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Maneuvering in Mountains on the Back Side of the Banked Power Curve

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Current recommendations for safe maneuvering of light aircraft at high altitudes are insufficiently supported by flight mechanics studies. The linearized propeller polar (bootstrap) approach to aircraft performance is analytic and, thus, affords a remedy. After review of current mountain maneuvering recommendations and a reprise of fixed-pitch bootstrap approach technology, bootstrap steady maneuvering diagrams are examined. Although those charts prove too complicated to use in the airborne cockpit, they graphically support flying on the front side of the excess power curve, at airspeeds above speed for banked absolute ceiling and at bank angles below that ceiling bank angle. Calculations allow construction of speed/bank/turn tables, check lists quantifying the prescription that one stay on the front side of the banked power curve. A relevant historical fatal aviation accident is analyzed. A speed/bank/turn table is given for a particular airplane for a given weight and configuration. That sample table also includes speeds and bank angles required for tightest level turns, but those optima require caution; they are on the back side of the power curve and are often stall limited. It is recommended that speed/bank/turn tables be produced for general aviation operators and pilots who maneuver at high altitude in constricted terrain.

Nomenclature

A = wing aspect ratio (span^2/area)
b = linearized propeller polar intercept
C = altitude engine power drop-off parameter
C_{D0} = parasite drag coefficient
D = drag
d = propeller diameter
E = composite bootstrap parameter
e = Oswald airplane efficiency factor
F = composite bootstrap parameter
G = composite bootstrap parameter
g = acceleration of gravity
H = composite bootstrap parameter
$\dot{h}$ = rate of climb or descent
h_ρ = density altitude
K = composite bootstrap parameter
M = engine torque
m = linearized propeller polar slope
n = propeller revolutions per second
P = power
Q = composite bootstrap parameter
R = aircraft turn radius; composite bootstrap parameter
S = reference wing area
T = thrust
U = composite bootstrap parameter
V = airspeed
W = gross aircraft weight
γ = flight-path angle
ρ = atmospheric density
σ = relative atmospheric density
Φ = Gagg–Farrar torque/power altitude dropoff factor
φ = bank angle

Subscripts

a = available; maneuvering
bg = best glide
$L_{\max}$ = lift maximum
LO = liftoff
M = maximum
md = minimum descent (rate)
m = minimum; mountain; maneuver
r = required
S = stall
x = best climb angle
xs = excess
y = best climb rate
0 = rated mean sea-level value

Introduction

IN August 1984 a Cessna L-19E crashed while maneuvering in the mountains near Tabernash, Colorado.[1] Both occupants were killed. One surprising aspect of this accident is that the airplane was flying with an operating video camera strapped to a wing strut. A second surprise was that when the wreckage was finally found, after three years (videotape draped in the trees, exposed to the elements), the tape could be reassembled into a coherent audiovisual record of that flight from takeoff to impact. A third surprise, at least to the author when he first viewed the tape, is that the airplane's final turn appears to have begun with only a very moderate bank. The airplane then stalled (the stall warning horn can be heard), turned inverted, and crashed into the trees. The National Transportation Safety Board (NTSB) probable cause is cited (along with "improper in-flight planning/decision") as "airspeed not maintained."[1]

Though correct, the NTSB gave only a superficial evaluation of the cause of the accident. One wants a deeper explanation, a more detailed train of (probable) events and, most of all, a way to prevent such accidents. Thus, although this paper is in a sense a postmortem examination of that Colorado crash, it attempts to go beyond one sad event to come up with a rational answer to a more general aeronautic conundrum: What mountain maneuvering limits and what speed and bank angle restrictions should a pilot follow?

The semipopular general aviation literature gives some guidance. Geeting and Woerner[2] suggest banking 60 deg for a course-reversal maneuver and executing it with no less speed than

$$V_{\text{ref}} = 1.83 V_S \tag{1}$$

where V_S is the wings-level flaps-up stall speed. Their V_{ref} turns out to be 1.3 times the 60-deg banked stall speed. They also term the speed in Eq. (1) "minimum safe maneuvering speed."[2] For a

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Cessna 172 at maximum gross weight (2400 lb), V_S is about 51 KCAS, and so their corresponding suggested minimum safe maneuvering speed is $V_{\text{ref}} = 93$ knots calibrated air speed (KCAS).

Imeson[3,4] suggests a mountain minimum maneuver speed of

$$V_{\text{mm}} = V_S / \cos\varphi \tag{2}$$

essentially squaring the multiplicative effect of banking. For a Cessna 172 banking 45 deg, this would mean $V_{\text{mm}} = 72$ KCAS. These values are only given for representative comparison. Neither maneuvering prescription is backed by sufficient reason.

This paper melds a venerable old idea, that of the nonintuitive actions required when flying in the airplane's region of reversed commands[5] (the back side of the excess power curve), together with a fairly new idea, namely, the author's[6–11] bootstrap approach to propeller-driven aircraft performance. This approach comes up with a detailed but easily implemented prescription for avoiding stalls, or loss of control, when maneuvering at high altitude in low-performance aircraft. Although downdrafts and turbulence are important practical maneuvering considerations, this paper will assume calm air. Even so, startling features of that unfriendly back side flight regime will be uncovered.

Some liberties will be taken with facts known about the accident. The L-19 is a constant-speed propeller airplane. Whereas the bootstrap approach encompasses constant-speed airplanes satisfactorily, it does so at the cost of having to invoke the General Aviation General Propeller Chart. That chart is a curve-fit entity, which obviates simple analytical discussion and calculation. Consider instead the more transparent fixed-pitch propeller airplane. In that way, formulas for all needed performance numbers can be displayed or referenced. Basic principles are the same for both types. Because these are relatively low-powered airplanes, at relatively high altitudes, full throttle will always be assumed. The specific airplane to be modeled is the ubiquitous Cessna 172, flaps-up configuration. None of these restrictions is essential.

After a brief discussion of the region of reversed commands, there comes a longer one adumbrating the bootstrap approach, its calculation-simplifying composite parameters, and its graphic if complicated steady maneuvering charts. Those charts show relations among airspeed, bank angle, rate (or angle) of climb or descent, load factor limits, and turn radius (or rate), how minimum level flight speed comes out from behind the stall speed curve at higher altitudes, and how speeds for best angle of climb and for best rate of climb increase as bank angles increase. Such a chart will support a plausible scenario of what happened to November 4584A, the hapless L-19 that failed to successfully turn around the afternoon of 10 August 1984. A preventive prescription is proposed, and the fine points behind its rationale are discussed. Effects of reducing throttle, or of using flaps, are considered, as are tightest turns under the subject circumstances.

Region of Reversed Commands

In the region of normal commands, a pilot desiring to climb faster pulls back on the control stick. The region of reversed commands gets its name from the fact that in it a pilot must push forward on the control stick to climb faster. The reversed command region is characterized by airspeeds $V < V_y$. In terms of power available P_a, power required P_r, and their difference excess power $P_{\text{xs}} = P_a - P_r$, V_y can be described either as the speed at which P_{xs}, plotted as function of airspeed V, is maximum, or as the speed at which the slopes of the P_a and P_r graphs are the same. The relation between rate of climb (ROC) and excess power is ROC $= P_{\text{xs}}/W$ (Fig. 1).

Minimum power required is at V_{md}, the speed for minimum (gliding) descent rate. Beginning pilots are often admonished against flying in the region of reversed commands. However, they do that about as often as they takeoff, at least once each flight. Liftoff speed is ordinarily about $1.2V_S$ or slightly less. For the prototype Cessna 172, that puts V_{LO} (under standard conditions) at or below 61 KCAS, but V_y is about 76 KCAS and, indeed, to climb out at V_y (which the pilot is also often advised to do), he or she pushes forward on the stick, soon after liftoff, thereby raising airspeed to climb out faster.

The region of reversed commands is ordinarily only considered in a wings-level context because keeping wings level maximizes climb rate. However, the definitions of region of reversed commands and of V_y are here to be extended to include banking maneuvers, with the same relation between the two as in the wings-level case. Given any bank angle φ there is a speed, to be called $V_y(\varphi)$, which (for any given airplane at full throttle, in a given configuration at a given weight and altitude) maximizes rate of climb (or minimizes rate of descent). When the bank angle is such that $V_y(\varphi)$ barely allows level flight, it is the banked absolute ceiling speed, $V_{\text{BAC}} = V_y(\varphi; \dot{h} = 0)$.

Bootstrap Approach

The airplane's full throttle (or gliding) quasi-steady flight performance can be obtained completely from knowledge of the nine

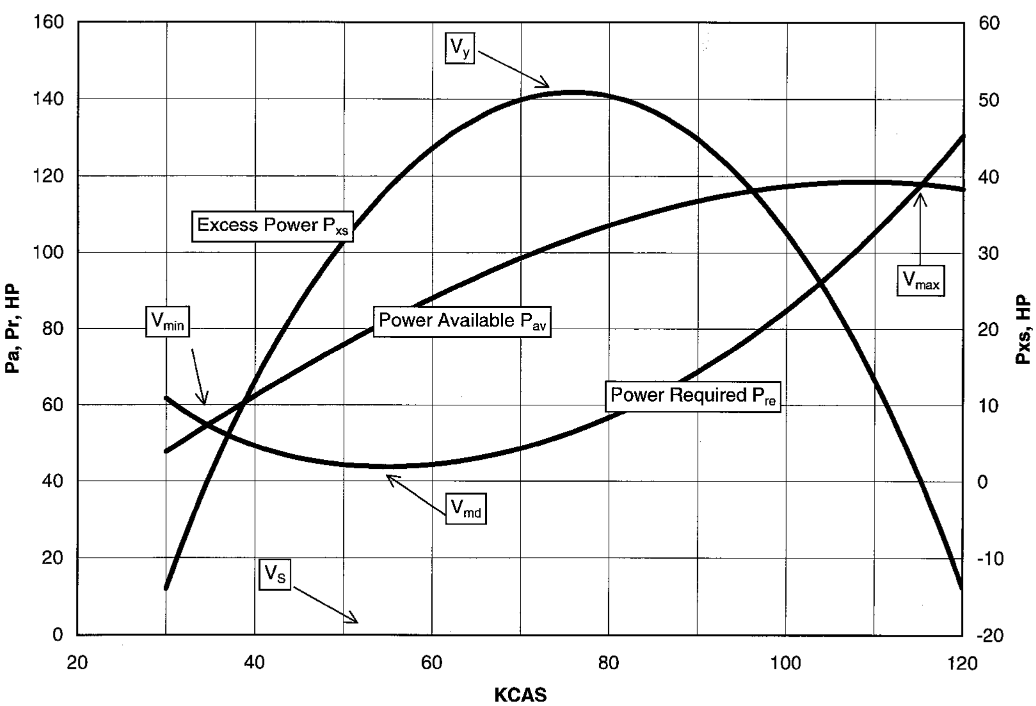

Fig. 1 Excess power P_{xs} peaks at V_y, speed for best rate of climb; minimum power required is at V_{md}, speed for minimum (gliding) descent rate.

parameters making up its bootstrap data plate (BDP) Table 1 and three operational variables: gross weight W, relative air density σ (or its surrogate, density altitude h_ρ), and bank angle φ. Because ultimately everything about the airplane's flight path depends on the four forces (lift, weight, thrust, and drag) on the airframe, the same combinations of BDP parameters appear repeatedly in performance equations. Those composite bootstrap parameters (note that K, Q, and R are always negative) have been standardized as

$$E = \Phi(\sigma)E_0 \quad \text{with} \quad E_0 = mP_0/n_0 d$$

$$\text{and} \quad \Phi(\sigma) \equiv (\sigma - C)/(1 - C) \tag{3}$$

$$F = \sigma F_0 \quad \text{with} \quad F_0 = \rho_0 d^2 b \tag{4}$$

$$G = \sigma G_0 \quad \text{with} \quad G_0 = \tfrac{1}{2}\rho_0 S C_{D0} \tag{5}$$

$$H = (W/W_0)^2(1/\sigma)H(\varphi)$$

$$\text{with} \quad H(\varphi) = 2W_0^2 \big/ \rho_0 S\pi e A \cos^2\varphi \tag{6}$$

$$K = \sigma K_0 \quad \text{with} \quad K_0 = F_0 - G_0 \tag{7}$$

$$Q = [\Phi(\sigma)/\sigma]Q_0 \quad \text{with} \quad Q_0 = E_0/K_0 \tag{8}$$

$$R = (W/W_0)^2(1/\sigma^2)R(\varphi) \quad \text{with} \quad R(\varphi) = H(\varphi)/K_0 \tag{9}$$

$$U = (W/W_0)^2(1/\sigma^2)U(\varphi) \quad \text{with} \quad U(\phi) = H(\varphi)/G_0 \tag{10}$$

In the expression for E_0, the ratio of rated full throttle power $P_0 = 160$ hp $= 88{,}000$ ft·lbf/s, and engine circular speed $n_0 = 45$ revolutions per second has been substituted for M_0. The bootstrap approach says nothing about the airplane's stall speed, or the corresponding $C_{L\max}$, but, because stalls are such an essential feature in this study, those aspects cannot be ignored. The flaps-up Cessna 172 $C_{L\max}$ is 1.54; at 2400 lb the corresponding stall speed is $V_S = 51.4$ KCAS.

Table 1 Bootstrap data plate for a particular Cessna 172

BDP item	Value	Units	Aircraft subsystem
Wing area, S	174	ft^2	Airframe
Wing aspect ratio, A	7.38	——	Airframe
Rated mean sea level (MSL) torque, M_0	311.2	ft · lbf	Engine
Altitude drop-off parameter, C	0.12	——	Engine
Propeller diameter, d	6.25	ft	Propeller
Parasite drag coefficient, C_{D0}	0.037	——	Airframe
Airplane efficiency factor, e	0.72	——	Airframe
Propeller polar slope, m	1.70	——	Propeller
Propeller polar intercept, b	−0.0564	——	Propeller

The small flight-path angle approximation in which

$$L = W/\cos\varphi \tag{11}$$

is assumed throughout. Thrust and drag turn out to be

$$T(V) = E + FV^2 \tag{12}$$

$$D(V) = D_P(V) + D_i(V) = GV^2 + H/V^2 \tag{13}$$

where only the induced drag term $D_i = H/V^2$ depends on bank angle. Expressions for rates and angles of climb or descent, turn radius or rate, etc., all follow, just as one would expect, from the preceding fundamental prescriptions. Bootstrap formulas for the major performance V speeds, each expressed as a true airspeed in ft/s, are

$$V_{M/m} = \sqrt{\left(-E \mp \sqrt{E^2 + 4KH}\right)\big/2K} = \sqrt{-Q/2 \pm \sqrt{Q^2/4 + R}} \tag{14}$$

$$V_y = \sqrt{\left(-E - \sqrt{E^2 - 12KH}\right)\big/6K} = \sqrt{-Q/6 + \sqrt{Q^2/36 - R/3}} \tag{15}$$

$$V_x = (-H/K)^{\frac{1}{4}} = (-R)^{\frac{1}{4}} \tag{16}$$

$$V_{\text{bg}} = (H/G)^{\frac{1}{4}} = U^{\frac{1}{4}} \tag{17}$$

$$V_{\text{md}} = (H/3G)^{\frac{1}{4}} = (U/3)^{\frac{1}{4}} = 0.7598V_{\text{bg}} \tag{18}$$

With simple expressions for thrust T and drag D, it is easy to arrive at concrete formulas for flight-path angle

$$\sin\gamma = T_{\text{xs}}/W = (E + KV^2 - H/V^2)/W \tag{19}$$

and for rate of climb or descent

$$\dot{h} = P_{\text{xs}}/W = (EV + KV^3 - H/V)/W \tag{20}$$

Steady Maneuvering Charts

Steady maneuvering charts use the preceding formulas, plus standard turn relations, to display information about load factor limits, stall speeds, rates of climb or descent, and either turn radius or turn rate. Figure 2 is such a chart for a Cessna 172 at MSL weighing 2400 lb, flaps up. The major features are as follows:

1) The structural damage load factor limit (3.8 for normal category airplanes) corresponds to maintaining a level turn at bank angle 74.7 deg.

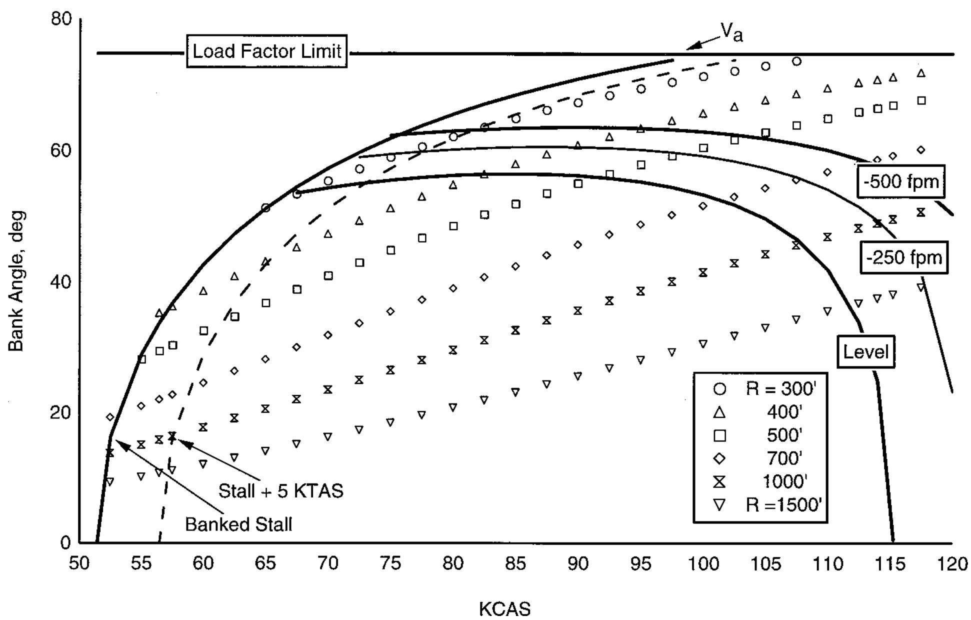

Fig. 2 Steady maneuvering chart for a Cessna 172, 2400 lb, flaps up, at MSL.

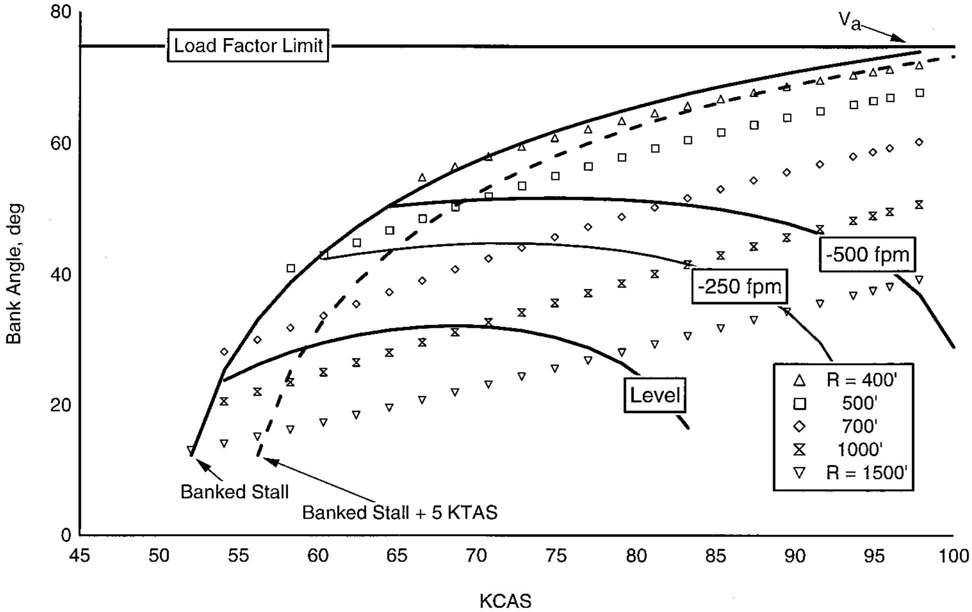

Fig. 3 Steady maneuvering chart for a Cessna 172, 2400 lb, flaps up, at 12,000 ft.

2) The banked stall limit curve swoops from lower left towards the upper right, where it crosses the load factor limit line at V_a, the so-called maneuvering speed. Five or so knots to the right of the stall curve one usually draws a stall safety buffer curve. This discussion ignores all such safety factors or buffers, but in reality a pilot would surely use them.

3) Several curves of constant climb or descent rate are another feature. Alternatively, one could select to have curves of constant positive or negative flight-path angle.

4) Other features of the chart are several marked traces of constant turn radius or, alternatively, of constant turn rate.

5) $V_y(\varphi)$, the speed at which (for a given bank angle) rate of climb is greatest, always increases with bank angle. One can show (without much calculation, playing with partial derivatives and the defining equations) that these peaks of the curves of constant rate of climb or descent always move to the right as bank angles increase, $\partial V_y(\varphi)/\partial\varphi > 0$. This means that wings-level speed for best rate of climb, $V_y(\varphi = 0)$, is always too low to be a safe lower limit mountain maneuver speed. Because $V_x(\varphi = 0) < V_y(\varphi = 0)$, this means that the possibility of safely optimizing either wings-level climb angles or rates should be off of the table whenever the airplane needs the option of turning around.

Explicit formulas for laying out all the steady maneuvering chart curves are given in Ref. 9. When that same airplane climbs up to 12,000-ft-density altitude, maneuvering possibilities become more restricted (Fig. 3).

What Likely Happened to Cessna N4584A

Just before initiating that final turn, the airplane was at full throttle, wings level, and climbing slightly. For the model situation the airplane is at its service ceiling, calculated to be 13,773 ft, the large dot in Fig. 4 at 65 KCAS. The airplane was climbing 100 ft/min, but the terrain was climbing faster. Although the valley they were ascending was broad, trees were uncomfortably close below. The pilot decided to turn around.

He banked 30 deg, putting the airplane at X in Fig. 4. The airplane began to descend (not stalled, just descending at about 100 ft/min). The pilot naturally gave a bit of back stick. This raised the wing's angle of attack, raised induced drag, and slowed the airplane a bit, to halfway between the X and the Y in Fig. 4. The airplane responded by descending even faster. To correct the situation, a bit more back stick was given. Rather than return to level flight, the airplane began to descend even faster and further slowed. Within a very few seconds the situation had slid into point Y in Fig. 4. with the airplane stalled.

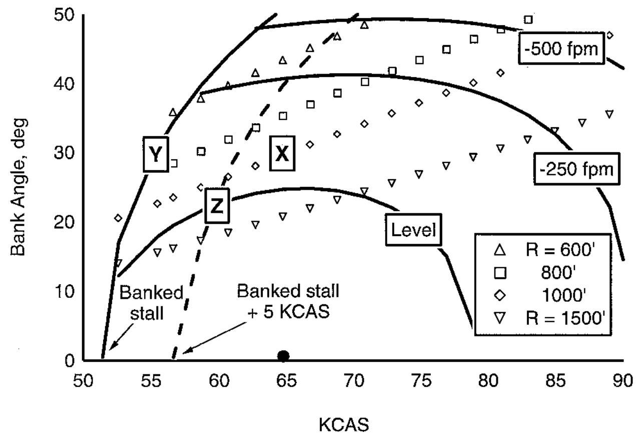

Fig. 4 Steady maneuvering chart for a Cessna 172, 2400 lb, flaps up, at 13,773 ft, the airplane's service ceiling.

Banked 30 deg, V_y for this airplane at this altitude is $V_y(\varphi = 30\text{ deg}) = 68$ KCAS. With the airplane at 65 KCAS, this puts it on the back side of the banked 30-deg power curve. However, because the best rate of climb for this bank angle at this altitude is −55 ft/min, pushing forward alone could not have halted the slight descent. The 30-deg bank angle, though moderate, precluded level flight at any speed. The pilot needed to have leveled the wings a bit.

As one can readily see from Fig. 4, a 20-deg bank at 65 KCAS would have resulted in a very slight positive rate of climb during the turn, with turn radius about 1250 ft. Point Z is the optimal (smallest radius) turn for level flight, banked 23 deg at 60 KCAS. However, point Z also is on the back side of the banked power curve. Whenever possible, pilots should stay on the front side.

Safety Recommendation for Mountain Maneuvering

Although the bootstrap approach steady maneuvering charts are worthy of production and close study, they are too detailed to be useful in the airborne cockpit. The charts are specific to a particular type airplane in a particular configuration, at a particular weight and altitude. That means many charts, each quite informative, but each overfilled, for our mountain maneuvering purposes, with irrelevant detail. Something simple and brief is needed.

Having focused on the level flight curve on the steady maneuvering chart, it is recommended that the pilot who may need to maneuver resolve to stay below and to the right of the banked ceiling point, that is, resolve to not let the speed get below that banked

Table 2 Sample mountain maneuvering speed/bank/turn table for a Cessna 172, 2400 lb, flaps up

	Density altitude, ft				
Maneuver	0	3000	6000	9000	12,000
Generally					
Keep speed, KCAS, above	85.1	80.9	76.8	72.7	68.7
And Keep bank angle, deg, below	56.5	52.4	47.3	40.9	32.2
Stall speed, KCAS at above bank is	69.3	65.8	62.5	59.2	55.9
Do not enter canyon narrower, ft, than	848	976	1151	1418	1917
For very tightest turn					
Reduce speed to, (KCAS)	66.5	63.2	59.9	56.8	58.1
Note	At stall	At stall	At stall	At stall	Not at stall
With bank angle, deg	53.2	48.5	42.6	34.8	28.0
To turn around in diameter, ft	585	684	828	1077	1623

ceiling speed and to not bank any farther than that banked ceiling angle. With airspeed and bank angle restricted to staying below and to the right of the peak of the level flight curve, the airplane will always be on the front side of its banked power curves. The pilot may yet overbank, to the point that the airplane descends, and consequent back stick will still slow the airplane. However, in this case the airplane will slide to the left, on its appropriate steady maneuvering chart, descending less steeply as it does so, to stabilize on the level flight curve.

As mentioned, this safety recommendation does not allow speeds for either best angle of climb or for best rate of climb. In addition, this recommended safety regime does not include the tightest possible turn. Perhaps knowledge of that additional point would be of value. It is included in Table 2. In general, however, pilots maneuvering near terrain would do well to not fly so near the banked stall curve.

With the problem thus simplified, it is easy to use bootstrap equations to come up with a cockpit-friendly chart such as Table 2. Suppose the pilot is getting into straitened circumstances and needs maneuvering guidance. Suppose the airplane weighs about 2400 lb and is near 12,000 ft. A glance at Table 2 tells the pilot to not bank more than 32 deg and to not let the speed get below 69 KCAS (still a healthy 13 KCAS above stall). (Higher precision than makes engineering sense has been maintained in Table 2 entries, so that readers can more easily verify their own calculations.) Furthermore, the pilot should not get into a canyon narrower than 1920 ft and must not find him- or herself in one narrower than 1630 ft.

Furthermore if the pilot does find him- or herself near that latter situation, the pilot must reverse course by banking 28 deg at 58 KCAS, not an insurmountable amount of information to keep in mind or on a scratch pad. The last three numbers cited will be unnecessary for pilots sensible enough to hold themselves to rational personal minimums.

One might hope that, for the airplane at 12,000 ft, going to full flaps would help the maneuvering situation. In this case it turns out (by a calculation off to the side) that added drag puts 12,000 ft above the airplane's wings-level absolute ceiling. Maneuvering without loss of altitude is impossible. Of course, there are possibilities of using only partial flaps, and there are certainly cases in which some loss of altitude is permissible. Reducing speed with reduced throttle will, for these airplanes, seldom be an option. These vagaries underscore a pilot's need to not run out of airspeed, altitude, and ideas all at the same time.

Many, though not all, of the fixed-pitch bootstrap formulas needed to calculate speed/bank/turn tables can be found near the middle of Ref. 9. Banked absolute ceiling speed, whereas given as Eq. (30) in Ref. 9, is pivotal and, hence, repeated

$$V_{\mathrm{BAC}} = \sqrt{\frac{-\Phi(\sigma)E_0}{2\sigma K_0}} = \sqrt{\frac{-Q}{2}} \tag{21}$$

At first blush it might seem strange that V_{BAC} is independent of the airplane's gross weight W. In mitigation, V_{BAC} makes operational sense only when combined with the corresponding absolute ceiling bank angle ϕ_{BAC}, which very much does depend on W. With the ground rules changed to a presumed altitude, rather than a presumed bank angle, it is convenient to have a new formula for that bank angle limit:

$$\phi_{\mathrm{BAC}} = \cos^{-1}\left(\frac{W}{\Phi(\sigma)E_0}\sqrt{\frac{-8K_0}{\rho_0 S\pi e A}}\right) \tag{22}$$

When the safety-limiting bank angle at this altitude and weight is known it is then easy to use the standard $1/\sqrt{(\cos\varphi)}$ factor to get from unbanked stall speed $V_S(\varphi = 0)$ to its banked partner $V_S(\varphi)$. The corresponding banked absolute ceiling minimum level turn diameter can then be readily obtained from knowledge of V_{BAC} and φ_{BAC}, but an explicit formula for it is

$$2R_{\mathrm{BAC}} = \frac{-\Phi(\sigma)E_0 W}{g\sigma K_0}\sqrt{\frac{-8K_0}{\Phi^2(\sigma)E_0^2\rho_0 S\pi e A + 8W^2K_0}} \tag{23}$$

Formulas for proper speeds and bank angles for tightest (and for quickest) level turns are given near the end of Ref. 9, but, as mentioned there, those must be filtered through the possibility of being within the stalled region. Notice, in Table 2, that it is only at the highest featured altitude, 12,000 ft, that a tightest turn is not stall limited. This is a consequence of that, as altitude increases, V_m (minimum speed for level flight) slowly comes out from behind the skirts of the banked stall curve. There are somewhat cumbersome bootstrap formulas for the corresponding turn radius or turn rate but, with speed and bank angle in hand, one might just as well obtain those from standard level turn relations.

Conclusions

Maneuvering at high altitude in lightly powered general aviation aircraft can be dangerous. As usual, knowledge is power, power at least to avoid hazardous maneuvers and flight regimes. Bootstrap approach steady maneuvering charts concretely point out the necessary performance numbers and associated safety bottlenecks. The best course, absent a genuine and unforeseeable emergency, is that the pilot not let the airspeed get below V_{BAC}, the speed for banked absolute ceiling for the airplane at its current weight and altitude, and that the pilot not bank farther than φ_{BAC}. That recommendation keeps the airplane on the front side of the banked excess power curve and ensures that even an inadvertent descent will be failsafe, taking the airplane to level flight. It is further recommended that aircraft manufacturers, operators, and pilots consider constructing speed/bank/turn reference check lists for representative aircraft weights and configurations.

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