The Penalties of Non-optimal Turnback Maneuvers

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Abstract

Turning back after engine failure during the take off phase of flight in a single engine aircraft is reexamined to determine the penalties for using non-optimum parameters. The effect of the three critical parameters: initial climb speed, bank angle in the turn and speed in the turn. The effects of using non-optimum parameters is least for small variations in initial climb speed increasing when using bank angles less than 45° and most critical when using higher speeds in the turn. For example, a 22% reduction in bank angle (45° to 35°) results in a 43% increase in turn radius and a 6.4% increase in altitude loss at the same speed during the turn. Flying at the best glide speed rather than 5% above stall speed in the turn increases the turn radius by 26% and the altitude loss by 22% at the same bank angle. The combined result is a 79% increase in the turn radius and a 30% increase in the altitude loss during the turn. An increase in required runway length for a return to the departure runway of 139% and an increase in critical failure altitude of 26% results from using a 35° bank angle and flying the turn at the speed for maximum lift to drag ratio rather than at the optimum parameters.

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Introduction

During the 16 years since the publication of the Rogers 1995 American Institute of Aeronautics and Astronautics Journal of Aircraft paper *The Possible 'Impossible' Turn* [1] there has been considerable discussion in the popular aviation press about this maneuver. Those discussions have given rise to several non-optimal recommendations for executing the maneuver. The recommendations are typically based on the premise that the average pilot cannot perform the maneuver using the parameters resulting from the analysis in the Rogers 1995 paper [1]. The recent article by Schiff [2] is representative of those recommendations.

Using a simplified model for an E33A Beech Bonanza, the analysis in the Rogers 1995 paper found that the optimal maneuver resulted when the initial aircraft climb occurred at the velocity for maximum climb angle, a turn into the wind using a 45° bank angle at a speed corresponding to the stall velocity in the turn (the model used $1.05V_{\text{stall}}$ in the turn) followed by a glide at best glide speed ($V_{L/D\text{max}}$). The flight path was teardrop shaped, as shown in Figure 1.

The Schiff article suggests the optimum angle for the initial climb is $1/2(V_{\text{x}}+V_{\text{y}})$, i.e., a speed halfway between the speed for maximum climb angle, V_{x}, and the speed for maximum rate of climb, V_{y}. Schiff provides no analysis justifying the initial climb speed of $1/2(V_{\text{x}}+V_{\text{y}})$. Schiff also suggests that a bank angle less than 45° be used even though he determined in flight tests that a 45° bank was optimal. Perhaps he thinks that the average pilot cannot perform a 45° descending banked turn. Perhaps he is right, perhaps he is not. Although careful analysis determined that a speed in the turn as close to stall as possible is optimal, Schiff recommends that the speed in the turn be that for best glide speed, $V_{L/D\text{max}}$. Schiff's recommendations conclude that a glide at best glide speed be used upon completion of the turn. Let's examine the penalties for using the Schiff recommendations.

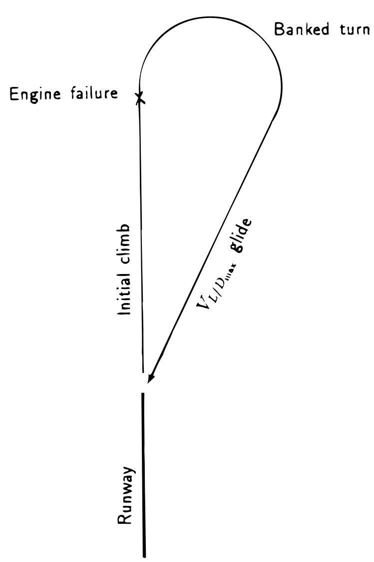

Figure 1. Teardrop flight path.

The Primary Parameters

There are three primary parameters to consider when evaluating the turnback maneuver: initial climb angle, bank angle and speed in the turn. The effect of these three parameters is evaluated using three equations from the Rogers 1995 paper.

The first is the initial climb angle. The Rogers 1995 paper established that initially climbing at the velocity for maximum climb angle, which keeps the aircraft closer to the runway, is more advantageous than climbing at the angle for best rate of climb.

The second, is the radius of the turn, R

$$R = \frac{V^2}{g\, tan\phi} \tag{1}$$

where g is the acceleration of gravity and ϕ is the bank angle. Minimizing the radius of the turn keeps the aircraft close to the end of the runway and thus results in a decreased glide distance after completion of the turn.

The third effect is the steady state rate of turn, $\dot{\Psi}$

$$\dot{\Psi} = \frac{d\Psi}{dt} = \frac{V}{R} = \frac{\Psi}{t} \tag{2}$$

where Ψ is the heading, $d\Psi/dt$ is the rate of turn, i.e., the rate at which the heading is changing, V is the velocity in the turn and t is time.

Neither the turn radius nor the steady state rate of turn require specific knowledge of the aircraft characteristics. Specifying the speed and bank angle determine the rate of turn using Eqs.(1 and 2) for any aircraft.

However, the steady state conditions for minimum loss of altitude, h, in a gliding turn to a new heading

$$\frac{dh}{d\Psi} = \frac{C_D}{C_L^2}\frac{4W}{\rho S g}\frac{1}{\sin 2\phi} \tag{3}$$

does require knowledge of the aircraft characteristics, specifically the drag polar, the weight, W, and the wing area, S, (see [1]). Here C_D is the drag coefficient, C_L is the lift coefficient and ρ is the density of the atmosphere.

Examining Eq.(3) shows that for a parabolic drag polar, $C_D = C_{D_0} + kC_L^2$, where the first term, C_{D_0}, is the parasite drag coefficient and k is a constant and rewriting the drag polar equation as

$$\frac{C_D}{C_L^2} = \frac{C_{D_0}}{C_L^2} + k \tag{4}$$

we see that the first term in Eq.(3), C_D/C_L^2, is a minimum when the lift coefficient is a maximum, i.e., $C_{L\max}$. Thus, the optimum speed for minimum loss of altitude in a gliding turn to a new heading occurs for $C_{L\max}$, i.e., at the stall velocity. Neglecting the small density change with altitude, the second term in Eq.(3), $4W/\rho Sg \sin 2\phi$, is a minimum for $\sin 2\phi = 1$ or $\phi = 45°$, i.e., the optimum bank angle during a descending gliding turn to a new heading is 45°.

The Simplified Model

For clarity, the simplified model assumptions are repeated here. The simplified model uses data from the manufacturer's pilot operating handbook (POH) [3] for the subject aircraft to determine the initial take-off ground roll, rotation and lift-off velocities and the distance over a 50 foot obstacle. An instantaneous transition from the velocity at 50 feet to the

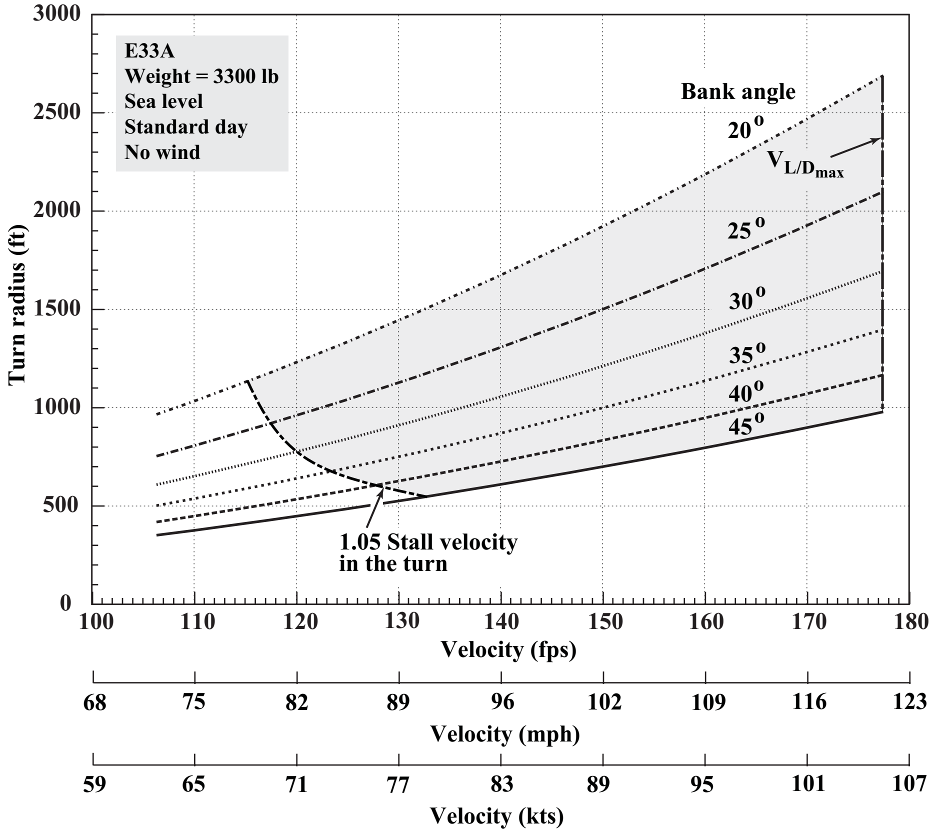

Figure 2. The effect of bank angle and speed on turn radius.

specified initial climb velocity is assumed. A steady climb at constant velocity from 50 feet to the failure altitude while maintaining runway heading is assumed. At engine failure an instantaneous transition to a banked descending gliding turn at the assumed bank angle and the assumed velocity is used. Upon completion of the turn an instantaneous transition to the velocity for $L/D_{\max}$ is assumed. A glide at $V_{L/D\max}$ until touchdown is assumed. No allowance for the effects of landing gear retraction/extension are made. The validity of the model is discussed in detail in the original Rogers 1995 paper [1].

The Aircraft

The example aircraft chosen for detailed study is a Model E33A 285 bhp single engine retractable Beech Bonanza equipped with a constant speed three-blade McCauley propeller. Gross weight is 3300 lbs and the wing area is 181 ft^2. All calculations are performed at gross weight at sea level on a standard no wind day. More details about the aircraft are given in [1 and 3].

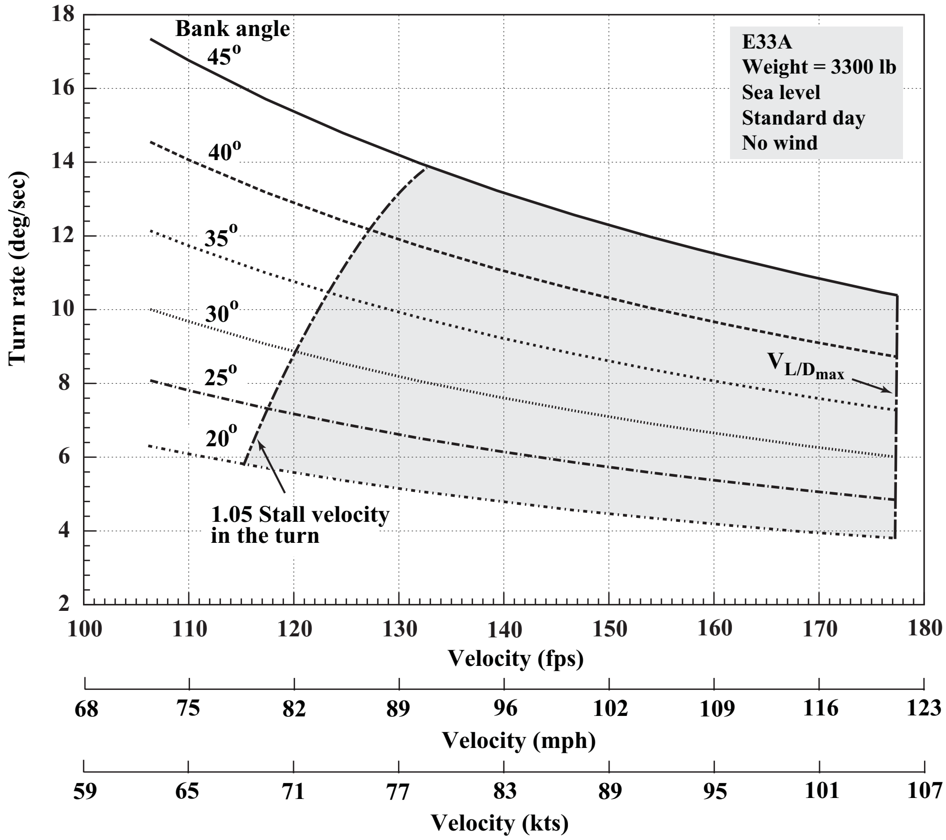

Figure 3. The effect of bank angle and speed on turn rate.

The Penalties For Non-optimal Turnback Parameters

Turn radius

Figure 2 shows the effect of bank angle and speed in the turn on the radius of the turn. Curves corresponding to five percent above stall velocity in the turn and for the best glide speed ($V_{L/D_{\max}}$) for an E33A at 3300 lbs are also shown. The gray area of the graph represents the envelope for the maneuver for the E33A. For the optimal conditions, i.e., $1.05V_{\text{stall}}$ in the turn and a 45° bank angle, the turn radius is 548 ft. For the parameters recommended by Schiff [2], i.e., at best glide speed and a bank angle less than 45°, say 35°, the turn radius increases to 1398 ft — a 155% *increase*. For a bank angle of 20° and best glide speed the turn radius increases to 2690 ft — a 391% *increase*.

Turn rate

Executing the turnback maneuver is an exercise in energy management, i.e., a trade-off between changing the heading while giving up as little altitude as necessary in a gliding turn. Hence, the turn rate becomes of interest. A high bank angle at a low speed yields a high turn rate but at the expense of a high sink rate, yet accomplishes the required heading change quickly. A low bank angle results in a low turn rate and a low sink rate but requires a longer time to accomplish the required heading change.

Turn speed

Figure 3 shows the effect of bank angle and speed in the turn on the rate of turn. For the optimal conditions of $1.05V_{\text{stall}}$ in the turn and a 45° bank angle the turn rate is 13.9 degrees per second. For the Schiff recommended conditions, the turn rate is 7.3 degrees per second for a 35° bank angle — a 48% *decrease*. For a bank angle of 20° and best glide speed the turn rate *decreases* to 3.9 degrees per second — a 72% *decrease*. The typical heading change for the initial turnback to the runway is on the order of 210° [1]. Hence, using the optimal conditions requires approximately 15 sec while the Schiff recommendations require approximately 29 seconds using a 35° bank angle, and a 20° bank angle requires approximately 54 seconds.

Altitude loss

The effects of bank angle, turn speed and turn rate are combined into the loss of altitude parameter the change in altitude with heading change, $dh/d\psi$, as expressed in Eq.(3). The results in Figure 4 are for an E33A at 3300 lbs, at sea level on a standard day with no wind.

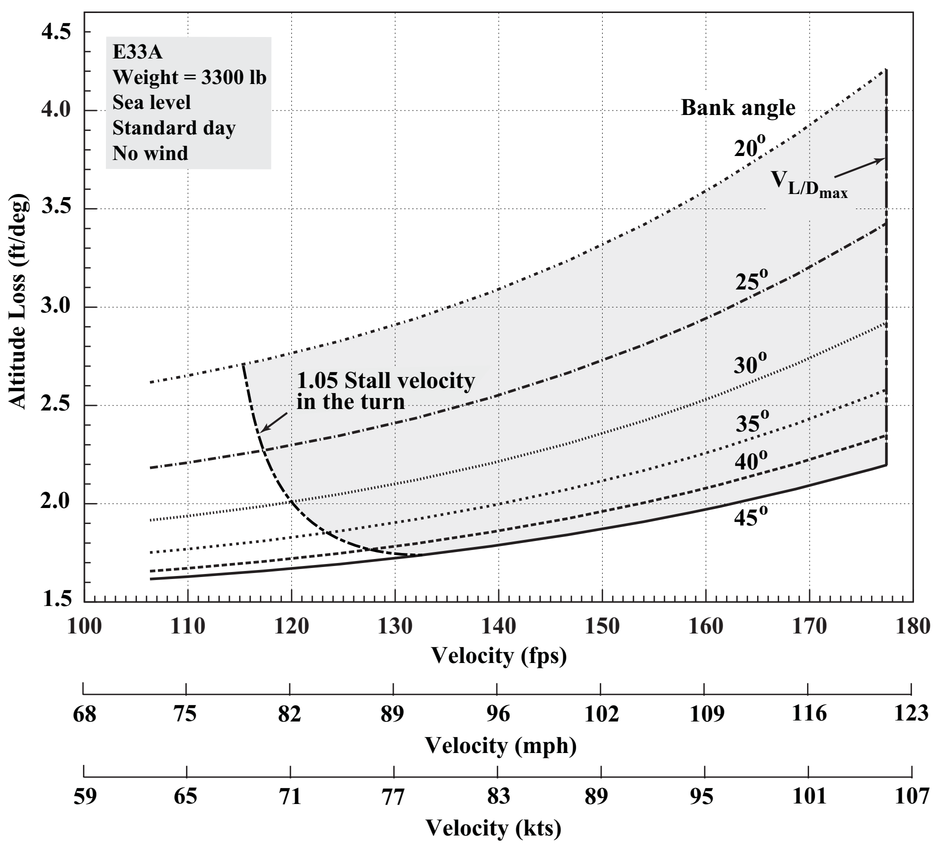

Figure 4. The effect of bank angle and speed on altitude loss for an E33A at 3300 lbs at sea level on a standard day.

For optimal conditions the altitude loss per degree of heading change is 1.72 ft/deg, while for the Schiff recommendations, i.e., a 35° bank angle flown at best glide speed, it is 2.58 ft/deg — a 50% *increase*. For a 20° bank angle flown at best glide speed it is 4.21 ft/deg — a 145% *increase*. Again, using the typical heading change of 210° degrees during the turn the altitude loss for the optimal conditions is approximately 361 ft while for the conditions recommended by Schiff it is 542 ft and using a 20° bank at best glide speed it is 884 ft. Both of the latter cases significantly *increase* the require failure altitude and runway length for a possible turnback.

The Foot Print Plots

The landing footprint, defined as the possible landing area from a given failure altitude, is determined by climbing to the failure altitude, executing a gliding turn at the specified bank angle through a specified heading change and then gliding at $V_{L/D\max}$ until touchdown. Heading changes from 0–360° are considered. The intersection of the footprint curve at the top of the graph represents the touchdown distance from brake release if the aircraft glides straight ahead after engine failure. Each symbol on a curve represents an incremental heading change of five degrees from straight ahead, e.g., the tenth symbol represents a heading change of 45°.

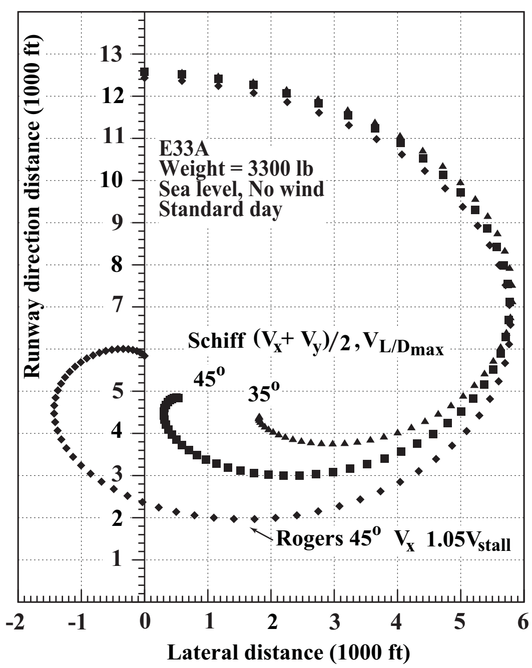

Figure 5. Comparison of the Rogers and Schiff turnback maneuvers for an E33A Bonanza at 3300 lbs no wind, standard day at sea level. The Schiff maneuver cannot make it back to a typical general aviation 3000 ft runway. The Rogers maneuver can.

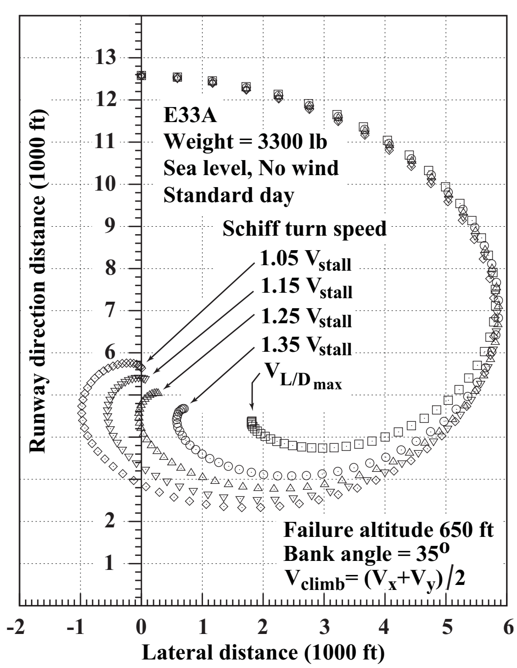

Figure 6. The effect of velocity in the turnback maneuver for an E33A Bonanza at 3300 lbs no wind, standard day at sea level. The climbout velocity is $1/2(V_x + V_y)$. The bank angle is 35°. The aircraft cannot make it back if the turn is flown at $V_{L/D\max}$ or $1.35V_{stall}$.

The second (numerically smallest) intersection, if any, of the footprint curve with the ordinate represents the length of runway required for the aircraft to touchdown on the departure end of the runway. Typically a heading change of approximately 190–220° is required for this intersection. Hence, the flight path is teardrop shaped as shown in Figure 1.

The third intersection of the curve with the ordinate represents the length of runway required for the aircraft to turn through a full 360° and touch down on the runway. If the footprint curve does not intersect the ordinate after a heading change, then a landing on the departure runway is not possible. Typically an off airport landing occurs.

Figure 5 compares footprints for the optimal turnback maneuver parameters discussed by Rogers [1] with that recommended by Schiff [2]. The simplified model from Rogers for a Beechcraft E33A at 3300 lbs at sea level on a standard no wind day is used. Climbing out at a speed halfway between V_x and V_y and flying the turn at best glide speed and either a 45° or 35° bank angle, the simplified model indicates that, for the Schiff maneuver, a return to the departure runway is not possible. Climbing out at V_x and flying the maneuver at $1.05V_{stall}$ in the turn using a 45° bank angle as discussed by Rogers, the simplified model shows that a return to approximately a 2300 ft long runway is possible. Figure 5 also shows that the effect of flying the turn at a bank angle less than 45° is significant.

Figure 6 shows the effect of velocity in the turn on the ability of the aircraft to return to the runway for the Schiff recommendations using a 35° bank angle. As in Figure 5 the aircraft is *not* able to return to the runway if best glide velocity is used in the turn nor is it able to return to the departure runway if a factor of $1.35V_{stall}$ is used during the turn. If a velocity of $1.25V_{stall}$ in the turn is used, then the aircraft can return to the runway. However, the required runway length is more than 4100 ft. Less runway length is required as the velocity in the turn decreases to 5% above stall velocity in the turn where the required runway length is approximately 2900 ft, an approximately 41% penalty when using the higher velocity. Furthermore, using the optimal parameters, i.e., an initial climb at V_x, a turn speed of $1.05V_{stall}$ in the turn and a 45° bank angle, the simplified model predicts a required runway length of only 2300 ft for the E33A. Consequently, using the Schiff recommended parameters results in a 26% penalty

Effect of Failure Altitude

The foot print plots in Figure 7 show the effect of failure altitude on the ability to turn back to the departure runway for both the optimal results from Rogers [1] and for the Schiff recommendations [2]. Again, the simplified model for an E33A Bonanza is used. The optimal conditions are initial climb at the velocity for maximum climb angle, velocity in the turn of $1.05V_{stall}$ in the turn and a 45° bank angle. The Schiff recommended conditions are initial climb halfway between the velocity for maximum climb angle and the velocity for maximum rate of climb, best glide velocity in the turn and a 35° bank angle. Notice, using the Schiff recommendations, that the aircraft cannot return to the departure runway from a failure altitude of 650 ft (see Figure 7b). A failure altitude of approximately 825 ft and a runway length of approximately 5500 ft is required for the aircraft to return to the departure runway using the Schiff recommendations.

In contrast, the results for the optimal conditions (see Figure 7a) indicate that the aircraft can return to the departure runway from a failure altitude of 650 ft. Furthermore, only a runway length of approximately 2300 ft is required as mentioned above. This is a *decrease* of 139% in required runway length and a *decrease* of 26% in failure altitude compared to the Schiff recommendations. Finally, notice that Figure 7a indicates that a

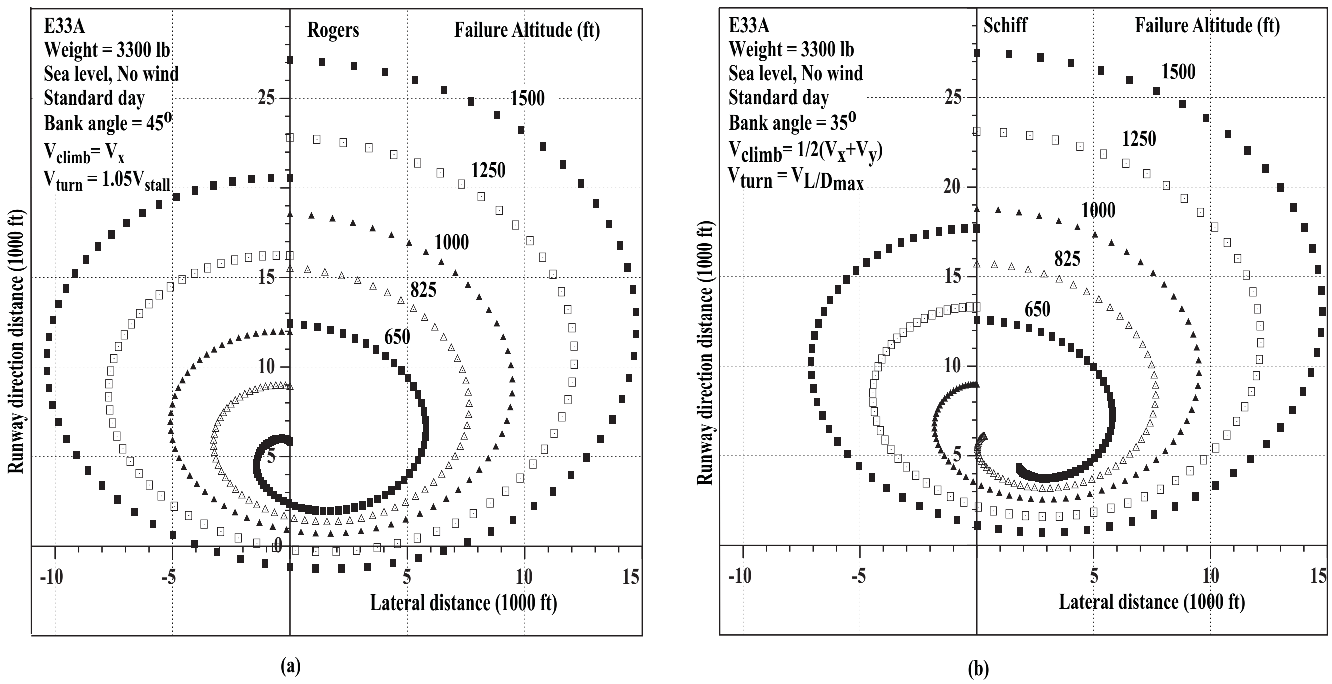

Figure 7. Comparison of the effect of failure altitude on required runway length E33A, 3300 lb, no wind, sea level, standard day, teardrop flight path; (a) Rogers: $V_{\text{climb}} = V_{\text{x}}$, $V_{\text{turning}} = 1.05V_{\text{stall}}$ in the turn, 45° bank angle (b) Schiff: $V_{\text{climb}} = (V_{\text{x}} + V_{\text{y}})/2$, $V_{\text{turning}} = V_{L/D\text{max}}$, 35° bank angle.

return to the departure runway for a failure altitude of less than 650 ft is possible for the optimal conditions, albeit the required runway length will increase somewhat.

Conclusions

Using the simplified model from the 1995 Rogers paper [1], the penalty for using the non-optimal parameters recommended by Schiff [2] in a turnback maneuver was determined and compared. In every case the optimal parameters were significantly more advantageous than the non-optimal parameters recommended by Schiff. For example, a 22% reduction in bank angle (45° to 35°) combined with best glide speed in the turn results in a 155% increase in turn radius and a 50% increase in altitude loss during the turn compared to using the optimal parameters.

Furthermore, for the subject aircraft in [1], i.e., an E33A Bonanza at 3300 lbs at sea level for the no wind worst case, flying at the best glide speed rather than 5% above stall speed in the turn increases the turn radius by 26% and the altitude loss by 22%. The combined result is a 79% increase in the turn radius and a 30% increase in the altitude loss during the turn. Finally, an increase in runway length of 139% and an increase in failure altitude of 26% using the Schiff recommendations compared to the optimal parameters found by Rogers in [1] results.

References

[1] Rogers, David F., *The Possible 'Impossible' Turn* AIAA Journal of Aircraft, Vol. 32, pp. 392-397, 1995.

[2] Schiff, Barry, *Unconventional Wisdom* Aircraft Owners and Pilots Association, AOPA Pilot, pp. 95-98, April 2011.

[3] Anonymous, *Pilot's Operating Handbook and FAA Approved Airplane Flight Manual for the Beechcraft Bonanza E33A,* P/N 33-590003-7B1 Revised: March 1983, available from Hawker Beechcraft, Wichita, KS.

APPENDIX A

Opinion: Additional comments on the Schiff AOPA Pilot article

The two-thirds rule of thumb

Barry Schiff [2] states that

> "A successful turnaround requires not only reaching the minimum turnaround height, it requires also that you climb to at least two-thirds of that height by the time you pass over the departure end of the runway."

Let's look at this in the context of the simplified model used for an E33A Bonanza. Using the POH for the E33A the no wind takeoff distance over the FAA 50 ft obstacle is 1525 ft . Again, assuming an instantaneous transition to a climb at $V_x = 91$ mph and a rate of climb of 1100 fpm along with a failure altitude of 650 ft the required runway length to achieve 2/3 of the failure altitude at the departure end is 4315 ft . Thus, according to the 2/3s rule of thumb, you should not consider that a turnback maneuver will be successful unless the runway is at least that long. Considering the results above that seems a bit excessive especially when you operate out of a typical 3000 ft general aviation single runway airport.

Furthermore, if, looking at Figure 7b, you note that the minimum turnback altitude using the Schiff recommended parameters, i.e., initial climb at $1/2(V_x + Vy)$, a 35° bank angle and a velocity of $V_{L/D_{\max}}$ in the turn is 825 ft , then using the Schiff 2/3s rule of thumb the required runway length for a successful turnback is considerably longer. Specifically, a runway length of approximately 6000 ft is required. It gets worse for higher turnback failure altitudes.

Thus, in my view, the 2/3s rule of thumb does not seem reasonable.

Nose high attitude and control force

Schiff is concerned about the apparent significant control push that is required if the engine quits during climbout. Specifically,

> "Climbing at V_x places the aircraft in such a nose-high attitude that a pilot must vigorously force the nose down to preserve airspeed following an engine failure."

Flight test results

> Flight tests show that for the standard trim setting of 3° nose up with only the front seats occupied in an E33A Bonanza the nose drops smartly when power is pulled during a V_x climb.

Now let's consider why this result is different than Schiff's. First of all, it depends. It depends on the aircraft configuration, e.g., high wing or low wing, flaps extended or not, trim setting and aircraft load configuration among other things.

High wing aircraft

Schiff has evidentally done experiments that show that a significant push is required. However, as I recall, those experiments were done in a high wing Cessna aircraft. Let's look at this.

The required push in a high wing aircraft is because the resulting drag force of the high wing is located a significant distance *above* the vertical center of gravity of the aircraft. Typically, on a high wing aircraft, the vertical center of gravity is located in the volume of the seat pan. In a high wing aircraft without engine power the wing drag generates a large nose up pitching moment because of the large moment arm. The resulting nose up pitching moment must be counteracted by a similarly large nose down pitching moment generated by the tail. The result is a requirement for forward stick with a significant stick force.

For aircraft with high wing or pylon mounted engines the effect is larger.

However, the takeoff trim setting, on some high wing aircraft, can result in the nose pitching down. The aircraft load distribution can also affect the result.

An additional factor is whether the engine is canted, e.g., tilted down and to the left to counteract propeller p-factor.

Low wing aircraft

For a low wing aircraft the vertical center of gravity is typically located within the root airfoil volume. Hence, with a low wing, the wing drag results in a much smaller moment because of the smaller moment arm. Hence, the required stick force (push/pull) is much smaller.

Rolling the aircraft

In either high or low wing aircraft the nose can easily be lowered by simply rolling (banking) the aircraft. The more the aircraft is rolled the more the nose will drop.

High deck angle

Now let's look at the difference in angle of attack for V_{x} and $1/2(V_{\mathrm{x}} + Vy)$. For an E33A at 3300 lbs the angle of attack for $V_{\mathrm{x}} = 91$ mph is 10.3° while for $1/2(V_{\mathrm{x}} + Vy) = 102$ mph it is 8.3°. The deck angle, which is directly related to the angle of attack, for a V_{x} climb vice a $1/2(V_{\mathrm{x}} + V_{\mathrm{y}})$ climb may be perceived to be much larger, but it is not. The deck angle for a V_{x} climb is on the order of 15–17 degrees. A $1/2(V_{\mathrm{x}} + V_{\mathrm{y}})$ climb is not significantly different.

Head turning, rudder and speed control

Schiff suggests that

> "Once a pilot opts to turn around and begins the maneuver, he should turn his head and look toward the runway..."

It is important that the turnback turn be coordinated.

If the pilot turns his or her head, there is a known tendency to add rudder, as well as aileron input, in the direction of the turned head. This can easily lead to excessive bottom rudder, excessive yaw and asymmetrical, wing lift i.e., uncoordinated flight.

In order to adequately achieve the pilot's target bank angle and airspeed or angle of attack, if fitted with that instrument, during the turn while maintaining coordinated flight, experience shows that the pilot should perform the maneuver with due regard to his or her cockpit instruments.

270° *failure altitude test*

Schiff suggests a test at altitude to determine an appropriate failure altitude. Specifically,

> "Continue the turn for 270 degree because reversing course to the runway requires more than a 180 degree turn...Forty-five degrees of additional turn are needed to return to the runway centerline, and then another 45 degrees to line up with the runway. This means that roughly 270 degrees (180 plus 45 plus 45) are needed to return to the runway."

In fact, as shown in the original Rogers 1995 [1] paper the heading change required to point the aircraft at the runway is between 190 and 210°. An additional realignment turn of approximately 30° is required. Thus, the total heading change is typically 240° and not 270°.

Schiff then recommends adding 50% to the altitude loss to estimate a failure altitude. Unfortunately, examination of the illustrations above suggest that the resulting failure altitude may result in an off airport landing unless the departure runway is quite long.

Conclusion

In my view, it is time that we took this discussion out of the realm of what the aviation pundits think the average pilot *cannot* do and turn it to the realm of what the aircraft *can* do. The pilot in command can then decide what s/he is capable of doing.

