Using Angle of Attack for Maneuvering and Aircraft Control

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A note on the term "on speed." This term was coined by the military to refer to a condition where the airplane is maintaining an angle of attack associated with the desired speed condition for approach and landing. Specific origin of the term is unknown and there is no agreed correct spelling. It is alternately spelled as two words ("on speed") or one word ("onspeed"). This paper uses the convention of spelling the condition "ONSPEED," one word, capitalized. An ONSPEED condition is a small angle of attack band, not an airspeed. The airspeed associated with ONSPEED angle of attack varies as a function of weight, and g load.

Introduction. Unintentional stalls remain a deadly threat to pilots regardless of qualifications and experience, resulting in fatalities almost 50% greater than non-stall mishaps. Most General Aviation (GA) accidents occur during day, VMC under light wind conditions (less than 10 kts). More stalls occur during the departure phases of flight (takeoff, climb or go-around) than during arrival (approach, pattern, and landing) [1]. The FAA eliminated the requirement for spin training in 1949, citing a high number of training accidents. The fatality ratio due to unintentional loss of control has remained consistent at 40-50% annually since the NTSB began maintaining accident databases in 1962, with a slight reduction in the number of accidents after 2008 that is likely the result of a change in way accident events are coded and named in the database [2]. In 1993, an extensive survey-based study was conducted comparing US military and civilian knowledge of spins. The survey spanned military pilots and instructors, civilian pilots, flight instructors and designated pilot examiners. All fixed wing military aviators receive spin training in an airplane. The study showed military student and instructor pilots demonstrated good working knowledge of spins but civilian pilots, even instructors and examiners, demonstrated poor to average knowledge with flight instructors who aspired to be airline pilots performing more poorly than their peers [3]. The military was early to adopt angle of attack (AOA) systems and energy management training for pilots. The combination of training and AOA technology substantially reduced the occurrence of loss of control mishaps in military aviation. The persistence of this accident cause over the past 60 years in general aviation is indicative of a weakness in pilot training and a lack of technological adoption that can reduce loss of control risk and save lives.

This paper explains how the ONSPEED standardized aural AOA cues can used to provide performance and energy maneuverability feedback to the pilot real time. The system accurately measures AOA across the speed band of the airplane to within ½ degree or better, has good transient response at gust or control inputs up to 2 g's per second to 6 g's, and utilizes automatic calibration providing standard, ergonomic cues that are as easy to interpret as an airspeed indicator and don't vary from airplane to airplane. It has been specifically designed and tested for this functionality. This video provides a brief overview of some of the topics discussed in this paper: https://youtu.be/zvpONUflyvk.

“If you want to go up, pull back on the stick. If you want to go down, pull back a little more. If you want to go down real fast and spin around and around, just keep pulling back…”

-Old Aviation Proverb

Background. There are pilots with extensive experience and a well calibrated “seat of the pants” feel for their airplanes. They can safely and masterfully fly the wing throughout the flight envelope, extracting maximum performance when required and maintaining positive aircraft control. There are also pilots that lose control of their airplanes, killing themselves and their passengers during normal pattern operations. What’s the difference? The first pilot has an intuitive feel for “flying the wing,” while the second does not. Sometimes, they are the *same* pilot. Pilots that stall and lose control aren’t restricted to any age, experience, or proficiency level. *No pilot intentionally spins an airplane into the ground*. They get into trouble due to misunderstanding, lack of information or become distracted, miss a cue and fail to recognize an impending stall until it’s too late.

Figure 1. Wreckage of an RV-4 destroyed after a low-speed loss of control during base to final turn. The ATP-rated pilot and non-pilot passenger were killed [4]. Experimental aircraft are not required to have stall warning.

The two fundamental skills required to fly an airplane are controlling angle of attack (AOA) to generate lift and power to generate speed and altitude. There is no way to see angle of attack, and there isn’t a power required gauge in the cockpit of the airplane, so there is no direct feedback for the two most critical tasks a pilot must perform. Learning to fly is a complicated process of using information provided by flight and power instruments and visual attitude cues to control the flight path of the airplane.

What if pilots could simply *see* and *hear* how hard the wing is working and how that work is trending? What if "seat of the pants" feedback is automated using modern technology and provided to the pilot in a simple, intuitive manner? What if an ergonomic aural cue allowed the pilot to adjust both angle of attack *and* power to achieve key performance parameters and maintain aircraft control when maneuvering without having to look at anything? What if the basis for that technology was patented by Orville Wright in 1913 and has been hiding in plain sight ever since? "*Aero and Hydro*, a weekly aviation magazine published at the time, reported on the invention of the Wright Incidence Indicator in August 1913: 'A new instrument for the use of aviators, which is of considerable interest, has been brought out the by the Wright Company at Dayton, Ohio. Orville Wright has for a long time strongly advocated the use by aviators of an instrument, showing the angles of incidence in the air.' Wright used the British term 'angle of incidence,' though 'angle of attack' became the favored term in the United States." [5]. It's also common to refer to AOA using the Greek letter α ("alpha"). Pilots use the terms angle of attack, AOA and alpha interchangeably. Angle of attack is *not* an emerging technology. Modern avionics can provide accurate, responsive AOA information in a pilot-friendly format.

"Directive" vs "Descriptive" Information. Conventional flight instruments present *descriptive* information to the pilot. That information must be interpreted, usually visually, and processed. Then the pilot must react. Assuming the pilot sees the cue, it takes about a half second to interpret and another half second to react; so, about a second to make a required adjustment. If the pilot becomes task saturated, channelizes attention or becomes distracted, the "see, interpret, react" loop fails. The AOA tone provides *directive* information. Pilots can respond in half of the time if they hear the cue. There is no requirement to look at anything or be perceptive enough to note an airspeed decay, or increase in buffet, for example. Like a flight *director*, the tone *directs* the pilot what to do with the pitch and power controls and is a more effective means to communicate critical information. A visual AOA display provides similar information when properly designed but requires scan and cognitive processing time. Consider the impact of moving map displays. It's much easier and intuitive to look at a moving map display on a smart phone or a panel mounted navigation display. Conveying information this way is so much more effective than old-fashioned navigation techniques that controlled flight into terrain accidents have been considerably reduced since widespread adaptation by GA.

A Simple, Standard Ergonomic Audio Cue. Audio cues are an effective way to transmit information to the pilot. There is no requirement for the pilot to look at a display and process the information—it is transmitted directly to the brain. Figure 2 shows a simple tone pattern that conveys key performance AOA's, trend information and stall warning. The "fast" tone is 400Hz and begins at L/D_{MAX} as the airplane decelerates (shaded blue). The tone pulses at a variable rate, at first slowly with the pulse rate increasing until it becomes steady at an "ONSPEED" condition (shaded green). ONSPEED is the AOA associated with minimum power required and V_{REF} at 1 G. If the pilot continues to increase AOA above ONSPEED, the frequency of the tone jumps to 1600Hz and begins to pulse. This "slow" tone is the yellow shaded area. If AOA continues to increase, the pulse rate and volume increase until stall warning heard at about 1 ½ to 2 degrees prior to stall. This provides not less than 5 knots of stall warning at any g-load. During stall warning (red shaded area), the high frequency tone pulses 20 times per second. These audio cues and color codes are superimposed on many of the diagrams in this paper. This tone logic was based on a system originally developed by the Royal Navy for carrier operations and was used by the US Air Force for over 50 years and hundreds of thousands of flying hours in the F-4, F-117 and U-2. Adoption was instrumental in reducing LOC mishaps. This short video demonstrates the tone pattern in an airplane during flight: https://youtu.be/Tpp4Ankiync.

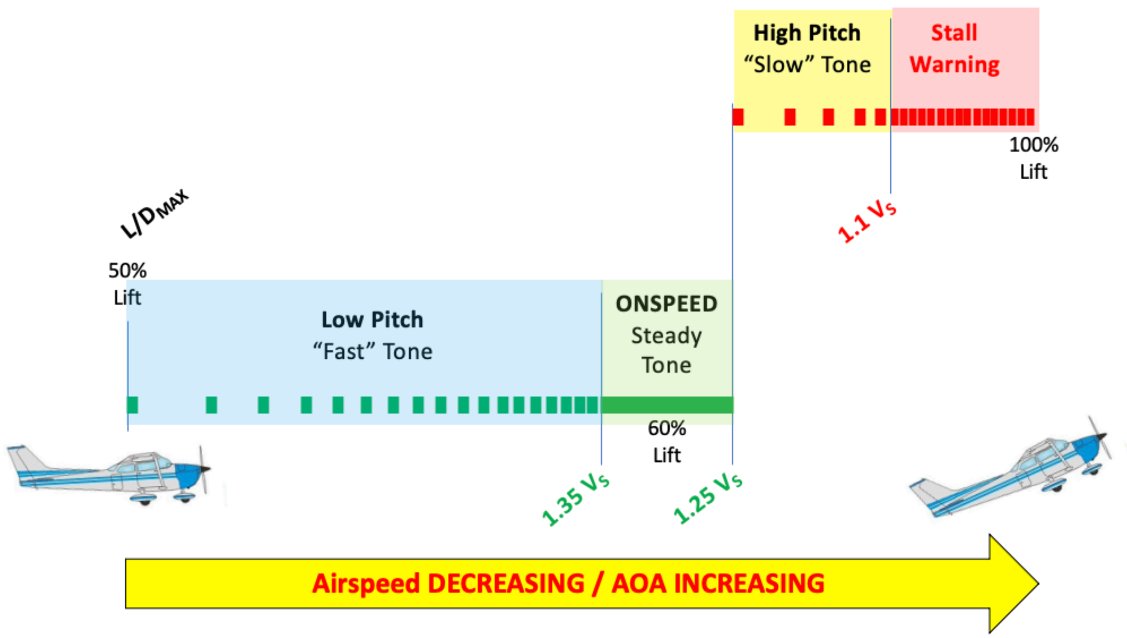


Figure 2. Aural AOA tone pattern that allows the pilot to hear different critical performance conditions. Increasing pulse rate means AOA increasing ("getting slower"). Steady tone means "ONSPEED." The pattern is optimized to provide critical trend information relative to ONSPEED.

Green Eggs and Ham Syndrome. Hearing is an underutilized cockpit resource. Unlike conventional instrumentation, an aural cue doesn't require the pilot to look at anything. The pilot's vision is freed up for more important tasks such as collision or terrain avoidance. The ONSPEED cue not only provides AOA information, but when integrated with a stereo intercom, it also provides sideslip feedback. The tone moves left and right in the sound field with the slip/skid ball. To properly coordinate rudder, the pilot "steps on the tone." Unlike conventional caution/warning logic, there is a "good condition" and a "bad condition" inherent in the logic. Volume is pilot adjustable (except for stall warning), and the tone is "readily internalized" in human factors terms. In other words, it peacefully coexists with radio chatter, intercom, etc. Many modern intercoms also provide some form of pilot-selectable attenuation logic; and the only system control is a big, intuitively operated volume knob. Most GA pilots don't have experience flying with a system like this, but there are two communities of aviators that do: military fighter aviation and the glider community. In both cases there is an extensive body of experience and demonstration of the efficacy of receiving direct feedback from aural cues. Truth in advertising, as attention is channelized and the pilot becomes task saturated, hearing is the first sense lost. No system is perfect, and this risk is offset by variation in pitch and volume as the airplane transitions from a "good" condition to a potentially "bad" condition. The bottom line, and why we call this "green eggs and ham syndrome," is do not pass judgment until you've flown with the system in both visual and instrument meteorological conditions. The fact that the pilot hears the tone is the feedback mechanism for ensuring proper system operation. This is why an ONSPEED condition is a solid vs "null" tone. In the demonstration videos, the tone volume is artificially high to ensure that it conveys properly.

What is Angle of Attack? AOA is the angle between an aircraft reference line (e.g., the chord line of the wing) and the incoming flow of air. It is the only operational parameter a wing "sees." The wing uses alpha to make the lift required to support the weight of the airplane. More alpha for a given airspeed means more lift, up to a maximum AOA at which point the wing stalls as shown in Figure 3. Maximum AOA is called "critical AOA." This critical (stall) AOA is always the same for a given wing configuration. It is not affected by gross weight, or g load. A stall occurs when the airflow over the top of the wing becomes sufficiently separated, as shown in the figure. An airplane can stall in any attitude at any airspeed, but critical AOA remains constant, with two exceptions: in ground effect and at extreme pitch rate onset. In both edge cases, a pressure derived AOA solution will still provide stall warning.

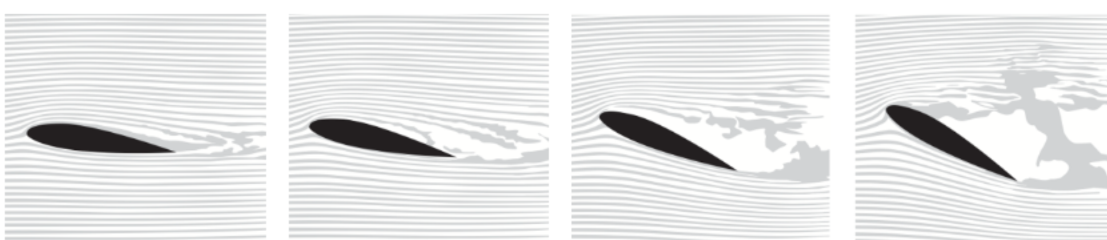


Figure 3. The wing stalls at critical angle of attack. This angle is always the same (for a given flap setting), whereas stall *speed* varies with gross weight and g load.

We can simplify the definition of alpha by taking most wing geometry out of the definition (angle of incidence, variable airfoil sections, washout etc.): it's the angle between where the airplane is pointing (pitch) and where it's going (flight path). This is shown in Figure 3 and is called "body angle." Body angle (AOA) is always affected by flap setting. That's why it's important that an AOA system has a separate calibration for each flap setting normally used.

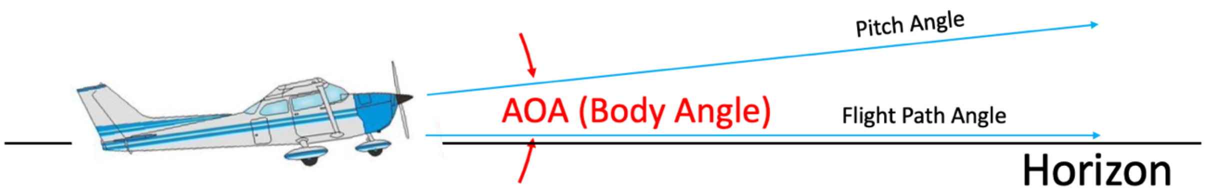


Figure 4. Body angle is the difference between pitch and the flight path angle. From a pilot perspective, *body angle is AOA*. This airplane is in straight and level, steady airspeed flight.

The simple fact is that the pilot cannot see AOA, but **knowing AOA is the key to understanding how hard the wing is working and, just as importantly, how that work is trending.** What a pilot *can* see is pitch, and we've used "pitch and power setting" to teach flying for a very long time. Airspeed, attitude, and power setting are used in lieu of having accurate AOA information. When we maneuver, climb, or descend, pitch is a poor surrogate for AOA. There is one condition where pitch and AOA (body angle) are the same: straight and level, trimmed, unaccelerated flight shown in Figure 4. We can see in still air, if everything is trimmed up, the flight path vector is on the horizon, and body angle is equal to pitch. Test pilots have used this relationship for years to measure aircraft performance and calibrate airspeed and AOA systems.

AOA may be displayed to the pilot visually or aurally. If a visual display is oriented vertically, it is referred to as an "indexer." Some visual displays are presented as a round dial or portion thereof. Displays vary because there is no industry standard. Accuracy and performance vary depending on the quality of the calibration, how angle of attack is measured and computed, and how the AOA signal is processed and presented to the pilot. In general, *when properly calibrated, all AOA systems provide excellent progressive stall warning and can eliminate the startle factor that usually accompanies an unintentional loss of control*. Depending on design, the system may or may not provide performance cues.

"While speed considerations have an important place in properly operating your aircraft, there are times when a speed reference is inappropriate. Years of training to speed approximations for wing efficiency have created a culture that is inherently susceptible to dangerous flight excursions."

-Vince Wawrzynski, USMC, Flight Safety Expert

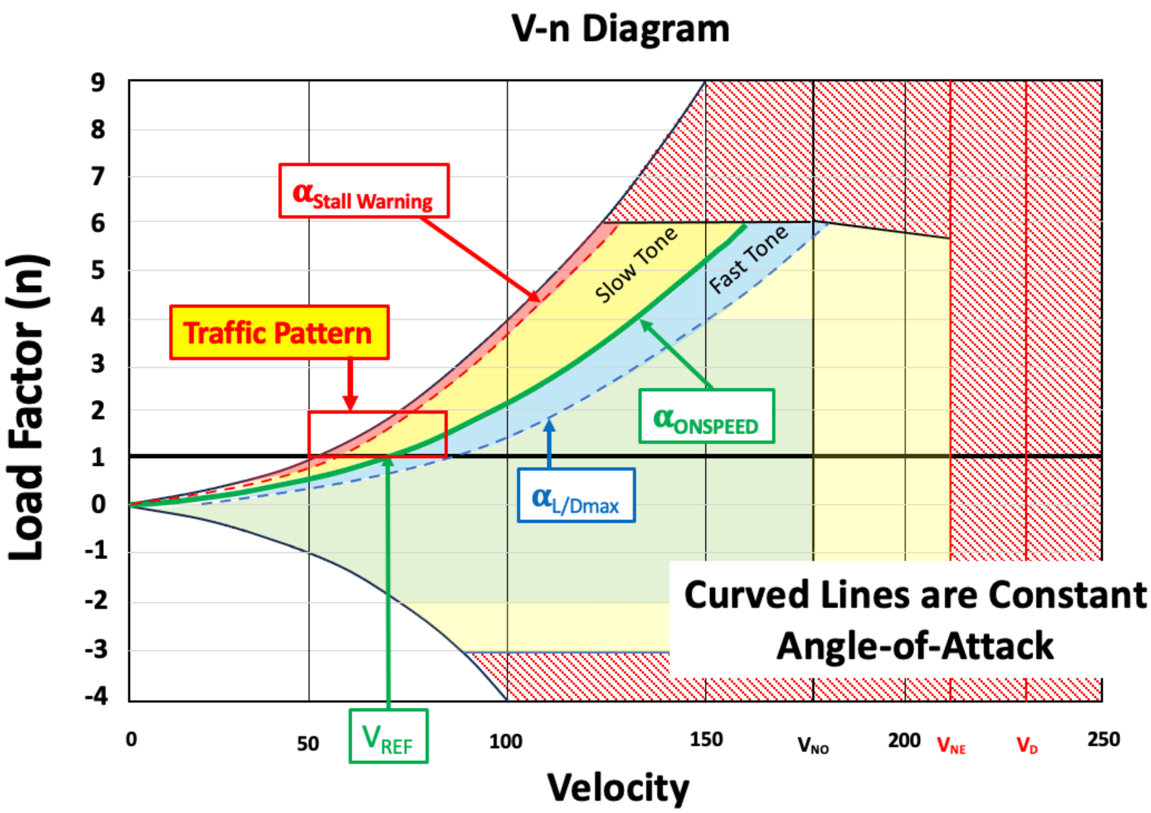


Figure 5. Van's Aircraft RV-4 flight envelope. The RV-4 has a 6g positive limit at 1375 pounds gross weight or less. Takeoff and landing occur in a very small portion of the envelope.

The Flight Envelope. Figure 4 is the V-n diagram for a light, two-seat Van's RV-4 experimental amateur built (EAB) airplane at or below a gross weight of 1375 pounds. A "V-n Diagram" is graphic depiction of the flight envelope. The expression comes from the fact that the plot looks like an open envelope. Load factor is on the vertical axis. Engineers abbreviate load factor as "n." Pilots call it "g" for gravity. The horizontal lines are g-load. Note the origin of the plot is zero-g, but we live in a 1g world. That's the thick horizontal black line aligned with 1g.

Airspeed is depicted on the horizontal axis. Notice that speeds greater than maximum structural cruising speed (V_{NO} or the top of the green arc on a properly marked airspeed indicator) are shaded yellow. This speed should only be exceeded in smooth air, because if the airplane encounters turbulence, structural damage may occur if the gust is strong enough. The red hashed areas on the diagram belong to the designer, not the pilot—structural damage or failure may occur if the pilot operates in that part of the envelope.

On a V-n Diagram, airspeed and g limits are straight, easily identifiable lines—a number on the airspeed indicator or g-meter. The 1g horizontal line is where all our handbook/flight test performance *airspeeds* occur. At 1g, we can fly the airplane using airspeed, adjusted for gross weight to achieve desired performance parameters and avoid exceeding the critical angle of attack.

The curved line on the left of the diagram is what engineers call the "aerodynamic" limit and pilots think of as the "stall" limit. The airplane runs out of lift to the left of this line. The shape of this curve is *parabolic* because *stall speed increases as the square root of g-load*. If our brains were fast enough, we could compute the indicated airspeed at which we would stall for our current gross weight. That way, we'd always know when we are approaching stall by looking at the airspeed indicator. Unfortunately, human brains are optimized for hunting on the open savannah, not math in public. There is, however, a device that does "curved line math in public" well, it's called an angle-of-attack (AOA) indicator. That's because the aerodynamic limit is a *single*, critical, AOA at which the airplane stalls. *Critical alpha isn't affected by gross weight or g-load. It's always the same.* This is why it is possible for an airplane to stall in any attitude and any airspeed.

We can plot other AOAs on a V-n Diagram besides critical alpha. Note that any AOA plotted on a V-n diagram is a curved, parabolic line. The fundamental AOA (the one that is designed into the airplane) is L/D_{MAX}. Note that when the airplane is clean, the fast tone starts at L/D_{MAX}. From L/D_{MAX} we can compute other key performance AOA's, the most useful of which is an alpha somewhat confusingly called "ONSPEED." ***An ONSPEED condition isn't a speed, it's an angle of attack.*** Because it's not possible to fly a precise angle of attack, it's a small range of angles, about $\pm 1^{\circ}$ in a typical light airplane. This results in an airspeed band about 4-5 knots wide ($\pm$ about 2 knots) at 1g. Because ONSPEED is the most useful performance alpha as it's used for takeoff and landing, it is an easily identifiable solid tone. To make things more confusing, we say that we are "fast" or "slow" relative to ONSPEED. This mixing of AOA and airspeed terms isn't nearly as odd as it sounds since airspeed is just a surrogate for alpha, and velocity is a key aerodynamic component. The tone pattern is optimized to provide the pilot with fast or slow cues relative to ONSPEED and how AOA is tending. Traffic pattern operations occur in a very small part of the flight envelope that is precariously close to the aerodynamic limit. This is the red box in Figure 4. *Note that this specific portion of the flight envelope can be expressed entirely as AOA.*

"From a practical standpoint, everything your aircraft does is based on an angle of attack. It takes off at a given angle of attack, it cruises under optimum conditions at still another given angle of attack, it flies final approach at another given angle of attack, and it stalls at a known angle of attack. Angle of attack, for all practical purposes, is a function of gross weight, indicated airspeed and G loading. Altitude is divorced from the picture altogether since we are interested in indicated airspeed, not true."

-Don Stuck, Test Pilot, McDonnell Aircraft, 1963

How Hard is the Wing Working? To understand how hard the wing is working, let's review the lift equation, the factors in that equation that the pilot can control, and how the coefficient of lift and alpha are related.

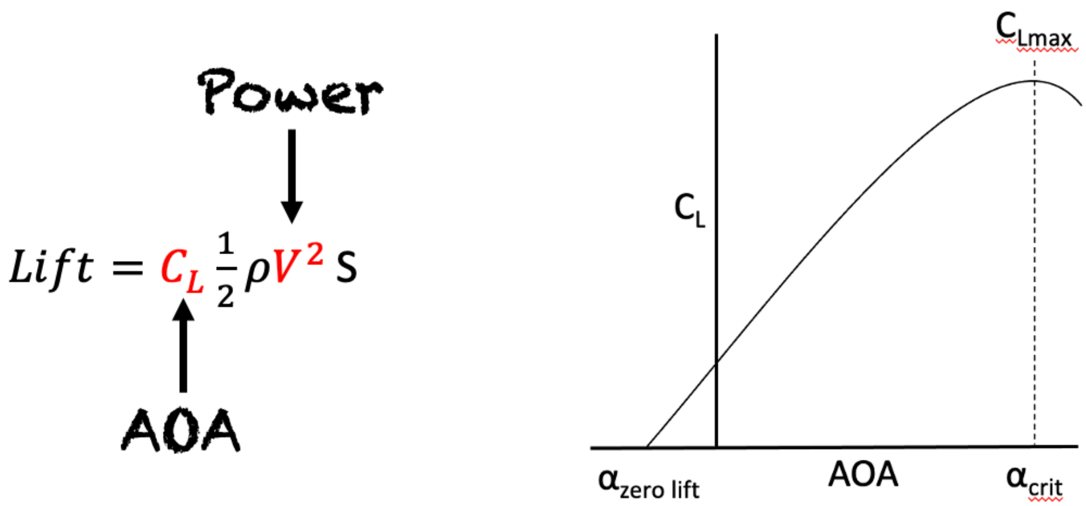


Figure 6. The lift equation and a "C_L Alpha" plot. *Pilots control lift with AOA and speed. We get speed from power*. In non-level flight, power is supplemented or decremented by gravity.

Let's break down the factors that make up the lift equation. The first is coefficient of lift (abbreviated "C_L"). The C_L is a dimensionless number that quantifies the amount of lift an airfoil produces relative the fluid dynamic forces acting on it. C_L is directly proportional to AOA. This is shown on the right side of Figure 6. Actual C_L is a function of the shape of the airfoil. *The pilot has control over C_L by changing alpha using pitch control.* More alpha = more C_L = more lift. The second factor is air density. Engineers use the Greek letter rho (ρ) as shorthand for density. Although density changes when we climb or descend, the pilot has no control over ambient density *right now* when maneuvering. The third factor is speed. *The pilot controls speed by adjusting power and clever use of gravity*. *We speed up by pushing the power up (making more thrust with the propeller) and/or going down (using gravity assist to increase thrust) or reducing g (decreasing drag). Conversely, we slow down by pulling the power back (reducing thrust) and/or going up (using gravity to decrease thrust) or increasing g (increasing drag).* More speed = more lift. The last factor is the size of the wing. The pilot has no control over wing area for a given flap setting. So, from a pilot perspective, we can simplify the lift equation:

Lift = AOA x Power

Maneuvering Flight. Control of AOA when maneuvering is a subject misunderstood by many pilots. Alpha control is basically the same in any airplane regardless of type of power plant, wing form, size, or color. Pilots get into trouble due to a lack of information or misunderstanding what they see or feel. This is where accurate, *real-time* AOA feedback comes into the picture. This feedback not only tells the pilot how hard the wing is working, but also how much thrust is required to manage the flight path of the airplane. The tone makes this easy and intuitive.

Let's look at the relationship between pitch and AOA during maneuvering flight. Since AOA is the difference between pitch angle and flight path angle, it's easy to visualize the theoretical extremes: an aircraft can be pointing straight up (90° pitch) and going straight up (90° flight path) with an AOA of zero. Conversely, an aircraft can be level with the horizon (0° pitch) but falling like a brick (-90° flight path), producing an AOA of 90°. The reality is less extreme and varies from very small angles during cruise to a maximum angle of about 15-20° in a typical GA airplane. The specific critical AOA depends on the shape of the airfoil and any high lift devices fitted.

Most academic flying discussions refer to *steady* flight conditions, so let's examine a simple, non-steady maneuvering condition that's easy to visualize: a 1 knot per second 1g deceleration from cruise flight to the stall. Figure 7 is a plot of recorded AOA across the "speed band" of the airplane, the difference between V_{MAX} and V_{MIN}. The AOA plot shows something important: ***the slower you go, the faster AOA increases.*** Also, note the shape of the curve: it's the same shape as the aerodynamic limit of the flight envelope.

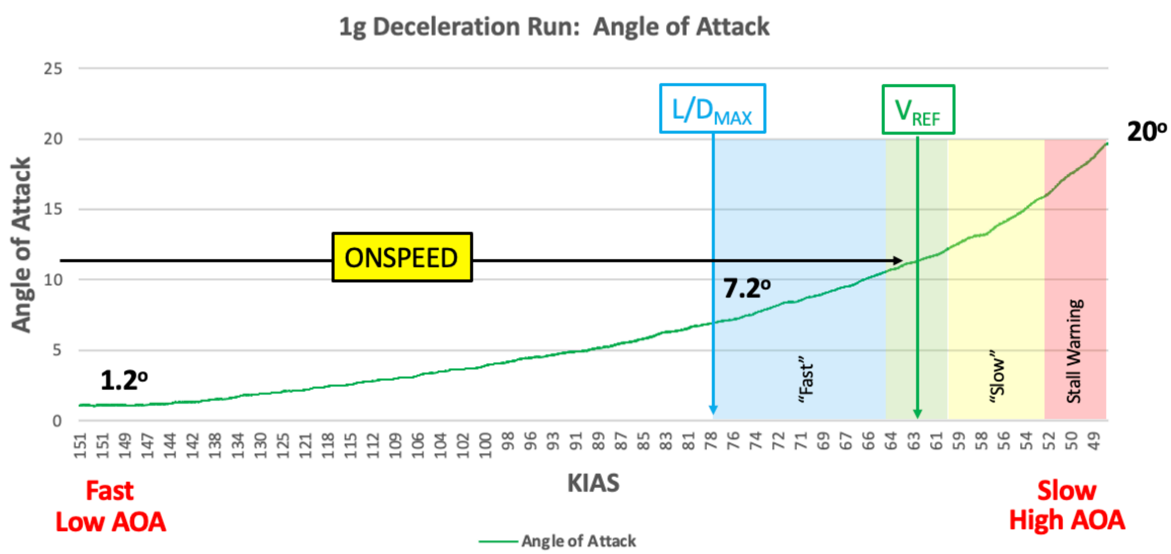


Figure 7. AOA during a 1g level deceleration from cruise speed to stall. **"The slower you go, the faster you go slower."**

Notice in Figure 7 that from a low AOA cruise condition to L/D_{MAX}, AOA only increases about 7 degrees, but from L/D_{MAX} to stall, AOA increases about twice as much. 50% of the wing's ability to generate lift occurs in the lower 1/3d of the speed band of the airplane. This is why things get sporty if you overshoot final at V_{REF} and start to pull the nose around to realign with the runway—you are already close to the aerodynamic limit when you start pulling, and alpha increases rapidly once you do. It's this steep slope near the stall that causes problems during maneuvering flight, even at low-g loads that are almost imperceptible. G-load is a result of maneuvering or wind gust. The pilot can control the former, but not the later. When an airplane is tested for certification under FAR 23, V_{REF} is computed as 1.3 times the stall speed at maximum gross weight OR the minimum speed in a 40° banked turn (1.3 g's) that *won't* trigger stall warning, whichever is faster.

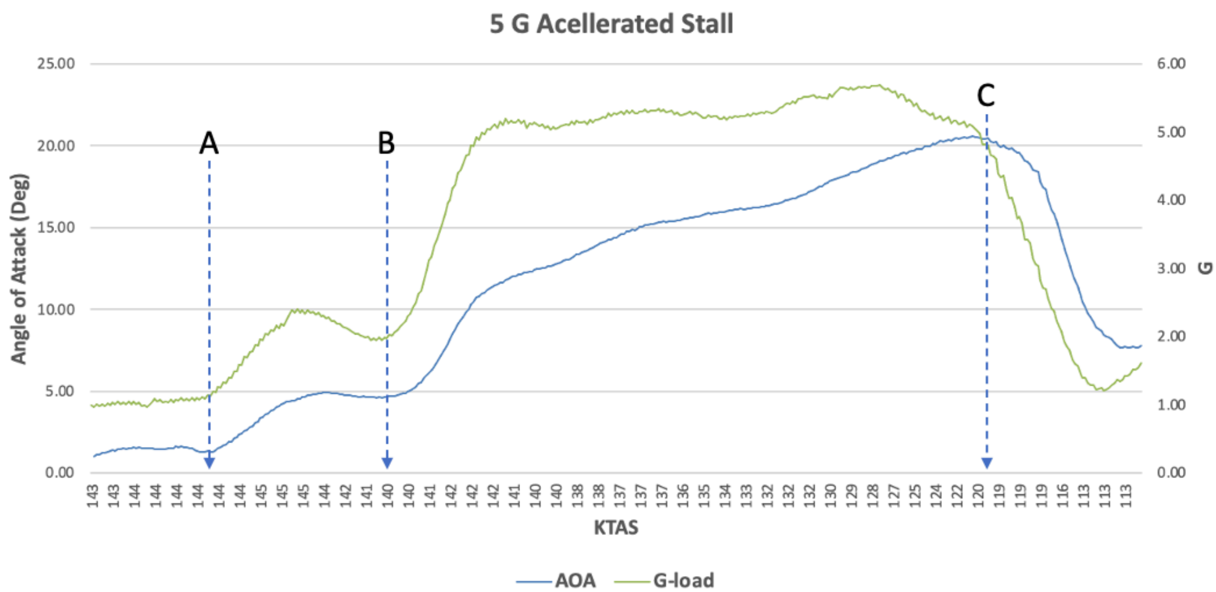
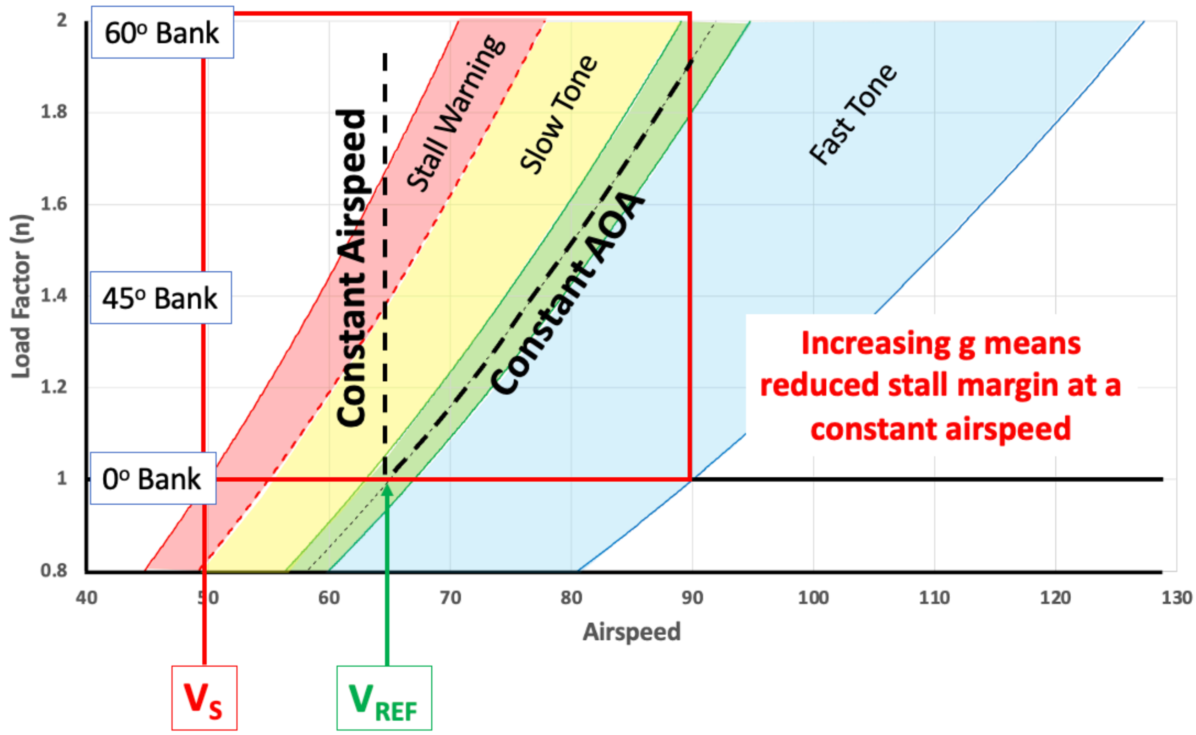


Figure 8. AOA and g during a 5g accelerated stall. Note that angle of attack tracks with g-load. At point A, airplane rolls to 100° bank angle. At point B, 5 g's are smoothly applied. The airplane stalls at point C.

Figure 8 shows the relationship between AOA and g in an exaggerated manner: a high g accelerated stall. ***As g increases, so does AOA***. This is true regardless of the magnitude of the g-load or the maneuver. Any time we are pulling more than 1 g, AOA tracks with g-load. As a matter of fact, g leads alpha by just a bit—the air molecules take a moment to catch up when the pilot moves the flight controls; but the correlation is effectively instantaneous from a pilot perspective. Increase g, and AOA increases. If we know our AOA, we know how hard the wing is working *right now*, and with the right cuing logic how that work is *trending*. To maintain positive aircraft control and extract desired performance, it's imperative to know both. To *anticipate* the need for a control input, or avoid being startled, we need to know how things are changing over time. The tone pattern is optimized to do this.



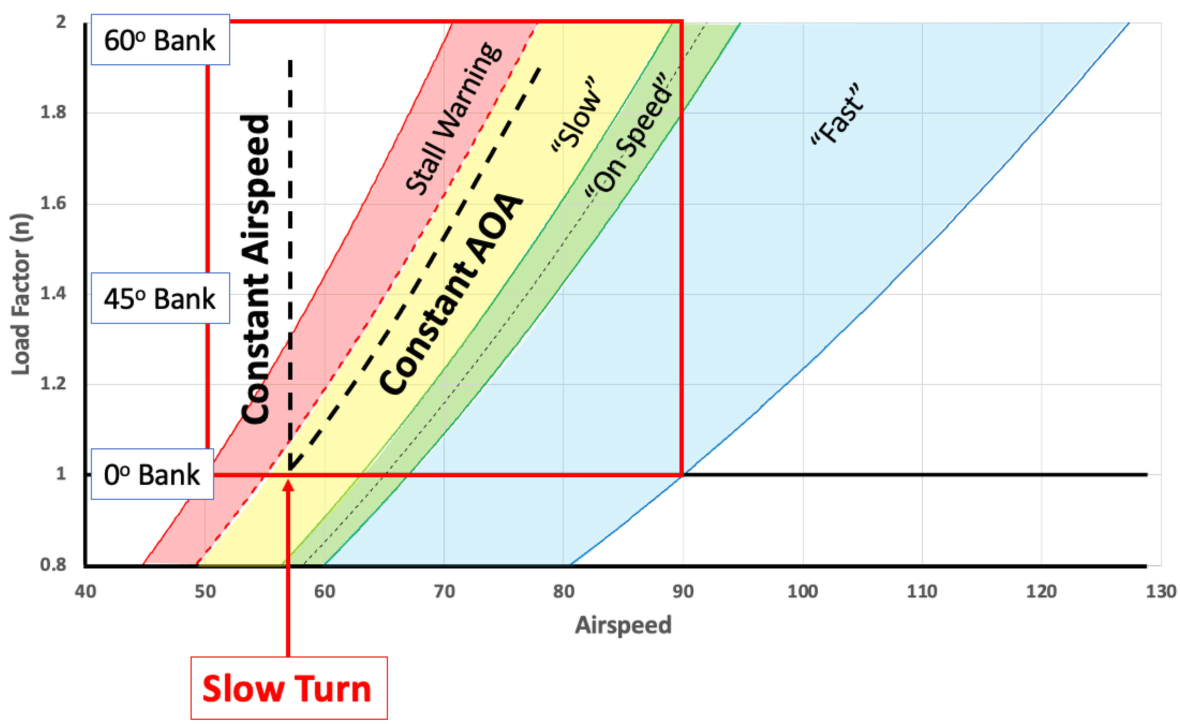


Figure 9. Constant airspeed vs constant AOA during low-speed maneuvering. The bottom portion shows reduced aerodynamic margin available if maneuvering at low airspeed/high AOA. This is what happened to the crashed airplane shown in Figure 1.

Because AOA tracks with g, so does stall *speed*: ***V_S varies as the square root of the g-load***. The markings on the airspeed indicator are for *maximum* gross weight at 1g. They are not accurate at other weights or g loads. V_S decreases as weight decreases. To determine the g associated with a bank angle, calculate 1 divided by the cosine of that angle: a 45° bank requires 1.4 g's. The square root of 1.4 is 1.18. If the stall speed is 50, multiply that by 1.18 to find the actual stall speed: 59. Another way to think about this is that V_S indicated airspeed increases by a percentage equal to the square root of the g-load, or 18% in this example. Either way, math in public is required. Now let's use our example to determine *aerodynamic margin* during a base to final turn. "Aerodynamic" and "stall" limit are interchangeable terms, just like AOA and alpha. It's simply how far the airplane is from the aerodynamic limit on the V-n diagram. If V_{REF} in our example airplane is 65 KIAS, we have a healthy 15 knot aerodynamic margin at 1 g, but that margin is reduced to about 6 knots at 1.4 g and it's gone at 1.7 g's if the pilot dutifully maintains V_{REF} and tries to pull the nose around quickly to salvage an over-shoot. These g-loads are so low as to be imperceptible by the pilot. ***An accurate, responsive AOA system automates the math, provides a simple, flyable cue and warns the pilot if they get too aggressive.*** The top portion of Figure 8 expands the V-n diagram at pattern speeds. Flying a constant airspeed reduces aerodynamic margin during maneuvering. *Loss of control in the traffic pattern is generally not a high g event*. GA pilots typically lose control at less than 2 g's. If the airplane stalled, we presume the pilot didn't intentionally try to use up the aerodynamic margin, so we must assume that the pilot failed to adjust V_S for weight and g-load and missed any aerodynamic or artificial stall warning. They failed to fly the wing. Here is a video demonstration of a low-g departure from controlled flight: https://youtu.be/2QSZTPFwEuw. In this case, a small amount of adverse yaw is present when the airplane stalls, i.e., the turn isn't coordinated.

"If we had a display on our instrument panel showing these [power] curves with a little airplane moving up and down the curve, the correlation would be obvious..."
-Richard VanGrunsven, Aircraft Designer

Power Required. We take power from the engine, convert it to thrust with the propeller and turn that thrust into some combination of airspeed and altitude. From the moment we push up the throttle on takeoff, we spend the rest of the flight using the power lever and a combination of flight control inputs to change our airspeed and altitude as required to accomplish the flight and get the airplane back on the ground. Technically this is called "energy management." Pilots call it "flying."

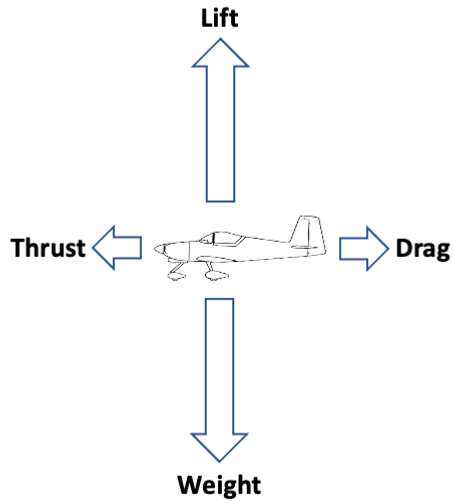


Figure 10. The four forces acting on an airplane in flight.

To understand this, we need to look at another concept: Power required and how alpha relates to it. Figure 10 shows the four forces that act on the airplane in flight. In straight and level unaccelerated flight, the forces balance each other in opposite directions. Lift equals weight (we maintain a steady altitude) and thrust equals drag (we maintain a steady airspeed/AOA). Note the relative *magnitude* of the forces. The wing produces considerably more lift than the propeller produces thrust. A typical light 2-4 seat airplane weighs 1500-3000 pounds, but the thrust produced by the propeller is only a few hundred pounds for the typical 160-250 HP engine. This results in a very low thrust to weight ratio, and why in light, piston engine airplanes we fight gravity so hard when we climb or maneuver. During takeoff, landing, or maneuvering at pattern speed, we use almost 100% of the wing's capacity to produce lift. We are literally "max performing" the airplane, and there isn't much margin for error as we saw in Figure 9. The more power we have available, the greater the margin for error. That's why it's easier to fly an F-22 than a 180 HP C-172 at maximum gross weight at sea level in gusty winds with a 0.16:1 thrust to weight ratio. If it's hot, the engine isn't making rated power or you are operating above sea level, the Cessna has an even *lower* thrust to weight ratio.

In steady, non-accelerated flight thrust is equal to drag, so the amount of thrust required is determined by the amount of drag. Academics would be easier if we all flew jets since jet engines produce thrust directly. The throttle in a jet airplane is a "thrust lever" whereas the throttle in a piston engine airplane is a "power lever." Let's look at why this is the case.

An aircraft drag curve is shown in the top portion of Figure 11. The curve is the sum of parasite and induced drag. *Parasite drag increases with airspeed* and *induced drag increases with alpha* (lift). At low airspeed and high alpha, parasite drag is minimal and at low alpha, high airspeed induced drag is minimal.

The thrust required curve (top portion of Figure 11) shows the amount of thrust needed to overcome drag at various speeds. The nadir of the curve is L/D_{MAX}. At L/D_{MAX} minimum *thrust* is required to maintain level, unaccelerated flight. On the portion of the curve to the right of L/D_{MAX}, it takes more thrust to fly faster. This is intuitively obvious. Parasite drag increases as the square of airspeed and eventually you get to a point where drag is equal to the maximum thrust available. This is as fast as the airplane can fly in level flight. Where pilots often get into trouble is on the portion of the curve to the left of L/D_{MAX} *where it takes more thrust to fly slower*. At low speed and high alpha more thrust is required due to increased induced drag. Add the requirement for more lift under these conditions (pulling g's to maneuver), and even *more* thrust is required.

Propeller driven airplanes don't produce thrust directly like a jet engine. Power required is the product of thrust *and* velocity: Power = thrust x TAS. As thrust required decreases with airspeed, power required decreases more because velocity is also low. That's why minimum power speed is lower than minimum thrust speed (bottom of Figure 11). *The shape of the power curve is more influenced by speed, and thus AOA, of the aircraft*. In other words, the thrust required curve focuses solely on the aerodynamic forces (drag) acting on the aircraft, while the power required curve incorporates aerodynamic forces *and* the effect of speed/AOA.

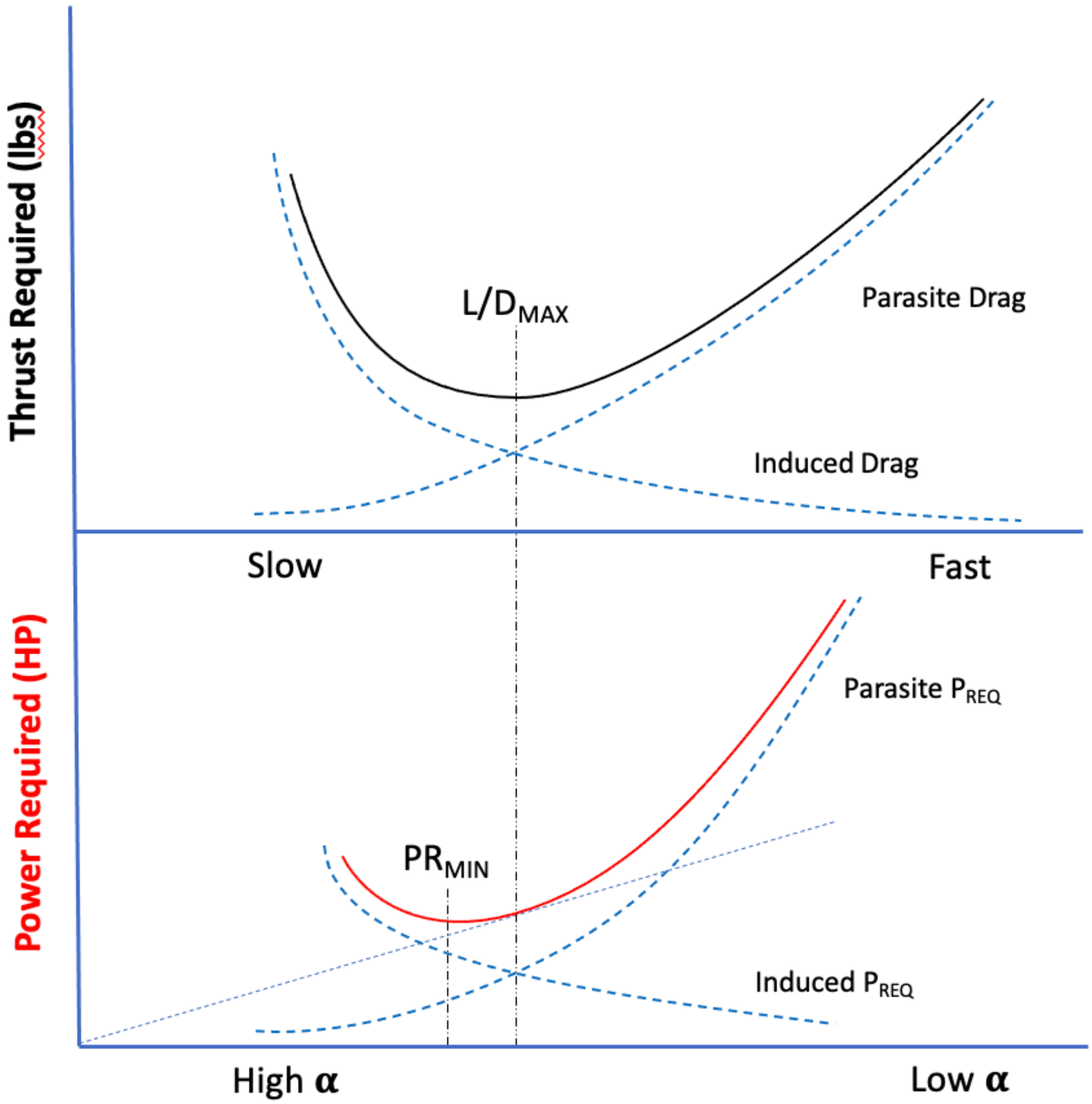


Figure 11. Thrust and Power Required Curves

Figure 12 is a 1 g power required curve. The AOA for minimum required power is a function of L/D_{MAX}. The alpha for L/D_{MAX} is determined by the airfoil design—it is engineered into the airplane. The alpha for min power required is 1.73 times L/D_{MAX} AOA and the velocity for min power required is 0.76 times the velocity for L/D_{MAX}. It's not necessary to understand the aerodynamics or remember the math, just that *alpha and velocity for min power required are a function of L/D_{MAX}*. At 1 g, the *speed* for min power required occurs at about 1.2 to 1.3 stall speed, allowing us to use a single cue that is optimized for landing kinetics *and* power management during maneuvering flight. These physics are the heart of the ONSPEED cues shown in Figure 12.

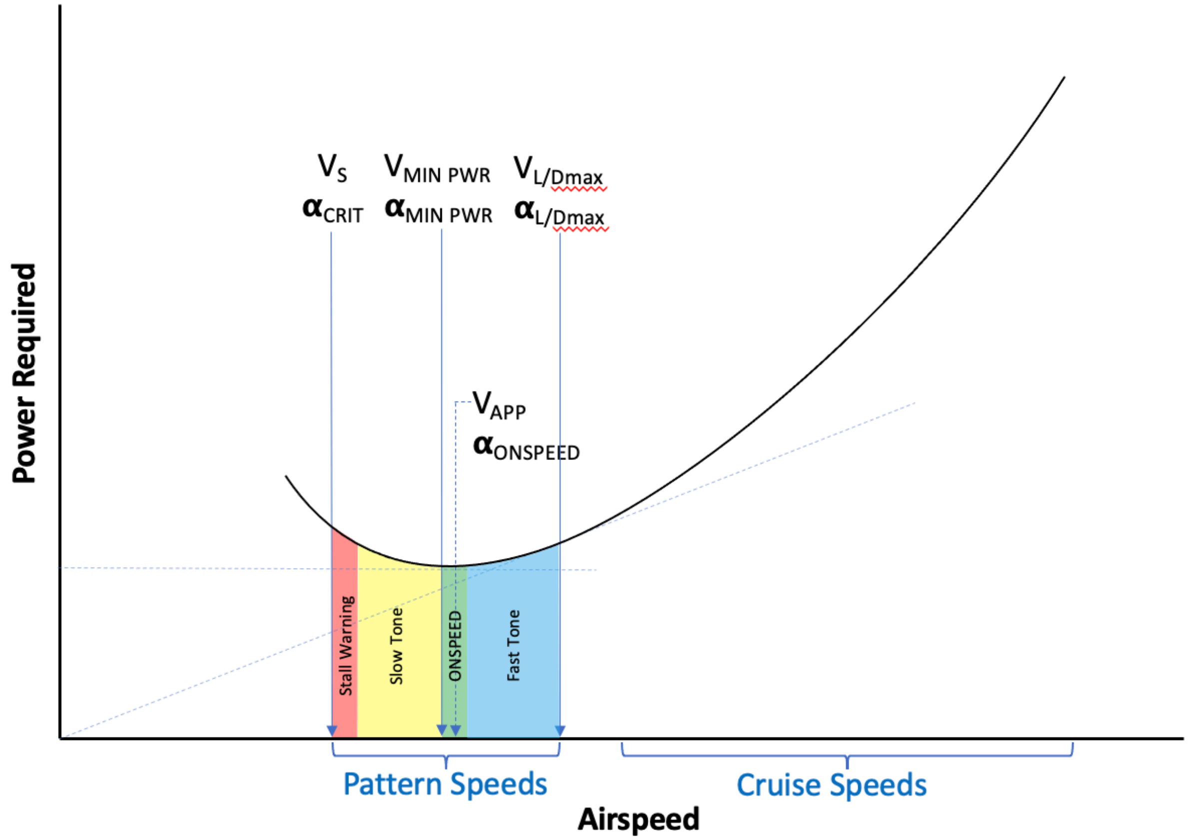


Figure 12. Power required for 1 g flight at ***steady*** airspeed/AOA.

"There's no base turn I can't salvage with enough afterburner..."
-Unnamed, Deceased Fighter Pilot

Power Available. The power generated burning fuel turns the prop and makes thrust. Only about 25% of the energy in fuel is converted to power and 80% or less of that power is converted to thrust due to propeller efficiency. The rate at which fuel is burned is a function of power used. During cruise, we optimize power for speed, distance, or some economical balance of each. *When we maneuver, we use power to make thrust to counter drag as a function of our "effective weight."* Effective weight is gross weight x g load—the amount of lift we need to generate *right now*. How much we can lift, how fast we can climb, how much g we can generate and how fast we can go are all a function of *power available*.

Figure 13 is a power available curve for a piston engine, propeller driven airplane. It illustrates the relationship between power available and speed as a function of propeller efficiency. Power available decreases with density altitude. This means that an increase in temperature, humidity or altitude causes a reduction in the amount of power the engine can produce. If the piston engine is turbo or supercharged, it can maintain sea level power until reaching "critical" altitude, at which point, power available begins to decrease.

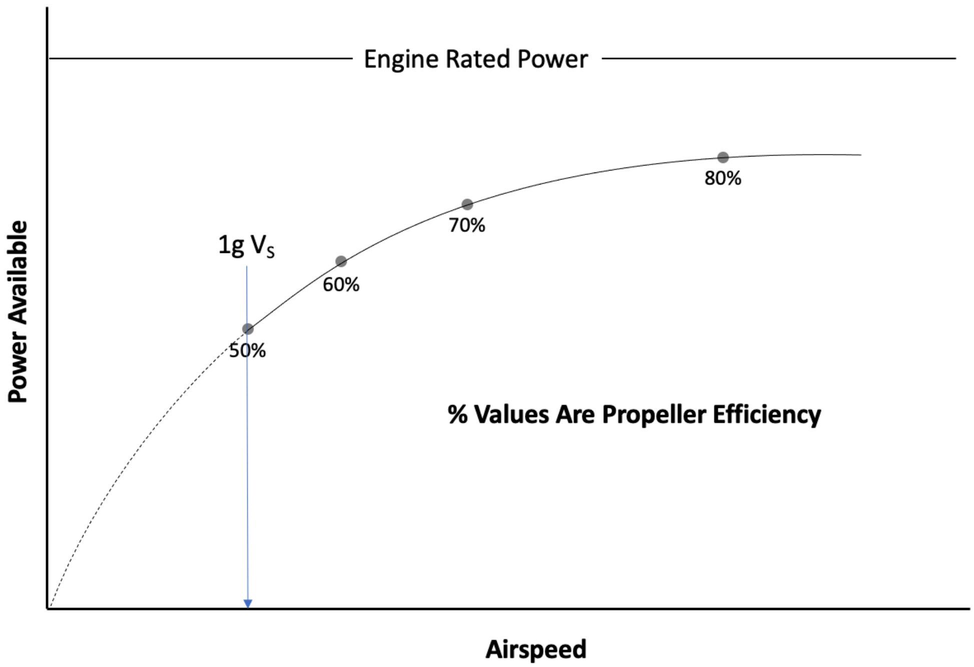


Figure 13. Power available is a function of propeller efficiency, which tops out at about 80%, and speed.

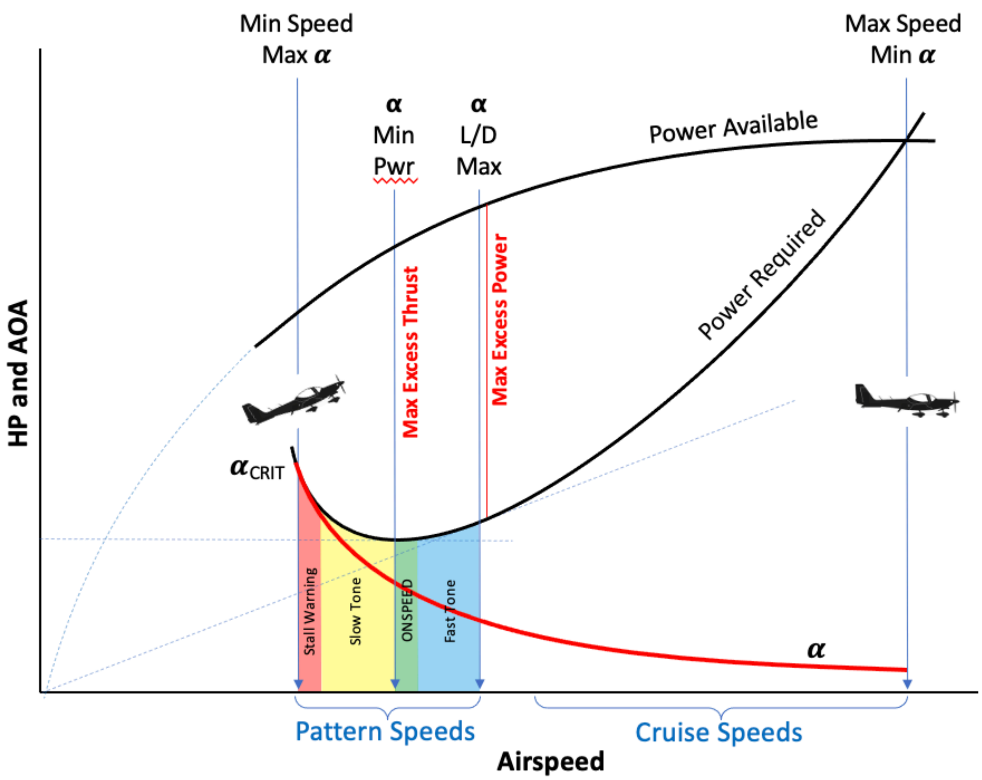


Figure 14. Power required and power available vs airspeed and alpha, 1g ***steady*** flight.

Figure 14 combines the power available, and power required curves for 1 g steady flight. We can derive key performance airspeeds and AOA when we compare the two curves. V_S is minimum controllable airspeed. This airspeed is not limited by power available at 1 g, it is limited by critical alpha. $V_{MIN\ PWR}$ is maximum endurance speed (or maximum endurance glide if the engine fails), it is also best *angle* of climb speed since maximum excess thrust is available from the propeller at this speed. No wind maximum range occurs at L/D_{MAX}. No-wind maximum range glide occurs at L/D_{MAX} power-off. Note the proximity of L/D_{MAX} to maximum excess power. Best *rate* of climb occurs when maximum excess power is available. Maximum speed occurs when power available equals power required.

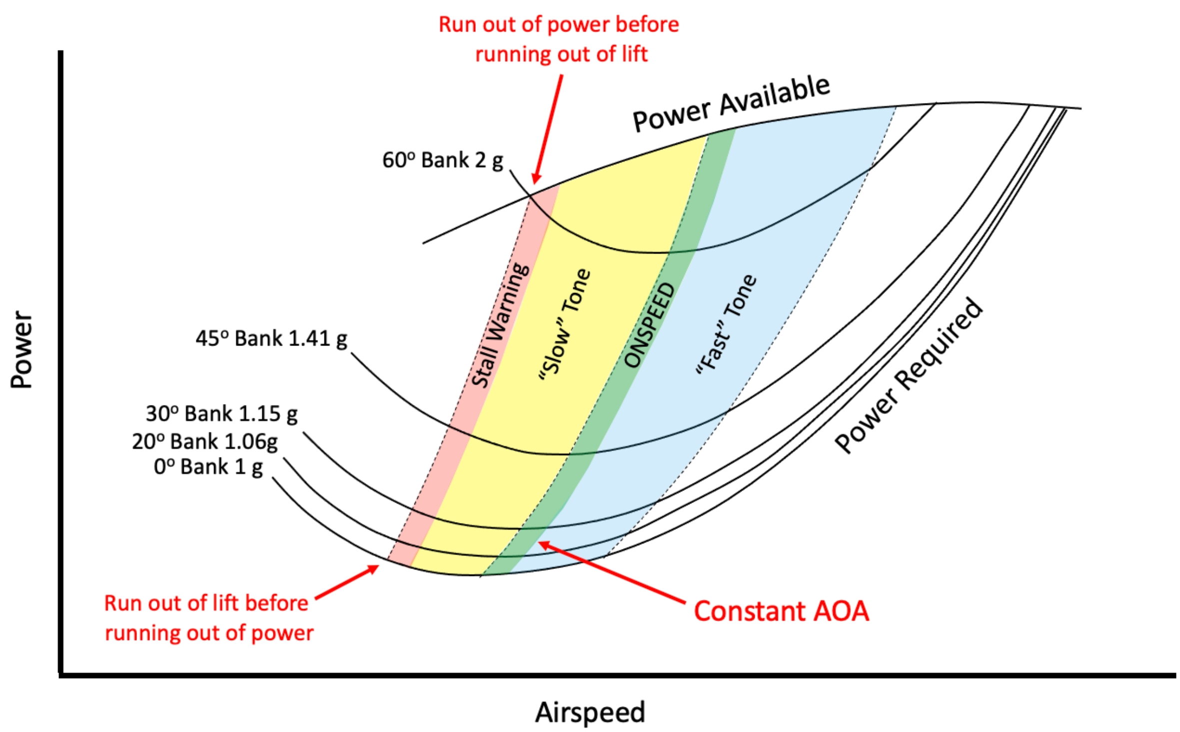


Figure 15. Power required/available "envelope" during ***maneuvering*** flight—a level turn in this example. Note the envelope shrinks as g-load increases. Like the flight envelope shown in the V-n Diagram, constant AOA are *curved* lines.

Figure 15 shows how the power required/available "envelope" shrinks when we maneuver. During maneuvering, the wing must work harder to generate lift to support the effective weight of the airplane. For a given density altitude, power available doesn't change when effective weight increases, but power required does. Figure 15 is a plot of power vs airspeed for an RV-4 at 1375 lbs gross weight and 5000 feet density altitude. The airplane has a relatively low power loading (horsepower divided by weight) and can maintain 2.5 g's in a full power, *level* turn. In other words, it has a better thrust to weight ratio than a C-172. But the power required curve shifts up and to the right for all propeller driven airplanes. Note the power available/power required envelope shifts up and to the right during maneuvering.

There is another critical takeaway from Figure 15: *at low g, we run out of AOA (i.e., stall) before we run out of power when we are maneuvering*. As effective weight (g) increases, eventually we get to the point where we run out of power before we stall. Figure 14 is demonstrated in flight in this video: https://youtu.be/V5sCflrjTb4.

Effective Power. In simple terms, we either have excess power to climb, speed up or maneuver or we don't. The physics behind this are simple: it's the balance between thrust and drag. In pilot terms:

$$\text{Effective Power} = \frac{\text{Thrust} - \text{Drag}}{\text{Effective Weight}}$$

In these terms, it's apparent that if we've got more thrust than drag, effective power is positive: we can go up and/or speed up for a given effective weight (actual weight times current g-load). On the other hand, if there is more drag than thrust, effective power is negative, the airplane is going to go down or slow down unless the pilot either increases power or reduces drag.

We control power with the power lever (throttle) and drag with AOA. Increasing AOA increases drag, and reducing AOA decreases drag. This is because AOA controls the amount of lift the wing makes and drag is proportional to lift. Reducing AOA also reduces g-load. So, we reduce lift drag ***and*** effective weight when we "unload the wing." "Unload" means pushing the stick or yoke forward to reduce AOA. This works in any attitude. This basic relationship is why a "drug in" final approach can be dangerous. We know that under these conditions you run out of alpha before power at 1 G (Figure 13) so you can only add so much power; and if you are low, reducing AOA is difficult because there simply isn't any room available to do that. The ground is in the way.

This means that any indicated airspeed which is a surrogate for an angle of attack varies any time we maneuver. The key is to take the variable, thus unreliable, "surrogate" out of the equation, directly measure angle of attack and provide that information to the pilot in an intuitive, ergonomic manner that doesn't require any cockpit math. What the pilot needs is simple "push" or "pull" information--the same feedback an instructor provides when we are first learning how to fly. This *directs* the pilot to do something, unlike conventional instrumentation that *describes* conditions to the pilot, but requires him to interpret the indications correctly, process and then react to that information. Using an audio tone is an effective means to do that. It transmits information directly to the brain and doesn't require the pilot to look at anything. This logic "automates" AOA and power required math for the pilot and is depicted in Figure 16.

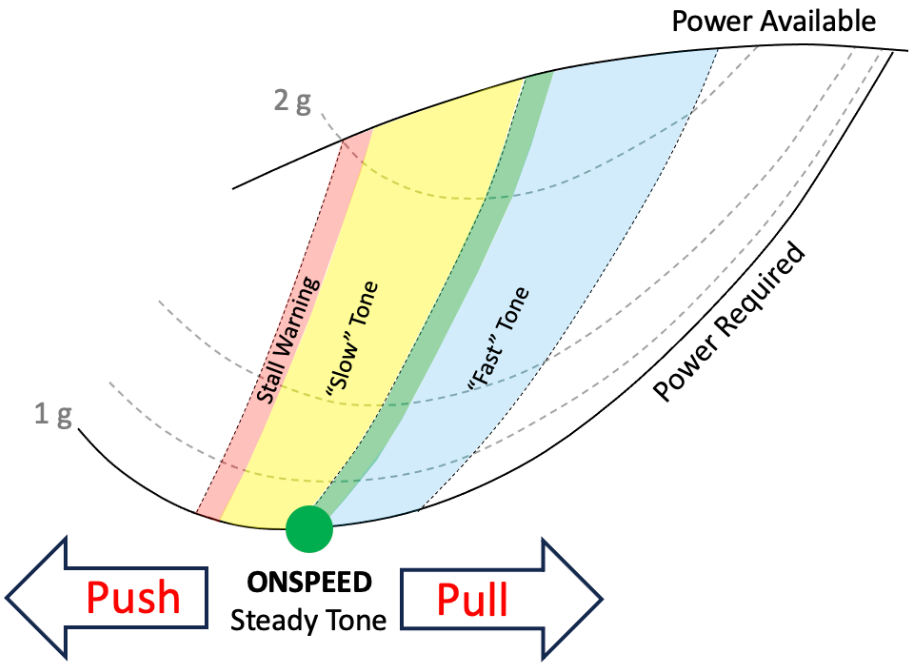


Figure 16. The AOA tone pattern provides directive feedback to either pull or push something: If fast, pull the power lever to reduce power or pull the stick to increase alpha, or both; if slow, push the power lever to add power or push the stick to reduce alpha, or both.

If the objective is to maintain an ONSPEED condition for approach (i.e., proper kinetic energy state for approach with a consistent and safe stall margin), the pilot simply reacts to the feedback provided by the tone. If there is slow tone, the pilot pushes something: either the throttle to increase power/airspeed or stick to reduce AOA, or both. Conversely, if there is fast tone, the pilot pulls something to correct to ONSPEED. If the airplane is maneuvering, any slow tone tells the pilot that effective power is negative and that combination of power and alpha (energy state) is unsustainable unless something is adjusted. This is shown in Figure 17. The tone pattern also allows for a simple "decoupled" approach to flying an approach and landing. Pitch controls AOA, power controls glide path and bank angle controls ground track.

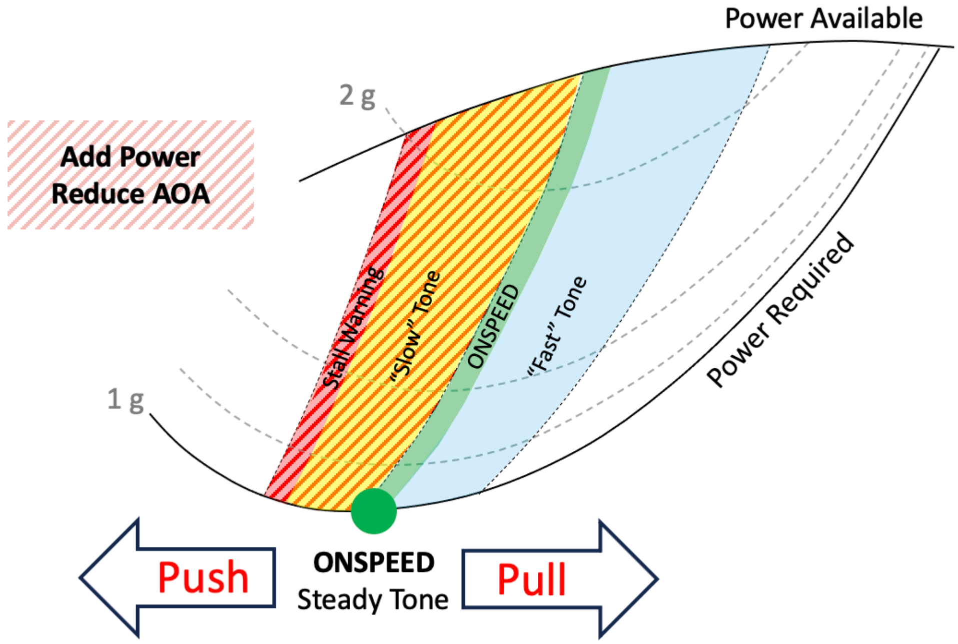


Figure 17. The "Slow Tone" tells the pilot to push something: power lever or stick to rebalance thrust and drag for effective weight.

Turn Performance. AOA is an excellent aid for managing turn performance. Before discussing that, let's review the factors that affect turn performance. Turn rate and radius are determined by only two factors: g in the plane and direction of turn ("radial g" or more correctly, centripetal force) and true airspeed. If you increase g for a constant true airspeed, turn rate increases and turn radius decreases. In other words, more g equals faster turn—up to the point at which the airplane stalls. Maximum *instantaneous* turn occurs just prior to the aerodynamic limit. Maximum *sustained* turn occurs ONSPEED. The key to understanding these two concepts in the nomenclature, *you can't sustain an instantaneous condition*. If you pull to the stall buffet and continue to increase g, the airplane will stall. If, however, you stop the pull ONSPEED, the airplane can *sustain* that condition. Thus, *an ONSPEED condition provides optimum turn performance*. It's OK to turn slower than ONSPEED, but the takeaway is you can't sustain that condition. Airspeed will continue to decrease if you try to. The slow tone will remind you to "so something," either reduce AOA or increase power in this case.

Let's take a moment to consider a gliding turn, say a base turn in the traffic pattern where power is at IDLE. There is a common misconception that this turn is "unloaded" or flown at a lower g load than a level turn. This is not the case. Remember, only two factors effect turn performance: airspeed and g. If there isn't g, the nose will not "rate" across the horizon (i.e., the airplane won't turn). Thus, a 45-degree banked gliding turn still requires about 1.4 g's. Even at lower bank angles, say 30 degrees, 1.2 g's are required. It's this subtle increase in g, sometimes combined with a gust-load that results in an unintentional stall.

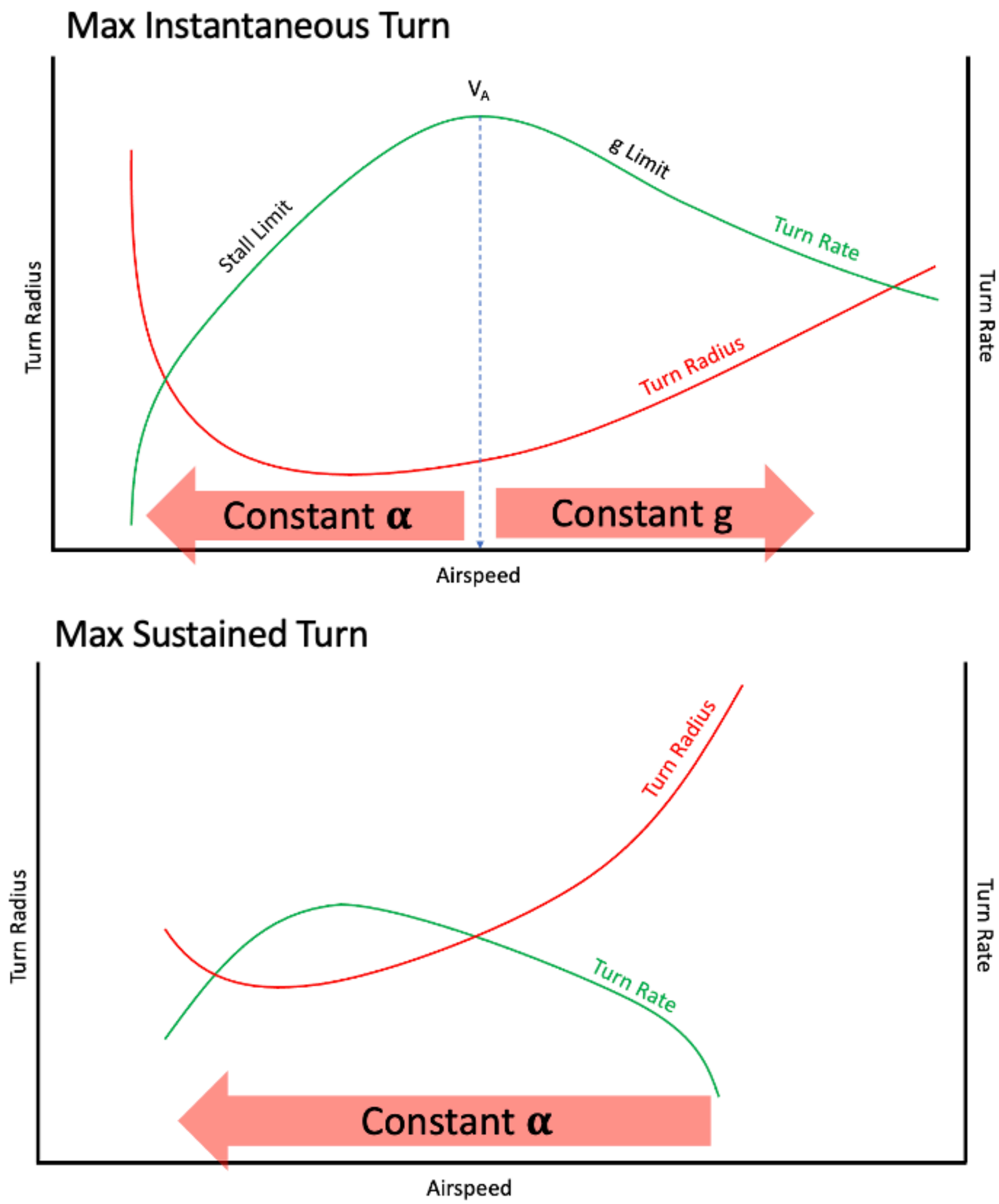


Figure 18. Maximum instantaneous turn rate (top) and maximum sustained turn rate bottom. Maximum instantaneous turn occurs with the airplane is at the g limit when faster than maneuvering speed, and on the stall warning tone when slower. Optimum turn occurs at ONSPEED AOA, regardless of g load. No airplane has sufficient power to fly an instantaneous turn indefinity, it will eventually stall. All airplanes have sufficient power to fly an optimum turn continuously.

Figure 18 is a plot of turn rate and radius based on airspeed. An airplane cannot maintain maximum instantaneous turn, airspeed will continually decrease throughout the turn until the airplane ultimately stalls. Above maneuvering speed, turn performance is g limited, and below maneuvering speed, turn performance is AOA limited. The transition from maximum allowable g to AOA occurs where the g limit of the airplane intersects with the aerodynamic (stall) limit (maneuvering speed). On the other hand, maximum sustained turn performance occurs when the airplane has sufficient power to produce enough thrust balance drag and the turn can be maintained. Maximum sustained turn is flown at a constant (ONSPEED) alpha. The "push/pull" feedback provided by AOA provides the pilot with directive feedback to fly either maximum instantaneous or maximum sustained turn. This is shown in Figure 19.

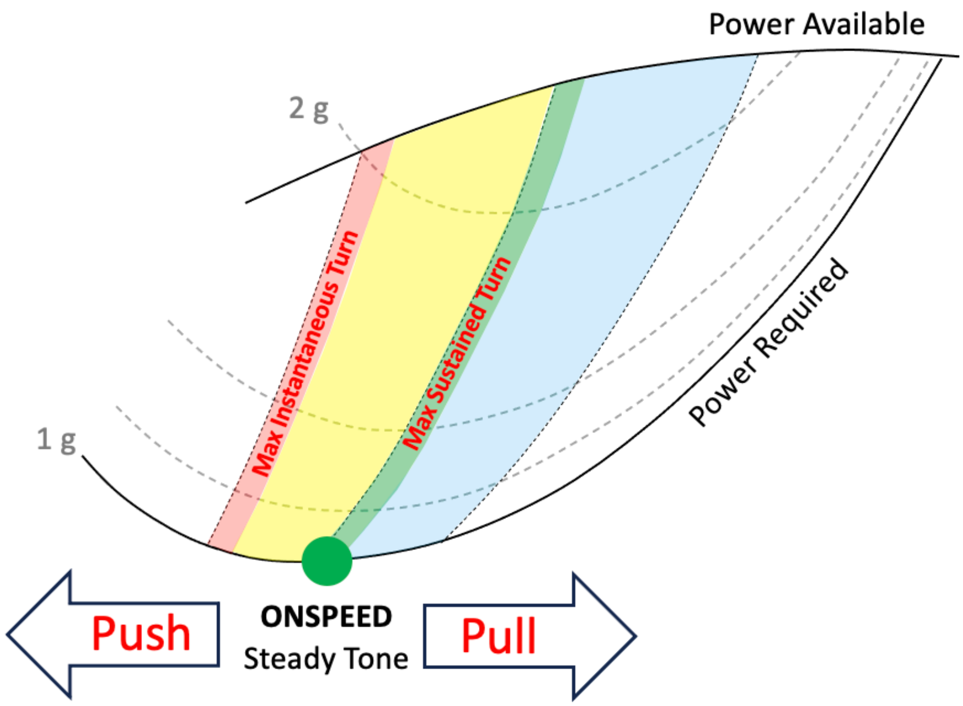


Figure 19. Using AOA to manage turn performance.

There usually is no need for maximum instantaneous turn performance. Some exceptions are emergency dive recovery or maneuvering to avoid a collision hazard in which case the need to maneuver over-rides any energy considerations (other than stall). Most of the time, an ONSPEED turn is sufficient "maximum performance."

Gravity Effect. As discussed previously, when we are maneuvering in other than level flight, we get (or loose) effective thrust, courtesy of Mother Earth. If the flight path of the airplane is below the horizon, we get a "gravity assist," or more effective thrust. If, on the other hand, the flight path of the airplane is above the horizon, we effectively decrement thrust available. An easy way to picture this is using the same example we used to picture the AOA extremes. If an airplane is 90 degrees nose low at full power, thrust is equal to the thrust produced by the propeller plus the gross weight of the airplane. So, our little RV-4 that produces about 300 pounds of thrust in level flight, has an effective thrust of 1675 pounds (1375 pound gross weight + propeller thrust) going straight down. The airplane will speed up rapidly in this attitude. Conversely, if we are going straight up, then effective thrust is *negative* 1075 pounds, and the airplane will rapidly slow down and eventually fall back to earth. For most non-aerobatic light plane maneuvering, the flight path is within about 20° of the horizon, so gravity effect isn't nearly as pronounced, but it is there, nonetheless. The "push/pull" feedback provided by AOA helps the pilot to compensate for gravity when flying a constant AOA cue. It effectively helps manage the flight path of the airplane by providing direct feedback to the pilot to manage alpha and power to maintain a desired condition.

Velocity Vector Control. The "velocity vector" is where the airplane is going, not necessarily where it's pointing. On advanced instrumentation, the flight path marker is aligned with the velocity vector. **We can fly any AOA at any airspeed and any attitude, so the pilot must still manage where the airplane is going.** We do this with roll, pitch and power inputs. Where we point the lift is called "lift vector management" and controlling the flight path is called "velocity vector management." For example, the airplane can be ONSPEED, wing's level at 1 g at V_{REF} airspeed. It can also split-S ONSPEED as demonstrated in this video: https://youtu.be/GvCjBzByaNw. In the Split-S, airspeed varies considerably, and where the airplane is pointing and where it's going are changing throughout the maneuver, yet angle of attack is constant. Another good example is an ONSPEED spiral. We can gradually increase bank, g and airspeed in a descending turn and still be ONSPEED. AOA is a critical tool for managing pitch and power inputs when maneuvering, *but the pilot must also be aware of where the lift is pointing.* Determining lift vector "placement" can only be done by looking out the window or at an attitude display.

Fractional Lift. We tend to think of alpha in degrees, but there is another way measure it as well. This is called fractional or "percent" lift. There is an AOA at which the wing produces no lift. Engineers call this the "zero lift line." A cambered airfoil achieves zero lift at a negative alpha, whereas a symmetrical airfoil is at zero lift when AOA is zero. Just prior to the stall and loss of longitudinal stability, the wing is generating 100% lift. This simple "0-1" scale is another way to think about how hard the wing is working. It's also another way to display AOA to the pilot. The easiest way to think of this is how much work the wing must do "right now" depending on how hard the pilot is pulling on the stick or yoke relative to the maximum amount of lift the wing can produce. For example, in a 60-degree banked turn, 2 g's are required, and your 1500-pound airplane requires 3000 pounds of lift to maintain altitude. If you encounter a 1 g gust load in that turn, the wing now needs to generate *4500* pounds of lift. We've learned that AOA always follows g, and stall speed varies with a change in weight, whether that change is the result of fuel burn (gross weight) or g load (maneuvering).

Like angle of attack, **fractional lift is directly proportional to effective weight.** All airplanes reach maximum lift at some critical AOA, usually about 15-20 degrees for the typical straight winged, piston engine GA airplane. At critical AOA, the wing is generating 100% lift. All airplanes approach at 60% lift and all straight wing airplanes achieve L/D_{MAX} at 40-50% lift. The fractional lift associated with maneuvering speed at 1 g is determined by dividing 100 by the g limit of the airplane. Thus, a normal category airplane is at maneuvering speed when fractional lift is 26% (100/3.8 = 26). This means that if fractional lift is greater than 26%, the airplane is below maneuvering speed and will stall before reaching the structural limit and no restrictions on the use of flight controls exist. This value is 23% for a utility category and 17% for an aerobatic category airplane. If fractional lift exceeds these values, then the airplane will stall before reaching the structural limit of the airplane, and flight control use is not restricted.

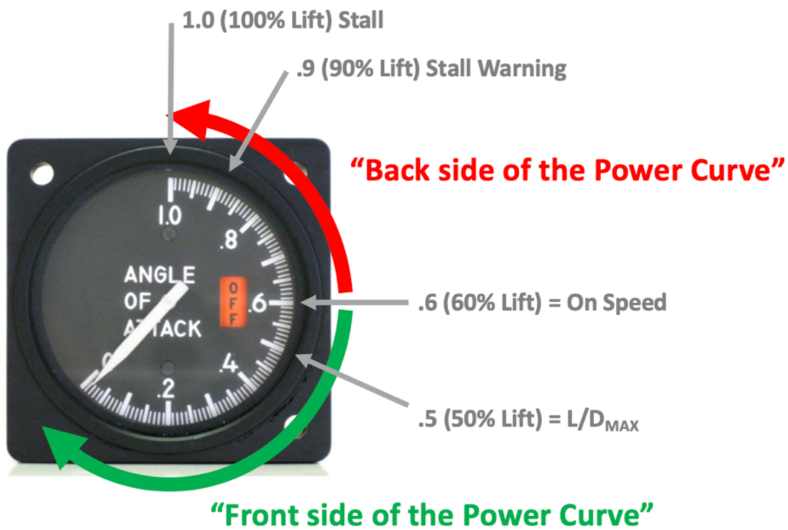


Figure 20. Classic mechanical fractional Lift AOA Instrument. Notice that 60% lift (ONSPEED) is at the right three o' clock position. This was an early military standard. It correlates with a properly scaled airspeed indicator where V_{REF} is at roughly the same position.

Figure 21 is a generic coefficient of lift (C_L) vs AOA plot for a cambered airfoil. The C_L is a dimensionless number that quantifies the amount of lift an airfoil produces relative the fluid (air) dynamic forces acting on it. In other words, how much lift the wing can generate as a function of speed, angle of attack, density and wing area. The higher the C_L, the more lift the wing produces and the harder it is “working.” A cambered airfoil means that the mean camber line is curved, and zero lift occurs at a negative AOA. This is shown on the right side of the figure. Most GA airfoils are cambered. We can use the C_L vs alpha plot to illustrate why an ONSPEED condition occurs at 60% lift. To do that, we need to do some simple proportional math to figure out how hard the wing is currently working vs it's maximum capacity and figure out our approach condition relative to stall.

$$\frac{\text{Current Alpha} - \text{Zero Lift Alpha}}{\text{Critical Alpha} - \text{Zero Lift Alpha}} = \frac{\text{Current } C_L}{\text{Maximum } C_L}$$

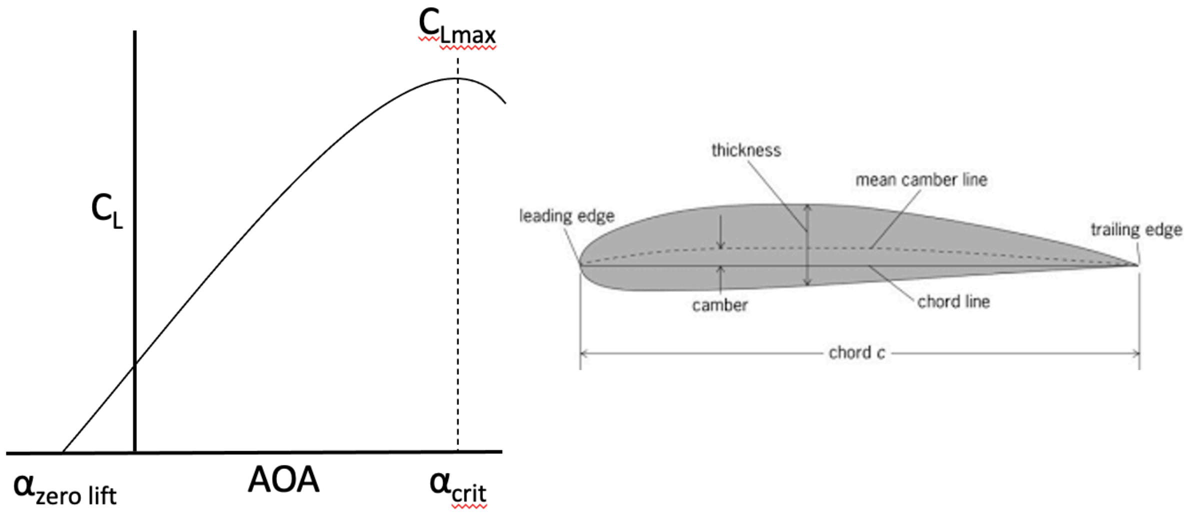


Figure 21. A generic C_L vs alpha plot and a cambered airfoil. Most GA airfoils are cambered, and a zero-lift condition occurs at a negative angle of attack.

To look at the ratio of lift we use for approach, we need to work backwards from our normal $V_{REF} = 1.3\ V_S$ to make sure that we accommodate change in weight and g load. V_{REF} is a kinetic condition, and we are simply using AOA to control our airspeed. In 1 g flight, V_{REF} is sufficient as a reference for approach, but if we maneuver at V_{REF}, actual stall margin is reduced. Since we know that airspeed for critical angle of attack varies with the square root of the g load, we'll just calculate the reciprocal of our approach speed ratio squared:

$$\frac{1}{(V/V_{STALL})^2} = \frac{1}{(1.3)^2} = .591$$

It's practical to combine fractional lift information and trend information with a conventional "doughnut/chevron" military-style alpha indexer. This is shown in Figure 22. Note that at an L/D_{MAX} condition the trend indicator (white line) is aligned with the pips and fractional lift is 50%.

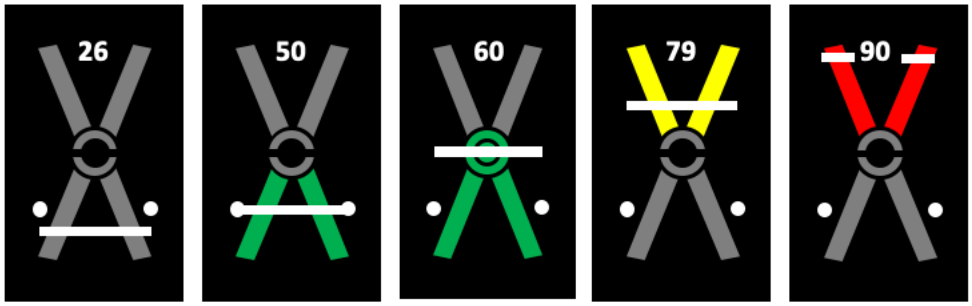


Figure 22. Fractional lift and visual indexer display for key performance conditions. Left to right: maneuvering speed for a Normal Category Airplane (3.8 g limit), L/D_{MAX}, ONSPEED, "slow condition," stall warning.

"Beating the Flight Controls." No cuing or warning system is perfect. It still depends on the pilot to interpret and react. And even excellent transient response isn't a match for a "high gain" pilot. A high-gain pilot moves the flight controls so quickly, the airplane doesn't have time to react or immediately blows thru aerodynamic or g limits. The only match for this pilot is flight envelope protection or fully automatic fly by wire controls, and a sick sack for their passengers. Even a good pilot will occasionally make an unintentional high-gain flight control input, usually when they become startled. Flight control inputs should always be proportional to need: small input for a small correction, and even a gross input needs to be *smooth*. Air molecules can't respond instantly, and there is always inertia to be overcome. For a conventional piston engine light airplane, a maximum input of about 2 g's per second is all one can expect the airplane to be able to handle when maneuvering aggressively. In the traffic pattern, a 1 second 2 g input has the potential to be fatal. And if mishandling the flight controls wasn't bad enough, Mother Nature can induce the same effect with a gust of wind. It doesn't take a big gust of wind to exceed the limited g we have available when we are taking off or maneuvering to land in the traffic pattern.

"Unload for Control." This concept is the bottom line to maintaining positive aircraft control. If we approach the limit of the wing's ability to generate lift and fail to do anything, the airplane will stall. This can happen at any airspeed and any attitude. Once stalled, an inappropriate control input, gust of wind or lack of pilot reaction could result in a loss of control. The "unload for control" concept simply means "unload the wing" by reducing angle of attack and g-load. An airplane cannot stall at zero g and any reduction in g below one *reduces* stall speed. For example, at ½ g, stall speed is 70% of 1 g stall speed. But AOA is always the key to control: the aerodynamic limit (critical alpha) is *always* the same. A timely reduction in AOA is all that is required to maintain aircraft control. Directive AOA cuing that provides trend information can eliminate startle factor and provide the pilot with the feedback required to "unload for control" when necessary.

Summary. The discussion and diagrams above show how an accurate, ergonomic AOA tone pattern effectively provides *directive* feedback to the pilot for controlling angle of attack and power to maintain positive control when maneuvering. AOA is the *only* direct indication of how hard the wing is working to generate lift. The amount of lift required depends on the effective weight of the airplane. No math is required to "fly the wing" using angle of attack. Tones are transmitted directly to the brain and don't require the pilot to look at anything. All key performance cues can be expressed in AOA, and those AOAs remain constant regardless of gross weight or g-load. AOA also provides power required feedback to balance thrust and drag when flying at constant AOA.

Summary of Key Performance Parameters Provided by an Accurate AOA Cue:

Stall Warning (≥ 90% Lift)

1. Maximum instantaneous turn rate

"Slightly Slow" (65-70% Lift)

1. Transition to landing
2. Short-field approach

ONSPEED (60% Lift)

1. Zero excess specific power (0 P_S) at WOT
2. Balanced effective power at any condition (thrust and drag balanced as a function of velocity)
3. Maximum sustained turn rate
4. V_{REF}
5. Best angle of climb
6. Maximum endurance
7. Maximum endurance glide
8. Optimum low altitude maneuvering
    a. Best blend of turn and glide performance, appropriate energy (airspeed) for landing transition with safe stall margin

Note: the ONSPEED band is approximately $\pm$ 1° wide resulting in an airspeed band of $\pm$ 2-2.5 knots of desired condition.

"Slightly Fast" (55-60% Lift)

1. V_{APP}
    a. Increased stall margin for gusty/turbulent conditions

L/D_{MAX} (50% Lift)

1. Maximum range
2. Maximum range glide
3. Approximate best rate of climb

Carson's Cruise (22% Lift)

1. Optimum blend of fuel consumption, range, and airspeed (slower than normal cruise speed)

2. Optimum high-speed climb (V_Z)

1 G Maneuvering Speed (varies with aircraft g-limit)

1. Fractional lift associated with V_A
    a. Divide 100 by the g-limit of the airplane to determine fractional lift associated with maneuvering speed

Summary of Pilot Math

1. Stall speed increases as the square root of g load:

$$Vs = \sqrt{g}\ load \times V_{STALL}$$

2. To determine the g load associated with a banked, ***turning*** condition, calculate the reciprocal of the cosine of the bank angle:

$$\frac{1}{\cos Bank\ Angle}$$

3. To determine the change in L/D_{MAX} ***speed*** in a turn, calculate the reciprocal of the square root of the cosine of the bank angle:

$$\frac{1}{\sqrt{\cos Bank\ Angle}}$$

4. To determine the AOA for ONSPEED, multiply the AOA for L/D_{MAX} by 1.73:

$$\alpha_{ONSPEED} = \sqrt{3}\,\alpha_{L/Dmax}$$

NOTES

[1] "Stall and Spin Accidents: Keep the Wings Flying," An analysis of stall/spin accidents, 2000-2014. AOPA Air Safety Institute.
[2] "An Analysis of Fixed-Wing Stall-Type Accidents in the United States." Fala, Nicoletta, Aerospace, 9, 2022.
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[5] AOPA, Johnson, 2022.

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