7 More About Energy and Power

7.1 Introduction

There is an age-old conundrum in the pilot community: Some people suggest that the yoke controls altitude while the throttle controls speed (just like in a car). Other people suggest just the reverse, namely, that the yoke controls airspeed while the throttle controls altitude.

So, which is correct?

Answer: neither one is correct. Both suggestions are based on wishful thinking. You might *wish* for an airplane where one control changes altitude and nothing else, while another control changes speed and nothing else, but that is not how real airplanes work.

The truth is simple enough:

- The yoke (in conjunction with trim) controls angle of attack, and hence determines airspeed. Airspeed is linked to altitude via the law of the roller-coaster and via the power curve.
- The throttle controls power. Power can be used to overcome drag, to speed up, and/or to climb.

This is the right way to think about the issue.

I like to say "the yoke is the main speed control, but it is not *just* the speed control". That is, if you want to change speed you simply must move the yoke and/or trim.[1] However, moving the yoke and/or trim has multiple effects: there is a not just a speed change but also a short-term change in altitude because of the law of the roller-coaster, plus a long-term change in altitude because of the power curve.

Your piloting performance is sometimes judged on how well you maintain your assigned altitude and airspeed. Since you do not have a simple up/down control or a simple fast/slow control, even seemingly simple maneuvers require using *combinations* of controls. Let's look at some examples.

7.2 Making Changes in Airspeed

Once upon a time, a friend of mine bought a fancy new airplane. Although he already had lots of experience piloting complex aircraft, this was a step up in performance, so he thought it would be wise to get lots of instruction, including a week-long course at an internationally-famous training center. Even so, after dozens of hours of experience in the new plane, he still didn't feel "in command". He kept getting into unpleasant high-workload situations. Among other things, he complained that it took forever to get the thing slowed down.

When I discussed this with him, it didn't take long to discover a couple of easily-fixable problems. For starters, he had been told to control airspeed using the throttle. He had the firm impression that to reduce speed somewhat, he should just close the throttle somewhat. I pointed out that such an idea couldn't possibly be right, for two reasons:

- Being high and fast is very different from being low and fast, so any rule of the form "if you are fast do such-and-such" must be dangerously wrong.

- Even when the right procedure calls for closing the throttle, you don't "just" close the throttle, for reasons that we now discuss.

This discussion assumes you want to change airspeed while maintaining straight-line flight. This includes straight and level flight, and it also includes the important case of final approach, where you are descending on a straight line, following a nice stable glideslope.

7.2.1 Front Side of the Power Curve

Figure 7.1 shows the obvious but not-recommended procedure for slowing down on the front side of the power curve.

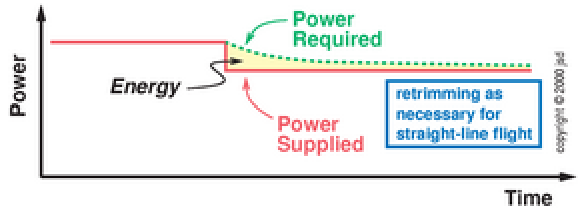


Figure 7.1: Slowly Slowing Down on the Front Side of the Power Curve

Since flying at lower speed requires less power, if you just reduce the power the right amount (as shown by the solid red curve), the airspeed will eventually dribble down. The power required is shown by the dashed green curve; it gradually decreases as the airspeed decreases.

The problem with this technique is that the airspeed keeps decreasing for a very long time. You will need to retrim over and over and over.

Slowing down means shedding kinetic energy. The area between the two curves[2] shows exactly how much kinetic energy you have shed.

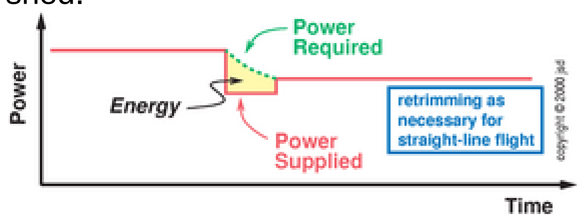


Figure 7.2: Cleverly Slowing Down on the Front Side of the Power Curve

Figure 7.2 shows a much cleverer procedure. The idea is to make a *temporary* reduction in power that is big enough so that the airplane slows down in a reasonable time. Then you can re-open the throttle to maintain the desired final outcome. If you do a little extra work with the throttle, you will do a lot less work with the other controls --- and you will get a nicer result (getting slowed down sooner).

Remember, slowing down requires shedding kinetic energy, as indicated by the area between the curves. The area in this figure is the same as the area in the previous figure; we have just "collected" the area so that we can shed the energy in a reasonably short time. That means you don't have to spend the rest of your life re-trimming as the airspeed gradually changes.

7.2.2 Back Side of the Power Curve

Imagine you are on final approach. On long final you are maintaining a speed near V_Y (a normal approach speed in many aircraft), using 1700 RPM of engine power. Then, suddenly, the tower controller asks that you land and hold short of a crossing runway. You decide to convert the normal approach to a short-field approach. This requires slowing down from V_Y to a somewhat slower speed.

The procedure is shown in figure 7.3.

You need to shed some kinetic energy, as shown by the shaded area in the figure. Since that always takes time, you should immediately retard the throttle. You are now getting rid of mechanical energy (via drag) faster than it is being replaced (via the engine). You want to pay for this energy deficit by cashing in airspeed, not altitude, so you must pull back on the yoke and then roll in some nose-up trim to get rid of the force on the yoke. When the airspeed reaches short-field approach speed, you re-open the throttle. Returning to 1700 RPM will not suffice; you will need *more* power to complete the approach at this low speed than it would have at the higher speed.

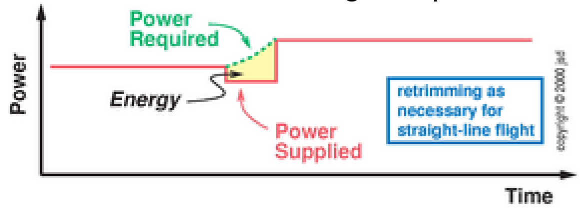


Figure 7.3: Slowing Down on the Back Side of the Power Curve

This is an interesting contrast with the previous situation (e.g. figure 7.2). The required power *increases* as the airspeed decreases. Therefore you do not even have the option of making the speed-change with only one power-change. It requires two (opposite and unequal) power changes.

7.2.3 Right versus Wrong Procedures

Another view of what is happening is shown in figure 7.4. The red dashed line shows the descent angle needed to remain on the glideslope; that is, the needed descent rate is proportional to airspeed (in no-wind conditions). You started out at point *A*, using 1700 RPM. You are now at point *B*, using more than 1700 RPM to remain on the glideslope.

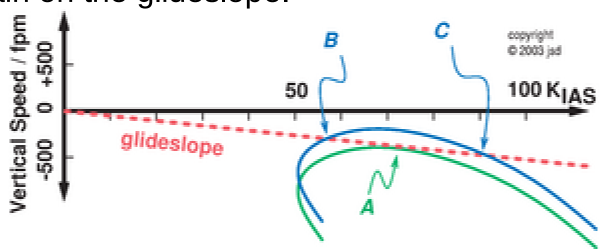


Figure 7.4: Energy Management on Approach

This combination of controls (close the throttle a little, pull the nose up, then open the throttle more than a little) is the only way to slow down without an altitude excursion when you are in the mushing regime.

The analysis given above --- thinking about the energy change in terms of the area between the two curves --- is simple, practical, and absolutely correct.

In contrast if you tried to analyze this maneuver in terms of an up/down control versus a fast/slow control, it would be very confusing. Let's try it anyway.

- Suppose you think of the yoke as purely the fast/slow control and the throttle as purely the up/down control. At the moment you decide to convert to the short-field approach, your only problem appears to be excess airspeed. Therefore you pull back on the yoke. Poof! You slow down sure enough, but you go above the glideslope in the process. You notice this, and reduce the throttle. You gradually descend back onto the glideslope. You re-open the throttle to 1700. That doesn't quite suffice, so you slowly drop *below* the glideslope. You notice this before too long and add power. Eventually find the right combination of settings. Summary: you get the job done, but it is rather sloppy. You have unnecessary altitude excursions and airspeed excursions, and you do some unnecessary work.

- In contrast, now suppose you think of the yoke as the up/down control and the throttle as the fast/slow control. At the moment you decide to slow down, you close the throttle a little. Contrary to your wishes, the airplane does not slow down; in fact it probably speeds up a little.[3] You pull on the throttle a little more. Still no decrease in speed. Now the airplane is starting to descend below the glideslope. You notice this and pull back on the yoke. Now things seem (but only seem) better, since you are now back on the glideslope at a reduced airspeed.

  At this point you are in real danger. You are losing energy rapidly, because you are operating on a draggy part of the power curve with a reduced throttle setting. The energy deficit must be paid by cashing in altitude and/or airspeed. Unfortunately, most pilots, especially beginners, pay more attention to altitude than to airspeed. As you lose energy you will keep pulling back on the yoke to maintain altitude. This allows you to stay on the glideslope in the short run --- but at a terrible cost. You might very soon cash in *all* of your airspeed.

  Let's hope that you notice the decreasing airspeed before you stall. Using the (fallacious) idea that the throttle controls airspeed, you shove open the throttle. This does not immediately cause the airplane to speed up; in fact it probably causes a slight decrease in speed (which is definitely not what you need right now). It also causes you to start climbing above the glideslope. You notice this and shove forward on the yoke.

  You might eventually stumble onto the right combination of yoke and throttle, but the process won't be pretty.

Conclusion: trying to pretend that the airplane has a pure up/down control or a pure fast/slow control is a losing proposition.

The yoke works by moving certain control surfaces at the back of the airplane. Fifty years ago, Langewiesche (reference 1) named those surfaces the *flippers*. He wisely refused to call them "elevators" lest you think that their primary effect was to "elevate" the airplane.

The flippers primarily control airspeed,[4] not elevation.

Of all the oversimplified wishful-thinking ideas, the notion that the yoke is the up/down control is the most deadly. You may think that neither you nor anybody else would be dumb enough to keep pulling back until the stall occurs --- but the accident statistics indicate otherwise. The stall/spin accident is the #1 most-common type of fatal accident, year in and year out.

Stall/spin accidents occur during departure as well as approach. Once again, during departure the airplane is normally at or near V_Y, so the notion that the yoke is the up/down control is guaranteed to be wrong --- dangerously wrong.

The problem is compounded because during approach and departure the airplane is at low altitude. At a higher altitude you would have more time to figure out the problem, and you would be able to regain vital speed by cashing in some altitude.

7.3 You Can Get Away With A Lot During Cruise

You may be wondering how such a dangerous notion could be come so widespread. The answer is simple: the notion that yoke is the up/down control appears to work, *most* of the time.

Nearly all of your pilot time is spent in normal cruising flight. Now suppose at some point you find yourself 100 feet below your desired cruising altitude . What do you do? You pull back on the yoke. This is what everybody does. It works. There's nothing wrong with it.

Here is the detailed analysis: You start out with a shortage of altitude which implies a shortage of mechanical energy. In the short term you can't change the mechanical energy, but you can convert airspeed into altitude using the law of the roller-coaster.

At this point you have returned to the desired altitude. You are still low on energy, but since the new airspeed is closer to V_Y, you are on a less-draggy part of the power curve and you will eventually make up the deficit. As the airspeed rebuilds, you gradually release your tug on the yoke. You don't need to touch the throttle during this maneuver.

There is an important assumption in this analysis that often goes unstated: Most pilots are very aware of their precise altitude, but (alas) not nearly so aware of their precise airspeed. Similarly: most flight instructors, air traffic controllers, and checkride examiners will complain immediately if you deviate from your assigned altitude, but they hardly ever seem to notice or care about airspeed excursions. This is not 100% logical, but it is a fact of life.

In this scenario, we corrected for an altitude excursion by means of an airspeed excursion. Under the circumstances, it was a perfectly reasonable thing to do.

For comparison, here's a scheme for correcting the same 100-foot altitude excursion *without* an airspeed excursion. You notice that you have an energy shortage, so you open the throttle a little. The airplane will enter a nice climb, with negligible change in airspeed. When you reach the assigned altitude, you return the throttle to its previous setting and the maneuver is complete. You leave the yoke and trim alone.[5]

This scheme might seem like the ideal way to perform the correction maneuver, but it is very rarely used in practice. There are a couple of reasons for this.

- Commonly, the purpose of the flight is to get somewhere as quickly as possible. Therefore, in cruising flight, the throttle is already as far open as it should go. When a shortage of mechanical energy develops, increasing the engine output is not an option. The only option is to choose a less-draggy speed (closer to V_Y) while the energy rebuilds.
- If you make a temporary reduction in speed by pulling on the yoke, when you let go the airplane will return to its previously-trimmed speed. It's simple. In contrast, there is no corresponding idea of "throttle trim". If you move the throttle temporarily, it is not particularly easy to move it back to exactly the right place afterward. What's worse, you also need to worry about the mixture control and (possibly) the engine RPM control. Making a temporary change in power might require moving *three* controls (or *six* controls in a twin), and it would be an obnoxious task to get them all back to their proper positions afterward.

I repeat that the aerodynamically logical way to fly the airplane precisely is to trim for the airspeed you want and then manage the altitude with the throttle. When in doubt, do it this way. If you were a 100% logical Vulcan you might do it this way all the time. However, during cruise, it is more convenient to leave the throttle alone, use the yoke as if it were the up/down control, and accept modest airspeed excursions.

It is OK to use the yoke as the up/down control provided:

- you are on the front side of the power curve, and
- you are willing to accept airspeed excursions.

The second proviso is just as important as the first. Suppose you decide to descend to a substantially lower altitude. You could do this by shoving forward on the yoke and/or dialing in lots of nose-down trim, but if you're not careful you could exceed the maximum normal-operations speed. As always, when in doubt, trim for the airspeed you want and then manage the energy situation by controlling engine power and/or controlling drag.

> It is OK to use the yoke as the up/down control provided you are on the front side of the power curve, and provided you are willing to accept an airspeed excursion.

7.4 Let "George" Do It

Sometimes I get a student who says "The yoke *has* to be the up/down control. I know because the autopilot controls altitude just by moving the yoke".

All I can say is that autopilots are not exempt from the laws of physics --- the power curve and the law of the roller-coaster. The same rule applies: "George" (the autopilot) can control altitude using just the yoke provided you are on the front side of the power curve *and* you are willing to accept airspeed excursions.

This point is so important that I will analyze the short-field approach scenario one more time --- using the autopilot.

Refer back to figure 7.4. You start out at point *A*. The autopilot is using the yoke as if it were the up/down control, trying to keep you rigorously on the glideslope. When you decide to slow down, you retard the throttle, whereupon the autopilot pulls back on the yoke, keeping the airplane on the glideslope by cashing in some airspeed. When the airspeed reaches short-field approach speed, you re-open the throttle.

You are now at point *B*. Things appear OK, but they're not. You're going to get into trouble, in one of two ways:

- Suppose a momentary updraft carries the airplane above the glideslope. The poor dumb autopilot will push forward on the yoke. This will convert the excess altitude to airspeed. The airplane will return to the glideslope, but since its new airspeed is closer to V_Y, it will tend to climb. The more it climbs, the more the autopilot will push forward on the yoke. This unstable feedback process will continue until the airplane reaches point *C* --- the other point where the airplane can stay on the glideslope with the chosen amount of power. Since this point is on the front side of the power curve, "George" can get away with controlling the altitude using just the yoke. This is not, of course, a good short-field approach speed.

This airspeed excursion from point *B* to point *C* will probably leave you unable to complete the approach. You can go around and try again. This may be disappointing, but there is something much worse that could have happened starting from point *B*.

- Using the same logic, let's see what happens supposing at point *B* a *downdraft* carries the airplane *below* the glideslope. The poor dumb autopilot will pull back on the yoke. This will convert some airspeed to altitude. The airplane will return to the glideslope, but since its new airspeed is farther than ever from V_Y, you will tend to descend. The more you descend, the more the autopilot will pull on the yoke.

  This is crazy! The autopilot is performing the "flare" maneuver while you are still way out on final approach, cashing in all your airspeed in the vain attempt to maintain altitude! At this throttle setting, there is simply not enough energy to carry the airplane along the glideslope at any speed below point *B*, and pulling back on the yoke temporarily disguises and permanently worsens the problem.

  We hope that the autopilot runs out of pull-back authority before it causes the wings to stall. In either case, the airplane is going to descend below the glideslope.

The only way out of this mess is to notice that you have an energy shortage. The sooner you open the throttle the better off you'll be. If you want to prevent problems of this sort, don't try to control altitude using the yoke unless you're on the front side of the power curve *and* you're willing to accept airspeed excursions. The easiest way to control both airspeed and altitude is to trim for the right airspeed, leave the yoke alone, and control altitude with the throttle.

7.5 Max Performance using the Power Curve

The purpose of this section is to get a deeper understanding of the power curve, and to see how it applies to maximum-performance climbs and descents. If you aren't interested in such details, you can skip to the next section.

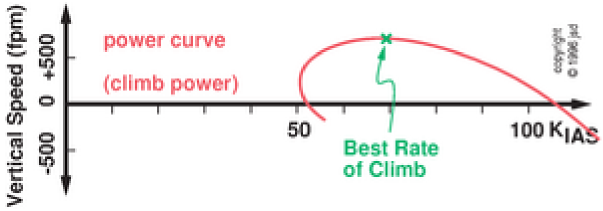
7.5.1 Calibrated Airspeed

Wing performance depends on angle of attack and on calibrated airspeed in accordance with equation 2.1. Therefore if you know the calibrated airspeed, you don't need separate information about altitude, density, or humidity, in order to determine wing performance, as discussed in section 2.12.

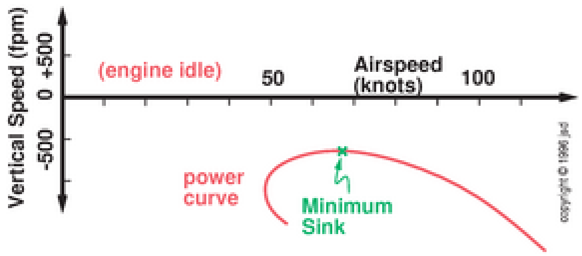
Engine performance is a more complicated question, as we now discuss.

7.5.2 Best Rate of Climb

Let's start by comparing figure 7.5 to figure 7.6. As shown in figure 7.5, the highest point on the power curve represents the best rate of climb. The corresponding airspeed is denoted V_Y.



[Figure 7.5](#): Best Rate of Climb



[Figure 7.6](#): Minimum Sink, Best Endurance Glide

Similarly, as shown in [figure 7.6](#), the highest point on the power curve is the point that causes the minimum sink rate. This gives the maximum *time* aloft. Again, the corresponding speed is denoted V_Y. Don't think of V_Y as a hard-and-fast number, but rather as a function $V_Y(...)$, because the value of V_Y depends strongly on weight and weakly on altitude, engine power setting, flap setting, and other variables, for reasons discussed in [section 7.5.6](#).

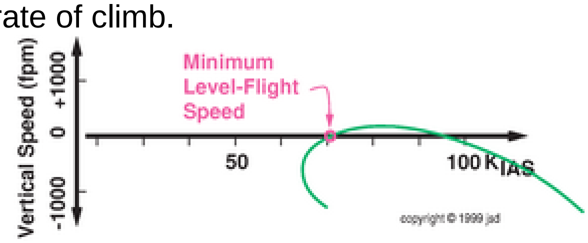
If V_Y is given in your POH as a simple number, that number is the value of V_Y at max weight and full power at sea level in the clean configuration. The POH silently assumes you are smart enough to correct for non-standard weight as explained in [section 7.5.8](#).

The point is that in all cases V_Y is the name we associate with maximum climb and/or minimum sink.

Not coincidentally, V_Y marks the boundary between the "front side" and the "back side" of the power curve. As discussed in [section 1.2.5](#) and [section 1.3.3](#), you have to know whether you are above or below this special airspeed to know whether speed changes will give you a long-term climb or a long-term descent.

[7.5.3](#) Minimum Level-Flight Speed

Another point on the power curve that is sometimes important is shown in [figure 7.7](#). If there is a point *in the mushing regime* where the power curve crosses zero, I will call the corresponding V_Z, the airspeed where there is zero rate of climb.



[Figure 7.7](#): Minimum Level-Flight Speed

In many airplanes, when the engine is developing full power there is no such point; the airplane can climb even at the critical angle of attack, as shown in [figure 7.5](#). On the opposite side of the same coin, with zero engine power, there is once again no such point as V_Z; the airplane cannot maintain level flight at any airspeed. Therefore the concept of V_Z is only useful in certain circumstances; these include: your airplane's engine could be small by design, or you could be operating at an altitude close to the airplane's absolute ceiling,[6] or you could be having some mechanical problems.

Imagine you are flying at V_Z, with the throttle already wide open, and you want to climb and maintain a higher altitude. Your only option is to *dive*. The dive will give you an airspeed higher than V_Z, closer to V_Y, and by maintaining this new airspeed you will be able to climb.

You can see that flying at V_Z just above the treetops would be a very bad situation. You would not be able climb at V_Z and you would not be able to speed up without diving. It's one of those situations where the rich get richer and the poor get poorer, in the sense that if you had just a little more airspeed you would be able to accelerate. The only real solution is to make sure you never get into such a situation.

Such a situations can arise from a botched takeoff, perhaps a soft-field takeoff, where you try to depart before you have sufficient airspeed. Related issues are discussed in section 13.3 and section 17.2.5.

Remember that V_Z is defined to be in the mushing regime; the corresponding zero-climb point on the front side of the power curve is completely benign. On the front side you can always climb; all you need to do is pull back on the yoke.

7.5.4 Best Angle of Climb

We see that the power curve is rather flat on top. That means that if you fly a couple of knots faster than V_Y, your rate of climb will hardly be affected at all. You will reach your destination a percent or two sooner, so this sort of "cruise climb" is generally a sensible thing to do.

A more interesting situation arises when you *don't* want to get where you are headed any sooner than necessary --- such as when you are trying to climb over an obstacle. In this case it makes sense to climb at an airspeed a few knots below V_Y. The more you slow down, the more time you will have to accumulate altitude before reaching the obstacle. But don't get carried away; the power curve tells you that if you slow down enough, you will degrade the climb performance to the point where further reductions in airspeed don't pay.

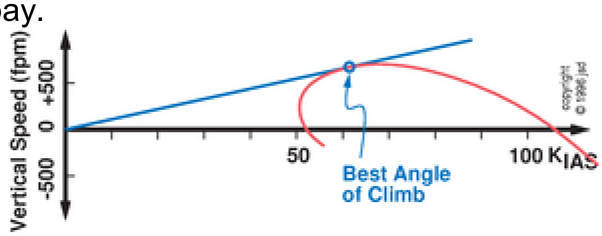


Figure 7.8: Best Angle of Climb

As indicated in figure 7.8, the optimal strategy for clearing a far-away obstacle is to maintain the best angle of climb. This is achieved at the point where the tangent to the power curve goes through the origin. That means that small changes in airspeed are causing exactly proportionate changes in rate of climb, hence no change in angle of climb. The airspeed where this occurs is denoted V_X. Larger changes away from V_X can only degrade the angle of climb.

We now consider the situation during a descent. This could happen because the aircraft is above its absolute ceiling (which is the normal situation for gliders) or because the engine is operating at a reduced power setting.

If all you want is maximum time aloft, you should fly at V_Y as discussed above. If, however, you want to clear an obstacle and/or glide to a particular place fairly far away, you care about distance (not just time aloft). Once again we observe that the power curve is rather flat on top. That means that if you glide a couple of knots faster than V_Y, your time aloft will hardly be affected at all, but you will get to your destination sooner, as indicated in figure 7.9. This gives you a better chance of getting there before you run out of altitude.

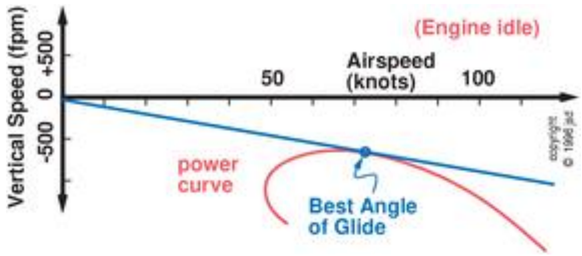


Figure 7.9: Maximum Distance Glide

We can use the tangent trick again. The best distance (i.e. best angle) is achieved at the point where the tangent to the power-off power curve goes through the origin. That means that small changes in airspeed are causing exactly proportionate changes in descent rate.

Once again, the airspeed where you get the best angle can be denoted V_X even though in this case it is a descent angle not a climb angle. In the particular case where you have exactly zero engine power, the best angle occurs right at the point where the aircraft achieves its best lift-to-drag ratio. The airspeed where this occurs is denoted $V_{L/D}$.

7.5.5 Power Depends on Altitude via True Airspeed

Let's compare high-altitude flight with low-altitude flight at the same angle of attack. Assume the weight of the airplane remains the same. Then we can make a wonderful chain of deductions.

At the higher altitude:

- the lift is the same (since lift equals weight)
- the lift-to-drag ratio is the same (since it depends on angle of attack)
- the drag is the same (calculated from the previous two items)
- the thrust is the same (since thrust equals drag)
- the indicated airspeed is the same (to produce the same lift at the same angle of attack)
- the true airspeed is greater (because density is lower)
- the power required is greater (since power equals drag times TAS)

The last step is tricky. Whereas most of the aerodynamic quantitites of interest to pilots are based on CAS, the power-per-thrust relationship depends on TAS, not CAS.[7]

This means that any aircraft requires more power to maintain a given CAS at altitude. This applies to propellers, jets, and rockets equally.

Another way of getting the same result is to observe that the drag *force* is the same, so getting from point *A* to point *B* requires the same amount of energy --- since energy is just force times distance. On the other hand, at altitude the airplane gets from *A* to *B* more quickly, because of the increased TAS. This requires more power, i.e. more energy per unit time.

This has no direct effect on V_Y or V_S, or on the general shape of the power curve; it just shifts the curve downward by a scale factor. At high altitudes, this shift will have a huge effect on cruise speed and rate of climb.

7.5.6 Other Power and Altitude Effects

There are lots of additional insights to be gained from thinking about the power curve and its tangents.

- During a climb, the airspeed for best angle of climb is necessarily less than the airspeed for best rate of climb.
- The V_X(•••) function increases as power decreases, as you can see by mentally moving the red curve downward in figure 7.8.
- An interesting case occurs when the airplane is at its absolute ceiling. Then full power is barely enough to maintain level flight at V_Y. The tangent (through the origin) is horizontal, so V_X must be equal to V_Y.
- In a descent, the airspeed for best (flattest) angle of glide is necessarily greater than the airspeed for best (slowest) rate of descent, as you can see in figure 7.9. This might not have been obvious from the numbers in your POH.

Previously (section 7.5.5) we considered how much power was *required* as a function of altitude, without any mention of how much engine power you were actually using. Now we consider the effects of engine power.

You might choose to change the engine power, or you might be forced to do so. As altitude increases, sooner or later its power output will decrease. Any power-change will cause small distortions in the shape of the power curve. Let's try to understand why.

Recall that $V_Y(100)$ denotes the airspeed for best rate of climb when the engine is producing 100% of its rated power, while $V_Y(0)$ denotes the airspeed for minimum sink (best endurance) with zero engine power.

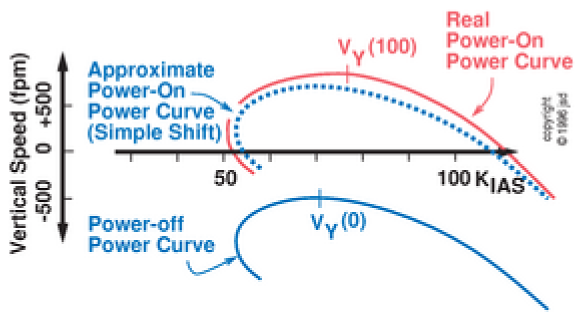


Figure 7.10: Power Curve Affected by Engine & Propeller Efficiency

It would be nice if engine efficiency and propeller efficiency were independent of airspeed, but this is only approximately true. Designers often sacrifice a little climb performance in order to get better cruise performance. This means that the effect of engine power is to raise some parts of the power curve more than others, as shown in figure 7.10.

In particular, points to the right of $V_Y(0)$ are raised a little more than points to the left thereof. As a consequence, $V_Y(100)$ must sit somewhere to the right of $V_Y(0)$. At intermediate power settings, V_Y is somewhere between $V_Y(0)$ and $V_Y(100)$. The shift is usually not large.

One reason why efficiency depends on airspeed is *propeller slip*. The propeller is not a solid disk that throws the air straight backwards; there is a certain amount of leakage between the blades and around the edge of the disk. Actually, propellers are typically about 80% efficient at cruise, which is surprisingly good.

At a given engine RPM, propeller slip depends in complicated ways on the indicated airspeed (which determines the drag on the airplane, hence the load on the propeller) and on true airspeed (which determines the angle at which the blades meet the oncoming air).

Taking the efficiency to be independent of airspeed is a reasonable approximation for constant-speed props[8] but not as good for fixed-pitch props.

Let's discuss how V_Y depends on altitude. There are a couple of issues:

- Obviously there is no point in asking about $V_Y(100)$ at an altitude where the engine is not capable of producing anywhere near 100% of its rated power. Instead we might ask about $V_Y(\text{ft})$, where "ft" stands for full throttle. For a non-turbocharged airplane, $V_Y(\text{ft})$ will decline somewhat as altitude increases, for reasons discussed in connection with figure 7.10.
- Propeller efficiency depends on TAS (not just CAS). The TAS/CAS ratio is a fairly strong function of altitude. Imagine having a fixed-pitch prop with a very fine pitch. As the altitude increases, the TAS might increase to the point where it overruns the pitch of the prop at any reasonable engine RPM. You would have to fly at a slower CAS to get any thrust at all. In this scenario, the power curve would be grossly distorted, and V_Y would be a declining function of altitude. Conversely, a propulsion system optimized for high-speed cruise might work *better* at high altitude. (For example, a turbojet -- with no propeller at all -- works better and better as the TAS/CAS ratio increases.)

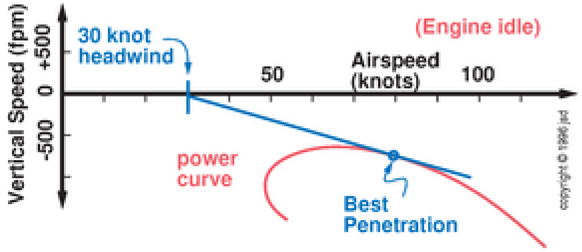
Bottom line: In a non-turbocharged fixed-pitch light aircraft, you can expect $V_Y(\text{ft})$ to decline slightly as altitude increases. Usually you don't need to worry about it, unless you have a special reason for flying close to the edge of the envelope (e.g. mountain flying) -- in which case you might hope that the POH documents how $V_Y(\text{ft})$ depends on altitude, weight, et cetera. (Some do, but most don't.) And POH or no POH, you should do some experiments to verify the critical performance numbers for yourself.

The power curve shifts (without changing shape) as a function of altitude, for TAS/CAS reasons as discussed in section 7.6.5.

There are various other non-idealities that affect the power curve. For example, a propwash over the wings changes the stall speed, which moves sideways the leftmost points on the power curve. Other propwash effects fiddle with the curve in various minor ways.

7.5.7 Best Glide: Wind, Downdrafts, etc.

V_Y is not affected by wind (because it only involves altitude and time, not distance). On the other hand, if you are gliding into a headwind toward a distant objective, you want to glide a little bit faster than in the no-wind case, because you want to give the wind less time to push you away from your objective.



[Figure 7.11](): Best Penetration of 30 Knot Headwind

Once again we can use the tangent construction, as shown in figure 7.11. If there is a 30-knot headwind, the tangent should go through a point 30 knots to the right of the origin. Because of the shape of the curve, the point of tangency does not move 30 knots, but only about 7 knots. Glider pilots call this point the *penetration* speed. As a rule of thumb, when gliding into a moderate headwind, increase the glide speed by about a quarter of the windspeed. Conversely, when gliding with a tailwind, you can go farther by gliding more slowly than in the no-wind case, but only slightly slower. Even with an infinite tailwind, it would never pay to glide more slowly than V_Y.

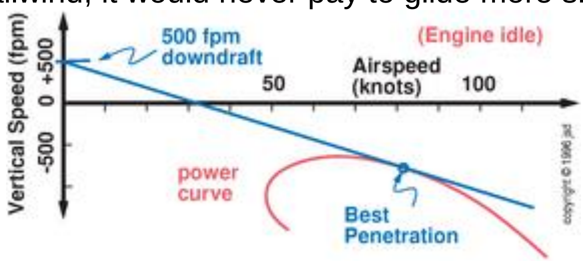


Figure 7.12: Best Penetration of 500 fpm Downdraft

If you are gliding through a downdraft, you want to fly a little faster so you can get out of it as soon as possible. The construction in figure 7.12 can be used to analyze the situation. Given a 500 fpm downdraft, the tangent should pass through a point 500 fpm above the origin. Conversely, if you are flying through an updraft, you want to stay in it as long as possible, so you can reduce the glide speed. The tangent should pass through the appropriate point below the origin.

7.5.8 Weight Effects

A Cherokee Six is a rather popular airplane. It has very good load-carrying ability; more than half of the legal max gross weight is useful load. Even allowing for a bantamweight pilot and a modest amount of fuel, you can imagine flying it at half of max gross weight.

For reasons discussed in section 2.12.4, at reduced weights every point on the power-off power curve is rescaled to a lower speed. In particular, if the weight is reduced by a factor of 0.5, the stalling speed, the best lift-to-drag speed, the maneuvering speed, etc. are reduced by a factor of 0.707 (a 29% reduction). The vertical speeds are reduced by the same factor. This is shown by the lower two curves (the power-off curves) in figure 7.13.

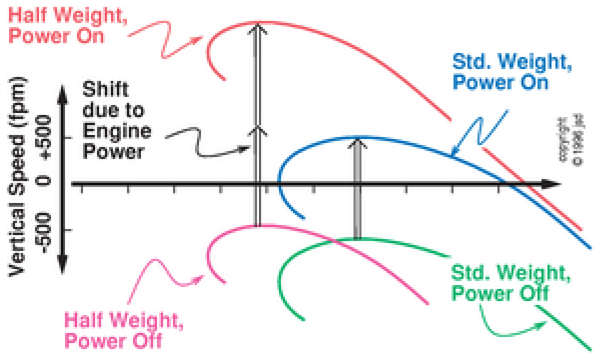


Figure 7.13: Power Curves at Reduced Weight

Start with the standard-weight, power-off curve, then shrink it. For each point, the new airspeed is 71% of the old airspeed, and the new vertical speed is 71% of the old vertical speed. This produces the half-weight, power-off curve.

Now, when we apply power, the full-weight curve moves up by about 1000 feet per minute, thereby turning a 500 fpm descent into a 500 fpm ascent at V_Y. When we apply power to the half-weight airplane, the same amount of energy is devoted to lifting half as much mass, so the curve shifts by twice as much --- 2000 fpm. At the lower weight:

- The best-rate-of-climb speed V_Y is reduced by about 30%. This helps with short-field landing and takeoff.
- The rate of climb you can obtain at V_Y is about 1500 fpm, i.e. more than twice the "nominal" value.
- The airplane's ability to operate at high altitudes is greatly increased.
- The cruise speed increases slightly, but only slightly. This is because almost all of the drag at high speeds is parasite drag, which depends on the shape of the airplane, not on its weight or angle of attack.

7.6 Variations in the Power Curve

As mentioned in section 1.2.5, the general shape of the power curve is more-or-less the same for all airplanes, but there are some variations.

7.6.1 Power Curve Depends on Aspect Ratio

Consider a typical airplane in which the stalling speed is 60 K_{CAS} and V_Y is 75 K_{CAS}. We know that V_Y depends on a balance between induced drag and parasite drag, so let's consider what happens if we rearrange things a little bit.

In particular, imagine replacing the wings. The new span will be twice as large, and the new chord will be half as large. This leaves the wing area unchanged, but increases the *aspect ratio* (the ratio of span to chord) by a factor of four.

In the modified airplane, the stalling speed will be very nearly the same, since this depends mainly on wing area. Also the parasite drag will be more-or-less unchanged.

However, the amount of induced drag at any particular airspeed will be less, since the long wing doesn't need to produce such strong wake vortices, as discussed in section 3.12.3.

Therefore V_Y will no longer by 75 K_{CAS}. We can fly slower (thereby reducing parasite drag) without incurring a proportionate increase in induced drag.

The same thing happens if you do something that increases the drag parasite, such as towing a banner. The airspeed V_Y representing the optimal tradeoff between induced and parasite drag shifts to a lower value.

In the extreme case of a high aspect ratio and lots of drag, V_Y might be only a few knots above the stall. You could reasonably take off, fly around all day, and land, without ever operating on the back side of the power curve.

At the other extreme, consider an airplane with a short wingspan, lots of chord, and not very much drag. A typical fighter jet is a good example. For such a plane, V_Y is very much higher than the stall speed. Takeoff, landing, and many other maneuvers must be conducted quite far back on the back side of the power curve.

7.6.2 Sketching the Curve

If you know a few points on the power curve, you can sketch the whole curve. As mentioned in section 1.2.5, the general shape of the curve is the same for all airplanes, so you just need to shift and rescale the curve to fit your particular airplane's performance numbers.

Some of the numbers are easy to obtain, while others are not. For instance:

1. The power-off and power-on stalling speed can be obtained from the POH, and can be easily measured. The corresponding rates of descent generally cannot be obtained from the POH, and would be very hard to measure.
2. The POH gives the airspeed for best rate of climb, and the resulting vertical speed.
3. The POH gives the airspeed for best angle of glide, and resulting angle, from which you can infer the vertical speed.
4. The cruise airspeed can be obtained from the POH. At cruise power setting, the rate of climb at this speed is zero by definition. But what is the power-off rate of descent at this airspeed? You cannot find that in the typical POH, so you may want to measure it experimentally.

You need an estimate of the cruise-airspeed power-off descent rate in order to plan your descent as you approach your destination, or when ATC asks you to cross a surprisingly-nearby fix at a surprisingly-low altitude.

On the other hand, the rate of descent at stalling angle of attack doesn't usually matter, because if you cared about rate of descent you'd be flying at some other airspeed.

I don't know all the details of the power curve for the airplanes I fly, and unless you are an airplane designer or test pilot, you probably don't need to know the details either. Accurately measuring the entire power curve is (a) unnecessary, (b) *much* harder than you might think, and (c) beyond the scope of this book.

7.6.3 Some Theory

The following mathematical formula may be of additional help in sketching and understanding the power curve. Using the basic lift/drag model introduced in section 4.5, we expect that

$$\frac{\text{dissipation at } V}{\text{dissipation at } V_Y} = 0.75\frac{V_Y}{V} + 0.25\frac{V^3}{V_Y^3} \qquad (7.1)$$

Using this formula, you can get an estimate of the shape of the front side of the power curve using only one measurement, at least for planes where V_Y is not too close to the stall. Here's the idea: measure the sink rate at V_Y, and attribute three quarters of it to induced drag and one quarter of it to parasite drag. Then, as the airspeed increases, the power dissipated by induced drag will go down like the reciprocal of the airspeed while the power dissipated by parasite drag will go up like the cube of the airspeed. As you can see from figure 4.15, this won't be exact, but it will be close.

Also keep in mind that the high-airspeed part of the power curve is almost entirely due to parasite drag, so in this region the curve is proportional to airspeed cubed.

Bottom line: the ideas in this section and in section 7.6.2 should enable you to sketch the power curve fairly easily and fairly accurately.

There is additional discussion of coefficients, forces, and powers in section 4.5. See also section 4.6.

7.6.4 Power Requirements versus Speed

Suppose we want an airplane with a reasonably high cruise speed. How much power does it take?

In particular, let's suppose our airplane can stay airborne at an airspeed of V_Y = 75 K_{CAS}, using 100 horsepower (at a particular altitude). Now lets suppose we want the cruise speed to be double that speed, namely 150 K_{CAS} (at the same altitude). Then we expect (based on the formula given above) to need 240 horsepower during cruise.

If we want to double the cruise speed again, to 300 K_{CAS}, we need to increase the power to over 1600 horsepower! We see that in the high-speed regime, doubling the power causes an eightfold increase in the parasite drag power. (The total increase in dissipation is somewhat less than eightfold, because the induced drag component isn't increasing.)

Note that when you increase the airspeed from 75 to 150 K_{CAS}, the power goes up by a factor of 2.4 but the gas mileage gets worse by only 20%. That's because mileage depends on fuel per unit distance, not fuel per unit time, and you would get to the destination in half the time. Similarly, when you increase the speed from 150 to 300 K_{CAS}, the power goes up by a factor of 6.8, but the gas mileage gets worse by only a factor of 3.4.

Of course, you can reduce the power requirement (and fuel requirement) by redesigning the airplane to reduce the coefficient of parasite drag, but big improvements are usually not very easy to achieve.

7.6.5 Power Requirements versus Altitude

The previous section considered different speeds at the same altitude; now we consider what happens when the altitude changes.

For starters, remember that the power curve depends on engine power and propeller efficiency, as discussed in section 7.5.6.

Meanwhile, there is something else going on, something very fundamental, that causes the power curve to shift as a function of altitude.

Suppose we try to fly at a high altitude, using the same CAS that we used at a lower altitude. The angle of attack is the same, the lift force is the same (just equal to weight), and the drag force is the same --- all independent of altitude, if we keep the indicated airspeed the same.

However, this does *not* mean that the required power remains the same. The drag power is equal to the drag force times the airspeed (true airspeed, not indicated airspeed). This means that for any given CAS, the power required grows as a function of altitude, in the same proportion as the TAS/CAS ratio.

This puts a limit on how high you can fly, even if you have a turbocharged engine whose output is independent of altitude.

To look at the same fact another way, let's consider speed at constant engine power (rather than required power at constant speed). Assuming the engine power stays the same, the net available power will decline as altitude increases, because the drag power is increasing. Therefore at high altitude your calibrated cruising speed must be closer to V_Y, so that you can operate at a point on the power curve appropriate to the reduced net available power.

At any altitude where you have plenty of power, the cruising CAS is large compared to V_Y and drops only slowly as the net available power declines (because required power depends roughly on the *cube* of the CAS). In this regime the cruising TAS is increasing even as the cruising CAS is dropping. In contrast, as the altitude approaches the absolute ceiling, the cruising CAS is near V_Y, where small changes in CAS have only an ultra-small effect on required power, and any decrease in available power causes the CAS to drop toward V_Y so fast that the TAS drops, too.

7.7 Energy Management Stunts

7.7.1 High-Speed Steep Descent

Here is an anecdote that illustrates a peculiar technique for getting rid of energy in a hurry. I tried this once, back when I was a private pilot with about 100 hours' experience. I was approaching a tower-controlled airport and had requested landing clearance. Unfortunately, the tower controller was tied up for a while, talking on his land-line. Eventually he said, "cleared to land, if you can make it from there". The problem was that I was 2000 feet above the runway, and less than two miles from the touchdown zone. That makes a ten degree glide slope --- pretty darn steep.

The wisest thing would have been to foresee and avoid the whole situation; that is, I should not have allowed myself to get so close at such a high altitude. Failing that, the next-wisest thing would have been to request approval for a 360° turn, so I could lose altitude smoothly.

However at that point in my pilot career I had more aerodynamic knowledge than wisdom, so I used another (rather unprofessional) method for getting rid of the excess energy. I'm not recommending this as an every-day pilot technique, but it definitely works (if properly carried out), and it illustrates a couple of interesting points about energy management. There are situations (e.g. forced landings) where it is appropriate and very useful.

Anyway, here's the story: I accepted the clearance, immediately extended full flaps, reduced the power to idle, and dived at the "top of the white" --- the maximum allowable flaps-extended airspeed.

The situation is illustrated in figure 7.14, which compares my steep, high-speed glide with a normal power-off glide. To give an indication of speed, the figure shows a stopwatch symbol every 15 seconds along each path.

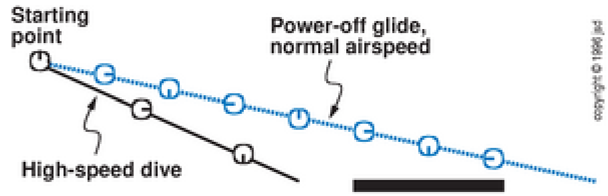


Figure 7.14: High-Speed Dive versus Normal Glide

The high-speed dive was different from the normal approach in several ways:

- At each instant, the airplane was at a lower altitude than it would have been if I had flown a normal-speed approach. (Compare the altitude of corresponding stopwatches in figure 7.14.) This is because my chosen airspeed was on a very draggy part of the power curve. I was relying on this to solve my energy problem.
- At each instant, the airplane was closer to the airport than it would have been if I had flown a normal-speed approach. (Compare the horizontal position of corresponding stopwatches in the figure.) This is an unavoidable consequence of the higher airspeed. It was unhelpful, because it meant I had less time to get rid of the excess energy.
- Effect (1) was bigger than effect (2). That is, the drag increase was disproportionately larger than the airspeed increase. This is true anywhere on the front side of the power curve, at speeds greater than $V_{L/D}$. (As discussed in section 7.5, at speeds near $V_{L/D}$, a small increase or decrease in airspeed leaves the direction of flight unchanged; you just move a little faster or slower along the same glidepath.)
- Even though I was cashing in altitude energy at a prodigious rate, I had to remember that at each instant I had more *airspeed energy* than I would have had normally. I needed a plan to deal with this surplus at some point.

If my high-speed glidepath had taken me directly to the runway threshold, I would have arrived at the threshold with far too much kinetic energy, and would have had a hard time landing the plane.

Fortunately, I could tell early in the maneuver that my glidepath led to a point about an eighth of a mile short of the runway. About a quarter of a mile from the runway, as my glide intercepted the normal glidepath, I smoothly pulled back on the yoke. This flare-like maneuver brought the airspeed down to normal. I retrimmed appropriately. I was then able to follow a steep but non-ridiculous power-off approach path the rest of the way to the runway, at a normal airspeed, followed by a normal flare and landing.

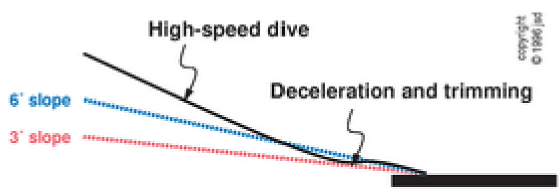


Figure 7.15: High-Speed Diving Approach Details

This strategy --- diving at a very high airspeed toward a point short of the runway, so there will be enough time and distance left to get rid of the excess airspeed, is diagrammed in figure 7.15. I reiterate that this stunt is not normal pilot technique. Still, it is a good energy-management illustration, and sometimes it is helpful during forced-landing practice.

There are many ways of getting rid of unwanted energy.

- Circling or otherwise choosing a longer flight path.
- Extending the flaps early.
- Extending the landing gear early.
- Slipping.
- High-speed steep descent.
- Combinations of the above.

7.7.2 Low-Speed Steep Descent

Looking at figure 7.9, you may suspect that you can increase the angle of descent by flying at speeds well below $V_{L/D}$. In principle, this is possible --- but such a procedure is even more unwise and unprofessional than the high-speed procedure discussed in the previous section.

The main problem is that by the time you achieve a significant increase in descent angle, your airspeed will be much too close to the stall. A slight gust, windshear, or imperfection in pilot technique could cause a stall. Remember, stalling on approach is the #1 way to cause a fatal accident.

A secondary problem with such a procedure is that it probably involves such a nose-high pitch attitude that you can't see where you are going. A third problem is that you might not have enough energy to flare; if you try to raise the nose too quickly it will just cause an accelerated stall.

It is possible to construct scenarios (such as landing on a very short runway with an obstructed approach) where a steep descent on the back side of the power curve is the only way to get the job done. However, before attempting such a task, you should make sure you have the appropriate specialized training and practice. In most cases it is wiser to just choose a different place to land.

7.7.3 Skimming in Ground Effect

Here is trick for *saving* a little bit of energy. I hope you never get into a situation where you need to use this trick --- but it might save your bacon if the situation arises.

Suppose no engine power is available, and the aircraft is too low and/or too far from the desired landing place. Using our energy-management logic, we see that the only real way to stretch the glide is to find a low-drag mode of operation. The solution is sort of the reverse of a soft-field takeoff (section 13.4) --- you should make use of ground effect.

Specifically, the procedure is to maintain best-glide speed[9] right down into ground effect, even if this means that you enter ground effect over the swamp a tenth of a mile short of the intended landing place. Once you are in ground effect, start pulling back on the yoke. Because there is very little induced drag in ground effect (as discussed in connection with soft-field takeoffs in section 13.4), the airplane can fly at very low airspeeds with remarkably little drag. You can then fly all the way to the landing area in ground effect. It is like a prolonged flare; you keep pulling back gradually to cash in airspeed and pay for drag. This technique will not solve all the world's problems, but it is guaranteed to work better than trying to stretch the glide by pulling back before entering ground effect.

Conversely: if you are approaching a short runway and have a few knots of excess airspeed on short final, you should pull back on the yoke and get rid of the excess airspeed *before* entering ground effect. If you think you can't get rid of it on short final, remember it will only be harder to get rid of in ground effect. A timely go-around might be wise.

If you want to practice skimming in ground effect, find a long, long, long runway to practice on, and be careful not to run off the far end.

7.8 Summary

Most pilots are very aware of their precise altitude, but (alas) not nearly so aware of their precise airspeed or angle of attack.

The airplane is trimmed for a definite angle of attack, and hence a definite airspeed at 1 *G*. The yoke is part of the angle-of-attack control system. Pulling back on the yoke will always make you slow down.

If you are on the front side of the power curve *and* if you don't mind airspeed excursions, you can use the yoke as a convenient, sneaky way to control altitude. This is because airspeed is linked to altitude via the law of the roller-coaster and via the power curve.

Warning: just because this works OK 99% of the time, don't get the idea that it works all of the time. Bad habits are easy to learn and hard to unlearn. Do not get the idea that pulling back on the yoke always makes the airplane go up. On the back side of the power curve, it doesn't work --- and might kill you. In critical situations (including approach and departure), you simply must control the airspeed using the yoke and trim.

The throttle controls power. Power is energy per unit time. To overcome drag requires power. To speed up requires power. To climb requires power.

In flight, if you open the throttle a normal airplane will not speed up --- it will climb.

Whereas opening the throttle causes energy to enter the mechanical system, you can also encourage energy to leave the mechanical system by extending the flaps, the spoilers, the landing gear, etc., and/or by choosing a draggier place to sit on the power curve.

If you want to fly precisely, you need to look at the altitude *and* the airspeed, size up the energy situation, and then decide what to do with the yoke *and* the throttle.

1
: Once again, this assumes the airplane is in flight (not resting on its wheels) so that the trim mechanism is effective. This also neglects the small nonidealities discussed in section 6.1.4.

2
: Be careful to call these the "power versus time" curves. If you shorten this to "power curve", people will think you mean the power-versus-airspeed curve.

3
: ...for reasons discussed in section 6.1.4.

4
: ...or (more precisely) angle of attack, as discussed in chapter 2.

5

...except for perhaps using the yoke to prevent slight phugoid oscillations at the beginning and end of the climb, where the pitch attitude changes.

6

The *absolute ceiling* is defined to be the altitude where the aircraft's best rate of climb goes to zero. At high altitudes, performance is reduced because the engine is starved for air, and power requirements are increased as discussed in section 7.5.5.

7

In this regime, IAS ought to be closely related to CAS, so for almost every statement in this chapter about changes in CAS, there should be a corresponding statement about IAS.

8

...which incorporate a governor that adjusts the pitch of the propeller.

9

Actually you might want to fly a tiny bit faster than best-glide speed, so you enter ground effect sooner.