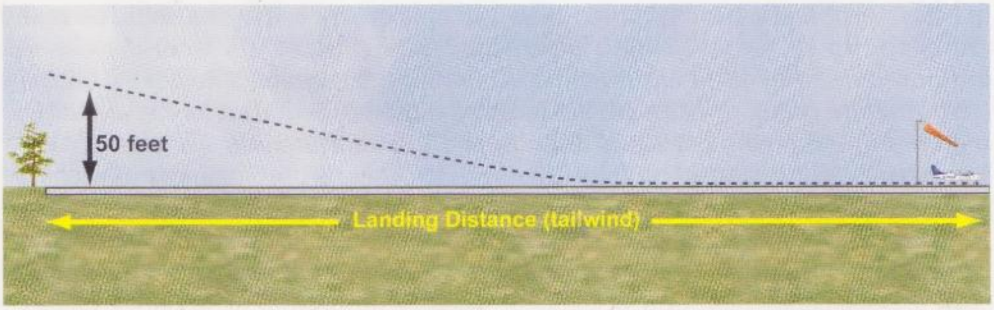


Figure 5.3b A landing with a tailwind.

Any tailwind component will significantly increase the landing distance required, so you must consider very carefully indeed whether a landing can safely be carried out, whenever a **tailwind component** is present. When calculating the **landing distance required**, it is highly recommended by the Civil Aviation Authority that you do not use the reported or observed, momentary **wind strengths** because **wind speed and direction** can vary greatly over a short time. The recommendation is to use **50% of the headwind component** and not less than **150% of the tailwind component**. Many performance graphs have these safety factors already applied.

There are two principal reasons why, whenever possible, the final approach and landing is made **into wind**. As you have already learnt, when landing **into wind**, the **ground speed** will be lower for a given touchdown **airspeed** by an amount equal to **the speed of the headwind component**. In this situation, **the landing distance required will be shorter**. Furthermore, an approach **into wind** gives a **steeper descent path** which, in turn, provides **better obstacle clearance performance**, and will reduce the **horizontal distance covered** during the **round-out and hold-off**. **Both these considerations reduce the overall landing distance required.**

Wind Gradient.

A landing, then, should wherever possible be made **into wind**. However, in **strong and turbulent wind conditions** a pilot must be aware of the effect of **wind gradient** on the performance of his aircraft. As far as the landing is concerned, the term **wind gradient** can be taken to mean ***the progressive decrease in wind speed in the lower layers of air near the ground***. **Wind gradient** is most pronounced when a **strong, gusting wind** is blowing, especially if it is passing over **surface obstacles**. However, **wind gradients** may be present in light winds, too.

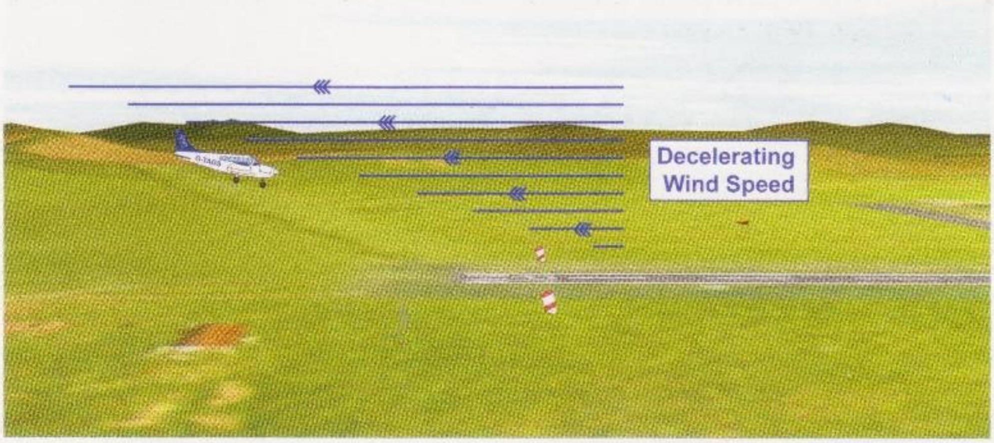


Figure 5.4 Approaching through a wind gradient.

Consequently, when an aircraft is approaching to land in a pronounced **wind gradient**, it is flying through layers of **decelerating wind speed**. (*See Figure 5.4.*) In this situation, the aircraft may suffer a sudden **reduction in indicated air speed**, and, therefore, **lift**, which will cause it to **lose height** suddenly. Sometimes, in very turbulent conditions, this **wind gradient** effect may be accentuated by the presence of downdraughts. Obviously, if the increase in **vertical descent speed** suffered by the aircraft were to occur unexpectedly, the aircraft may **undershoot** the runway badly and hit the ground firmly, causing damage to its structure and injury to its occupants.

So, if you suspect that **wind gradient** is present on the approach, **increase your approach speed** by a suitable amount (seek guidance from your instructor on this) and consider using **power** to arrest the extra rate of descent as the aircraft starts to sink. **Wind gradients** are invisible, but may be expected to be significant in **strong, gusting winds**. Often, pilots who have experienced a **wind gradient** will broadcast that fact over the RT, so listen out carefully for such reports when the wind is strong.

Runway Slope.

If a landing strip is not horizontal, the landing distance required will be affected.

An **uphill slope** to a landing strip will **decrease the landing distance required** because, when rolling uphill, a **component of the aircraft's weight acts rearwards, adding to the braking forces** acting on the aircraft. (*See Figure 5.5.*)

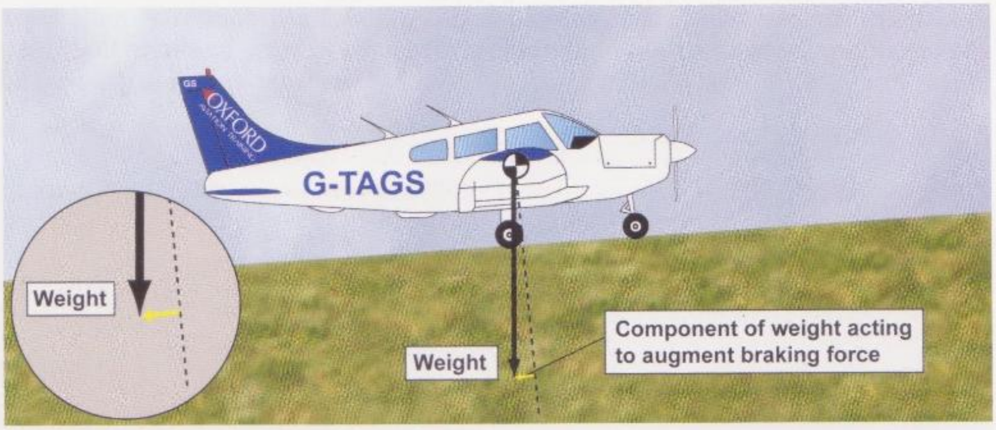


Figure 5.5 Upslope reduces the landing distance required owing to a component of the aircraft's weight acting backwards to augment braking.

Conversely, a **down-hill slope** to a landing strip will **increase the landing distance required** because, when rolling downhill, **a component of the aircraft's weight acts forwards, partially counteracting the braking forces** (rolling resistance and application of brakes) acting on the aircraft (*See Figure 5.6.*)

A down slope increases the landing distance required by 5% for every 1% of slope.

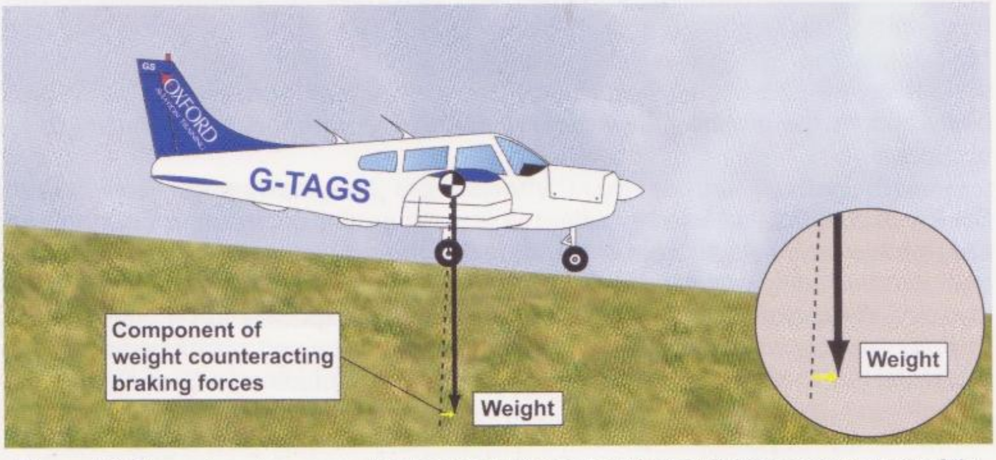


Figure 5.6 Downslope increases the landing distance required owing to a component of the aircraft's weight acting forwards, acting against the braking force.

For every **1%** of **down-slope**, the landing distance required is **increased** by approximately **5%**; in other words, landing distance is increased by a factor of **1.05**. Bear in mind that this is the factor which should be applied to the **landing distance**, that is, from a height of **50 feet** above the landing strip. The increase in the **landing run** will be proportionally greater.

Pilots should treat as a "bonus" any advantage gained from **landing on an up-slope** or **taking off on a down-slope**, and not include any allowance for these two latter circumstances in their performance calculations.

Runway Surface.

Most landing performance graphs assume that the aircraft is landing on a paved hard surface. If the surface of the landing strip is not paved, corrections must be applied to the calculated **landing distance required**.

Many small airfields have grass runways. Grass will increase the rolling resistance of the wheels, but, more importantly, will **reduce** the friction between the tyres and runway. This means that the brakes cannot be applied as firmly as on a paved surface, otherwise the wheels will lock and slip. Consequently, assuming that the wheel brakes are always used, landing on a grass surface will increase the **landing distance required**.

Dry grass of up to **8 inches (20 cm)** in height will increase the **landing distance** by **20%** or a factor of **1.2**, if brakes are used. However, assuming that brakes are not used, landing on grass will shorten the **landing run** and, thus, reduce the overall **landing distance required**, compared to landing on an asphalt surface without brakes.

A wet surface, either grass or paved, will reduce the **friction** between the wheels and the surface, preventing effective braking and increasing the **landing distance required**.

The following approximate factors will help you estimate the effect of different surfaces on **landing distance required**:

- On a **wet hard surface** the landing distance will be increased by **15%**, a factor of **1.15**.
- **Short dry grass** will increase the landing distance by **15%**, a factor of **1.15,** assuming that brakes are used.
- **Wet grass** will increase landing distance by **35%**, a factor of **1.35**.
- If there is **surface snow or slush**, the landing distance will increase by approximately **25%**, which is a factor of **1.25**.

A wet paved surface will increase the landing distance required by 15%, dry grass up to 20 cm by 20%, wet grass up to 20 cm by 35% and soft ground, snow or slush by 25%.

Use of Flap.

As you have learnt elsewhere, both in **Performance** and **Principles of Flight**, the **deployment of flap increases the total drag** acting on an aircraft, thereby **decreasing the lift/drag ratio**. Both these effects of flap influence the **landing distance required**.

The extent to which the use of **flap** increases **total drag** depends on the **angle of flap** selected.

The **drag equation** (**Drag** = $\frac{1}{2} C_D \frac{1}{2} \rho v^2 S$) shows us that **drag is directly proportional to C_D**. **C_D**, as you have learnt, is a measure, among other things, of **aerofoil profile** and **angle of attack**. Lowering **flap** modifies the **profile of the**

aerofoil, and will therefore alter the value of C_D. In general, then, we may conclude that **drag is proportional to the amount of flap selected**. Furthermore, because **lift** must remain constant for a given aircraft on a given flight (ignoring the change in weight resulting from fuel consumption), **as drag increases, the lift/drag ratio will decrease, and, in the approach at any given power setting, the descent angle will be steeper**.

If the pilot selects a large angle of **flap**, then, the increase in **drag** will be large, and, at a given power setting on the approach, or on a glide approach, the **descent angle** will be steeper. **The steeper descent angle, together with the high drag during the ground run, will shorten the landing distance required.** The steeper **descent angle** will, of course, also improve **obstacle clearance performance**.

In addition, lowering **flap** will reduce the aircraft's straight flight **stalling speed**; so both V_{SO} and the **50 feet** airspeed V_{REF} will be lower, resulting in a decrease in the aircraft's **momentum** and a consequent further shortening of the **landing run**.

It follows, then, that the smaller the angle of **flap** deployed, the lower will be the **drag** acting on the aircraft, the better the **lift/drag ratio**, the shallower the **descent angle**, the lower the **obstacle clearance performance**, the higher the **airspeeds** V_{SO} and V_{REF}, and, consequently, the longer the **landing distance required**.

Figures 5.7, *5.8* and *5.9* depict the different **angles of descent** on the **approach** and the differences in the **landing distance required** for an **approach** flown with a **large angle of flap**, a **small angle of flap**, and **no flap**, respectively. In each case, we have assumed that the aircraft achieves the **50 feet screen height** correctly. You can see, however, that if an approach into a field were necessary, following an engine failure, the use of **flap** would increase the aircraft's **obstacle clearance capability**.

The use of flap on final approach and landing reduces V_{REF} and landing distance required, and gives a steeper approach path with a lower nose attitude which improves forward vision.

Figure 5.7 A landing with a large angle of flap selected.

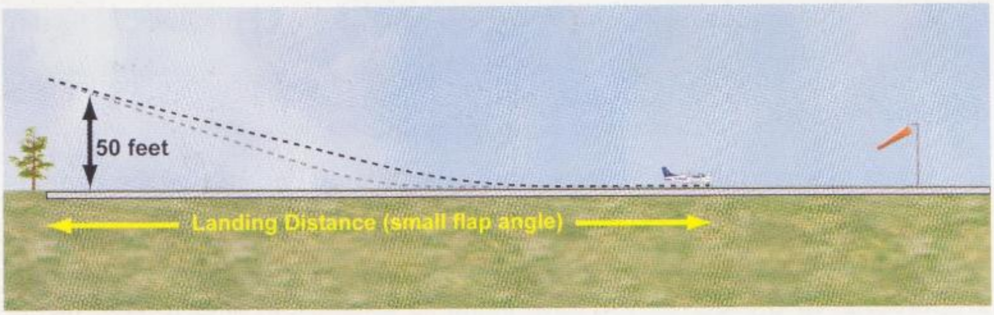


Figure 5.8 A landing with a small angle of flap selected.

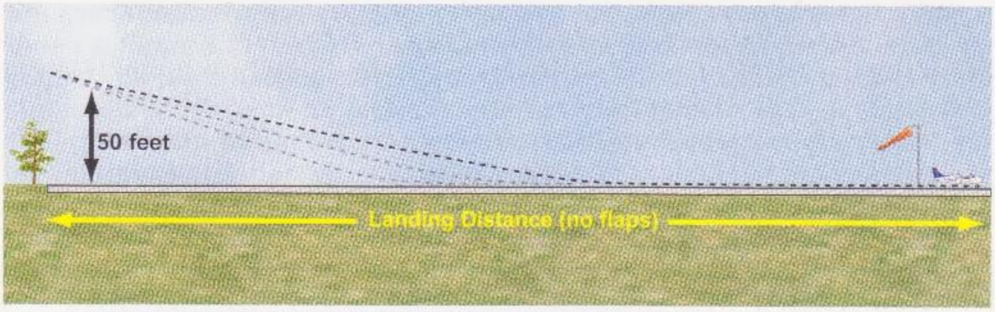


Figure 5.9 A landing with no flap selected.

It is always advisable for the pilot to land using the manufacturer's recommended **landing flap** setting for the aircraft.

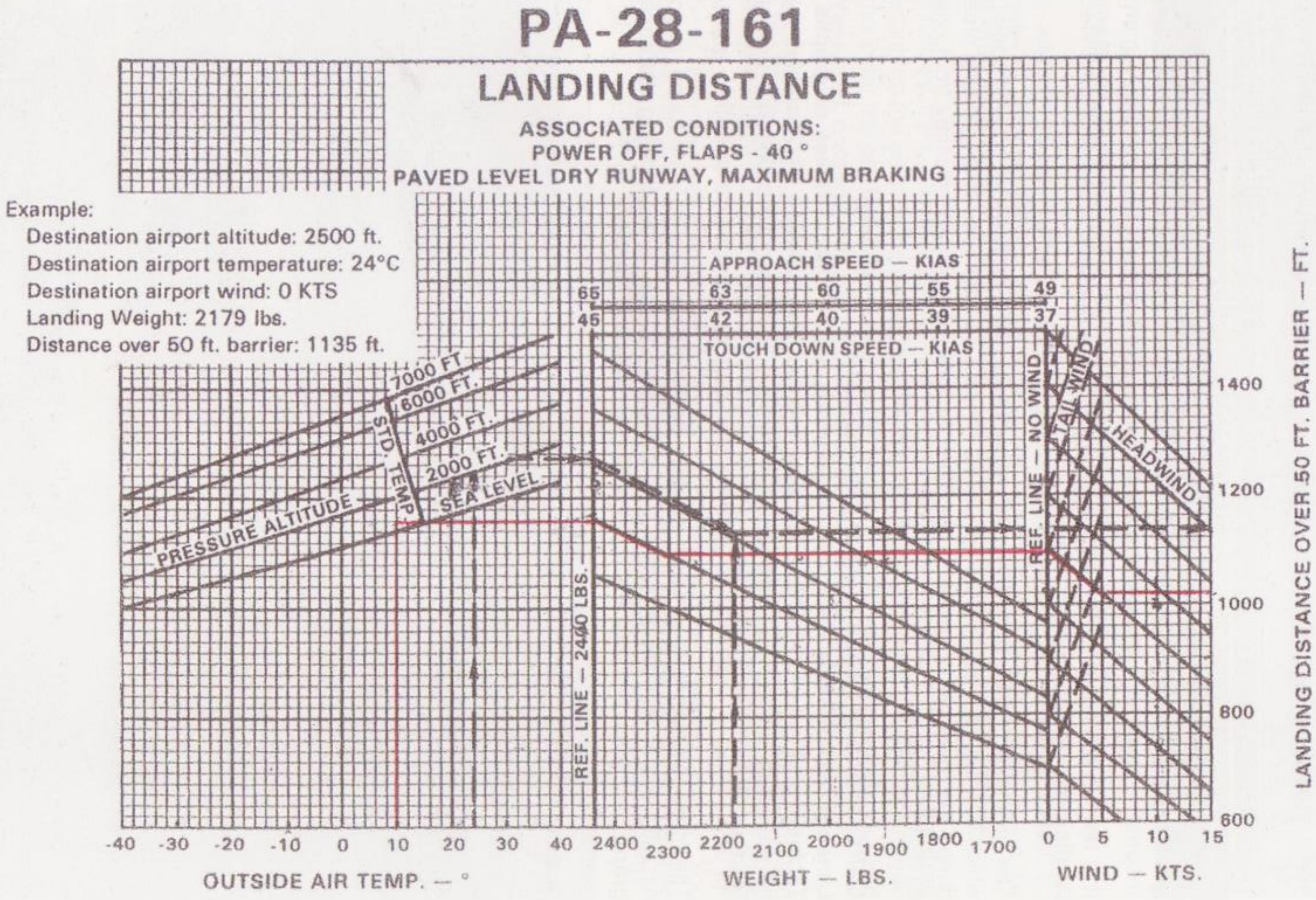
The extension of **flap**, generally, requires a **lower nose attitude** for a given speed, which has the added advantage of giving the pilot a better view of the landing area during the approach. However, the effect of **flap** may vary significantly from one aircraft to another.

Calculations of Landing Distance Required.

Landing performance data may be presented in the form of **tables** or **graphs**. **Tables** are straight forward to interpret and if you have followed the examples we have used in the previous sections, you will have no trouble extracting data from a **landing distance required** table.

The most common form in which **landing performance data** is to be found, in an aircraft's **Flight Manual** or **Pilot's Operating Handbook**, is the **landing distance graph**, such as the one for the **PA-28-161 Warrior** depicted in *Figure 15.10, overleaf.*

Figure 5.9a An airfield with a grass runway. By kind permission of David Henson



Example:

Destination airport altitude: 2500 ft.
Destination airport temperature: 24°C
Destination airport wind: 0 KTS
Landing Weight: 2179 lbs.
Distance over 50 ft. barrier: 1135 ft.

Figure 5.10 Landing distance graph showing example calculation.

You can read from the **associated conditions** box at the head of the graph (also shown at *Figure 5.11*) that the parameters which must be assumed when using the **graph** to calculate **landing distance required** are that the **approach** will be flown with **power off** (from the **50 feet** reference point) and with **40° of flap**. It is further assumed that the landing will be on a **dry, level, paved runway** and that the pilot will use **maximum braking** during the **landing run**.

PA-28-161

LANDING DISTANCE

ASSOCIATED CONDITIONS:
POWER OFF, FLAPS - 40°
PAVED LEVEL DRY RUNWAY, MAXIMUM BRAKING

Figure 5.11 Associated Conditions to be assumed when using the Landing Distance Graph.

If the **associated conditions** are not present at the airfield at which the landing is to be made, or if the pilot selects a different **angle of flap**, or does not select **idle power** at the **50 feet** point, the figures extracted from the **graph** will have to be modified to allow for those deviations from these assumed conditions.

The graph at *Figure 15.10* allows the pilot to calculate the **landing distance required** for approaches flown in accordance with the stated **associated conditions**, for different **pressure altitudes**, **outside air temperatures**, **approach and touchdown speeds**, **aircraft weights** and **wind conditions**.

Example of Calculations of Landing Distance Required.

Let us now carry out an example calculation, as a pilot might wish to do before landing at an airfield with which he is unfamiliar and for which he wishes to compare the **landing performance** of his aircraft against the **landing distance available**.

After checking all the information available from official publications or flight guides concerning his destination aerodrome and obtaining a **weather forecast** for the estimated time of arrival (ETA), the pilot discovers that the following conditions will prevail.

Pressure Altitude of Destination Aerodrome:	500 feet
Surface Air Temperature at ETA:	10° Celsius
Expected Headwind Component at ETA on Runway-In-Use:	5 knots

With the above information and, with the knowledge that the **weight** of our aircraft on landing will be **2 300 lb**, we are now ready to begin our calculation of the **landing distance we will require** on arrival at our destination.

Examining the **landing distance graph**, we see that an example calculation has already been carried out, and that there are dotted vertical and horizontal lines on the graph, which illustrate the manufacturer's example. If we are unsure about how to use the graph, we can work through the manufacturer's sample example, but let us assume that we are already happy about the method to apply, and so we begin. In *Figure 5.10*, our use of the graph is marked by red lines.

It is important to note that correction and safety factors are cumulative, and must be multiplied by each other.

On the left-hand side of the graph, we locate the horizontal **temperature scale** at the foot of the graph and draw a vertical line from the **10° C** mark until it meets a point among the **pressure altitude lines** corresponding to **500 feet**: the **pressure altitude** of our destination airfield. There is no **500 feet line**, so we have to interpolate, choosing a suitable point between the **sea-level** and **2 000 feet** lines.

We then draw a horizontal line from the **500 feet** point to the next **vertical reference line** which marks the beginning of the **weight/approach/touchdown speed** section of the graph. From that reference line, we extend our line parallel to the slope of the nearest **weight-line** down to a point which corresponds to our expected **landing weight of 2 300 lbs**, read from the horizontal scale at the foot of the graph.

We note, reading vertically upwards to the **approach and touchdown speed scales**, that the speed at which we should fly our approach, at our landing weight of **2 300 lb**, is **64 knots**, as near as makes no difference, and that out touchdown speed should be **43 knots**.

Drawing, now, a further horizontal line towards the **vertical reference line** which marks the beginning of the **wind section of the graph**, we extend our line parallel to the nearest **downwards-sloping headwind line** to a point which corresponds to **5 knots** on the horizontal scale at the foot of the graph.

From that point we conclude the graph part of our calculation by drawing a horizontal line to meet the vertical scale at the extreme right-hand side of the graph which gives the **landing distance required**. We read from that scale that the **landing distance that we require is 1020 feet**. We note that this distance is the **horizontal distance** from the **50 feet screen height**, assuming a **V_{REF}** of **64 knots** at that height, to the point on the landing strip where, after applying brakes, we should come to a stop, provided all of the **associated conditions** apply.

Finally, we complete the calculation for our particular flight by applying any **correction factors** which must be applied to allow for any deviation from the **associated conditions**. For instance, if the surface of the landing strip was **short dry grass**, we would need to multiply **1 020 feet** by **1.15** to give us **1 173 feet**, and if the strip also had a **2% down slope in the landing direction**, we would have to multiply **1 265 feet** by **1.10** to give **1 290 feet**. (Note that when more than one correction factor applies, each new factor requires a further multiplication.) If other conditions prevailed, for instance, if the landing surface were wet, further factors would have to be applied.

The last action of all which should be taken is to multiply whatever answer we have arrived at by the **recommended overall safety factor of 1.43 for the landing**, to account for the fact that the graph's data assumes ideal conditions, a new and perfectly maintained aircraft, flown by an expert pilot. So, if we were landing on a **dry, short-grass strip with a 2% down-slope**, we would multiply **1290 feet** by **1.43** to give us a net **landing distance required** of **1 845 feet**.

This is the distance we must compare with the Landing Distance Available at our destination airfield.

If the **landing distance available** does not provide a generous safety margin over and above the calculated **landing distance required**, make sure that you set your

aiming point appropriately for the **approach**, that you maintain your **aiming point** correctly throughout the **approach**, and that you keep to the recommended **approach speed**. If you misjudge your **approach** make an early decision to go around.

Conclusion.

Whatever the phase of flight, but especially on **take-off** and **landing**, it is of crucial importance that pilots be aware of the **performance capabilities and limitations** of their aircraft. Many performance-related accidents have occurred where aircraft fail to get airborne on take-off, collide with obstacles on the climb-out, or overrun the runway on landing. Inevitably, such accidents are most likely to occur at small, grass airfields, especially if the strip in use is wet and/or soft, with a pronounced slope, and on a day when there is zero headwind component, or a tailwind component, on the runway-in-use.

Unless the dimensions of an airstrip, the prevailing conditions and the nature of the terrain surrounding the airfield are such that there is absolutely no doubt whatsoever that you can take-off and/or land with a healthy margin for error, you must carry out the **appropriate performance calculation** using the graphs in the **Pilot's Operating Handbook (POH)**, applying all the **correction and safety factors** that you have learnt about in this and the preceding chapters.

Remember that, when several correction factors apply to the performance data extracted from graphs, every applicable factor involves a further multiplication being made to your landing distance required.

Always apply the **overall safety factors**, **1.33 for take-off and 1.43 for landing**, which are mandatory for public transport flights and strongly recommended for general aviation flights. These **overall safety factors** are designed to take into account **a pilot's inexperience** or **lack of currency**, **the age and condition of the aircraft**, and **less than favourable ambient conditions**.

Finally, before using the performance figures contained in the **POH**, always check whether any **CAA Change Sheets and/or Supplements** instruct that modifications of the **POH performance data** apply.

Representative PPL - type questions to test your theoretical knowledge of Landing Performance.

1. What effect would a 2% down-slope have on the landing distance required?

    a. Increase it by 5%
    b. Decrease it by 5%
    c. Increase it by 10%
    d. Decrease it by 10%

2. Compared to a level runway, what would be the effect of landing on a downward sloping runway?

    a. The landing performance will improve
    b. The landing distance will be decreased
    c. The landing distance will be increased
    d. The landing distance will be unaffected

3. Landings are carried out into wind because:

    a. it increases the ground speed and reduces the landing distance required
    b. it decreases the ground speed and reduces the landing distance available
    c. it gives the pilot greater control over the aircraft at lower speeds..
    d. it will reduce the ground speed and reduce the landing distance required

4. If the stalling speed in the landing configuration is 55 knots, V_{REF} would be approximately:

    a. 65 knots
    b. 75 knots
    c. 71 knots
    d. 69 knots

5. If the aircraft mass is increased by 15%, the landing distance required will increase by approximately:

    a. 15%, or a factor of 1.15
    b. 33%, or a factor of 1.33
    c. 10%, or a factor of 1.1
    d. 20%, or a factor of 1.2

6. Why is flap used for landing?

   a. The approach speed is increased and a flatter approach path is flown which improves forward vision
   b. The approach speed is reduced and a steeper approach path is flown which improves forward vision
   c. The approach speed is reduced and a flatter approach path is flown which improves forward vision
   d. The approach speed is increased and a steeper approach path is flown which improves forward vision

7. If the approach and landing speeds flown in an actual landing are higher than the speeds recommended in the aircraft manual, the effect will be that:

   a. the landing distance will be increased
   b. the landing distance will be decreased
   c. the landing performance will improve
   d. the landing distance will be unaffected

8. The V_{REF} to be achieved by the landing screen height of 50 feet must be:

   a. 1.15 times the stalling speed in the take off configuration
   b. 1.3 times the stalling speed in the landing configuration
   c. 1.43 times the stalling speed in the landing configuration
   d. 33% of the stalling speed

9. When landing, if an aircraft's indicated airspeed is lower than its true ground speed, then the aircraft is experiencing:

   a. a tailwind
   b. a headwind
   c. increased atmospheric pressure
   d. a 90° cross wind

10 . What is the effect of an increase in mass on the stalling speed and landing distance required?

   a. Increased stalling speed and decreased landing distance
   b. Decreased stalling speed and decreased landing distance
   c. Increased stalling speed and increased landing speed
   d. Decreased stalling speed and increased landing distance

Question	1	2	3	4	5	6	7	8	9	10
Answer										

The answers to these questions can be found at the end of this book.

JAR-FCL PPL THEORETICAL KNOWLEDGE SYLLABUS FLIGHT PERFORMANCE AND PLANNING.

The table below contains the principal topics and subtopics from the current outline syllabus for the theoretical examination in **Flight Performance and Planning** for the **Private Pilot's Licence**, as published in **JAR-FCL 1**. In this book, **Flight Performance and Planning** is covered in the section **Aeroplane Performance**. Syllabuses may be modified, so always check the latest examination documentation from your **national civil aviation authority**, or from **JAR-FCL/EASA**.

In the United Kingdom, **Flight Performace and Planning** is examined in the same paper as **Mass & Balance**.

FLIGHT PERFORMANCE AND PLANNING	
PERFORMANCE	
Take-off:	take-off run and distance available; take-off and initial climb; effects of mass, wind and density altitude; effects of ground surface and gradient; use of flaps.
Landing:	effects of mass, wind, density altitude and approach speed; use of flaps; ground surface and gradient.
In flight:	relationship between power required and power available; performance diagram; maximum rate and maximum angle of climb; range and endurance; effects of configuration, mass, temperature and altitude; reduction of performance during climbing turns; gliding; adverse effects (icing, rain; condition of the airframe; effect of flap).

ANSWERS TO THE AEROPLANE PERFORMANCE QUESTIONS

ANSWERS TO THE AEROPLANE PERFORMANCE QUESTIONS

Chapter 1 *Introduction*

No Questions

Chapter 2 *Take-Off*

Question	1	2	3	4	5	6	7	8	9	10	11	12
Answer	a	c	a	c	d	b	b	c	d	d	a	b

Chapter 3 *Climb*

Question	1	2	3	4	5	6	7	8	9	10	11	12	13
Answer	b	b	d	c	d	c	d	a	b	c	a	d	a

Chapter 4 *En-Route Performance*

Question	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Answer	c	c	b	c	c	b	a	d	b	a	b	b	a	d	d	c	a	a

Chapter 5 *Landing*

Question	1	2	3	4	5	6	7	8	9	10
Answer	c	c	d	c	a	b	a	b	a	c

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