Dealing with engine failure on departure and the “impossible turn” decision

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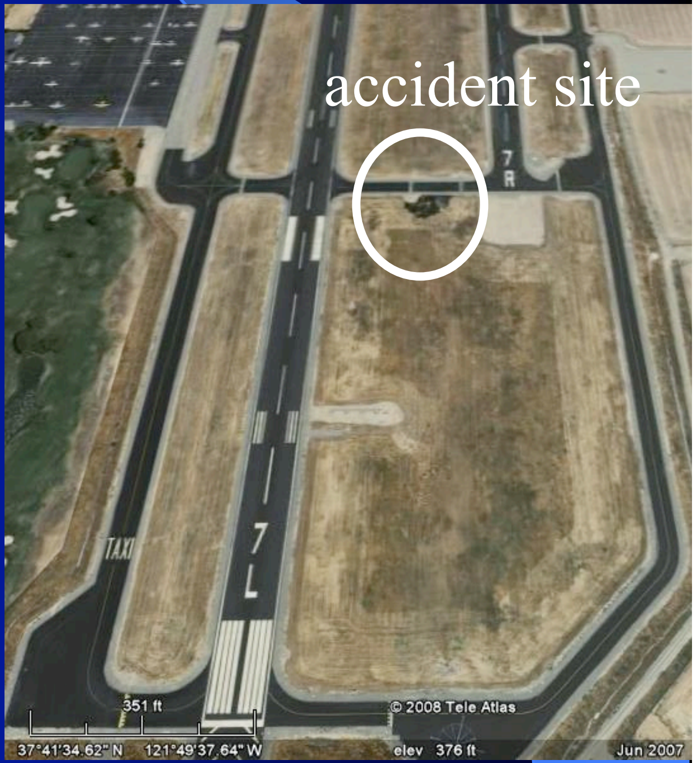
KLVK turnback fatal accident 6/16/07

- Aircraft: Hill / Europa XS (experimental)
- CFI witness:
  - “observed the airplane reach about 400 above ground level (agl) while approaching the end of the runway… The airplane then sunk about 100 feet in a level attitude… and as it reached about 300 feet agl, it made a hard left turn. The airplane continued to descend and reverse course. As the airplane came close to completing a 180-degree turn, the nose dove toward terrain. The airplane impacted in a near-vertical attitude and erupted into flames.
- NTSB probable cause:
  - The loss of engine power for an undetermined reason during the initial climb, and the pilot's failure to maintain adequate airspeed while attempting a return to runway maneuver, which resulted in a stall/spin.



The decision to turn back is controversial
Two options exist:

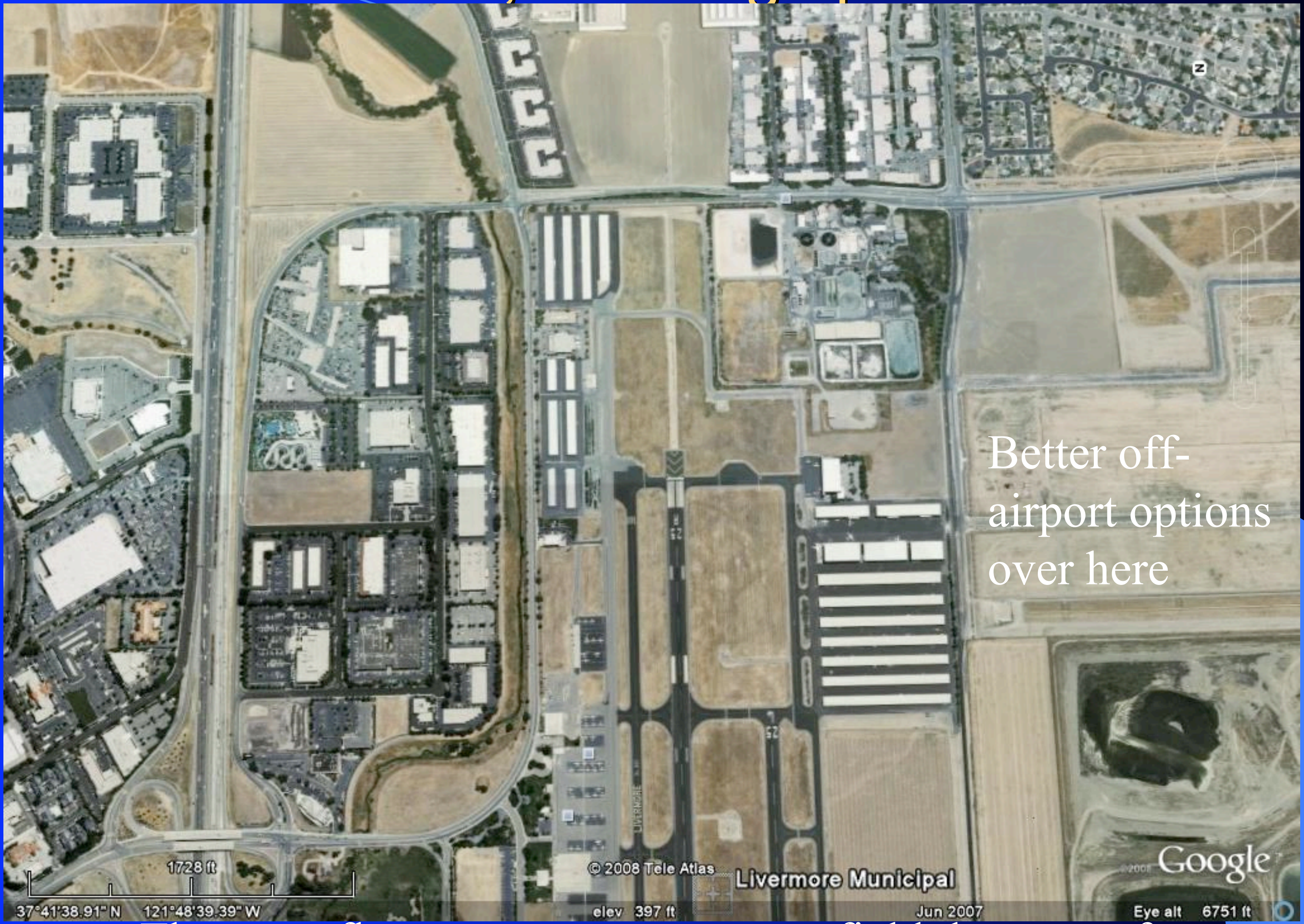
- Land off airport
- Pros:
  - Minimal low and slow maneuvering required
  - Statistically more likely to walk away*
- Cons:
  - Possible/likely aircraft damage
  - $ required for recovery
  - Attract unwanted attention from FAA, FPI, etc.
  - Suitable landing sites might not exist!

- Land on airport
- Pros:
  - Minimize damage
  - Unlikely to attract attention from FAA
- Cons:
  - Must maneuver airplane low and slow, with higher chance of fatal injury
  - Maybe have never done this before, especially in an emergency
  - May not be clear if this can be done beforehand

*Validity of statistics is uncertain; to be discussed later

KLVK 25R,L landing options

KLVK 7R,L landing options



There are flat non-runway areas on-field that are safe emergency landing spots (taxiways, grass areas, etc.)

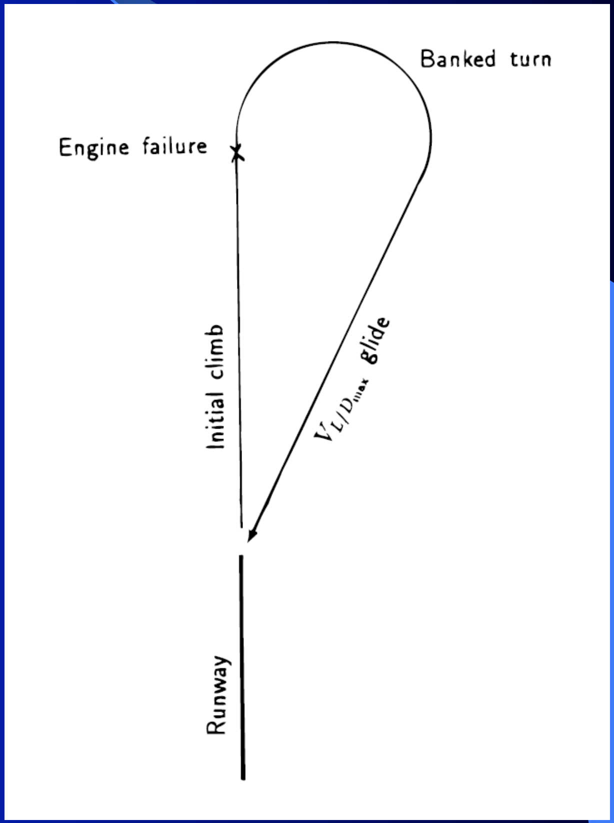
KRHV 31R,L forced landing options are fewer than around KLVK

Success/failure of the turnback is determined by many factors

- Altitude of aircraft at failure
- Airplane performance characteristics
- Human factors: pilot technique, reaction time, experience with turnback maneuver, total pilot experience
- Environmental factors: wind, runway length, density altitude

Turning with minimal altitude loss

- A turn with minimum loss of altitude (and minimum turn radius) is a key part of the teardrop maneuver
- Altitude loss through a specified heading change is minimized with:
  - 45 bank angle
  - airspeed near stall
    - Note that aircraft stalls at higher indicated speed in vertically unaccelerated flight with 45 degrees of bank: ~1.2v_{stall}



reproduced from Rogers

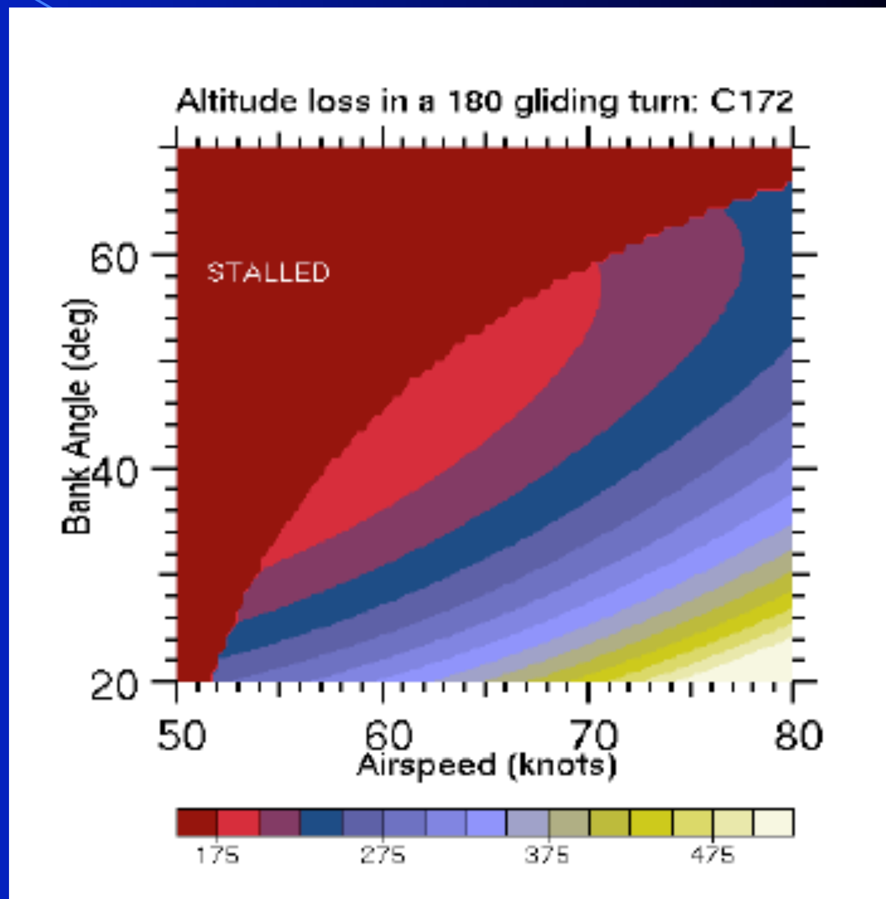
C172 theoretical minimum altitude loss for 180 gliding turn occurs at 45 degrees of bank and accelerated stall speed

Altitude loss per radian can be determined by equating forces (assume steady flight) and assuming parabolic drag polar:

$$\frac{\alpha v_g^2}{g\sin(2\theta)}\left[\left(\frac{v}{v_g}\right)^4\cos^2\theta+1\right]$$

This is valid for $v>v_{stall}$ (accelerated).
α = best glide ratio (1/9),
v_g = best glide speed (65 kts),
g = gravity acceleration,
θ = bank angle

*steady flight assumption may be invalid for higher bank angles (much more than 45 degrees), making altitude loss more than depicted



There is no performance increase by using bank angles greater than 45 degrees. Increasing airspeed 10-20 kts above stall adds 100-150’ to descent.

Altitude loss in optimal turn varies with aircraft characteristics

At stall and 45 deg. bank (optimal conditions), altitude loss to make the turn back is proportional to:

$$\frac{\alpha v_g^2}{g}\left[\left(\frac{v_s}{v_g}\right)^4 + 1\right]$$

α= best glide ratio,
v_g = best glide speed,
v_s = level flight stall speed,
g = gravity acceleration

- Glide angle α might naively be considered to be the dominant performance spec, but v_g^2 actually dominates the altitude loss for some airplanes with smaller α
  - most piston singles have comparable glide ratios, but best glide speeds vary considerably, e.g. Bonanza (>100 kts) and C172 (65 kts)

- Flaps increase α but decrease v_g, might result in small performance increase (and might not).
  - Using flaps in the turn reduces glide performance after the turn is complete
  - Probably not a good idea to use them

Aircraft with larger glide speeds require more altitude to make the 180 turn. Bonanza and Mooney pilots beware.

Rogers theoretical teardrop maneuver performance analysis

- D. F. Rogers, "The Possible 'Impossible Turn'", AIAA Journal of Aircraft 32, 392 (1995).
- Performance numbers for Beech Bonanza 33A
- Take-off and initial climb per POH distance and airspeeds
- Turn:
  - 45 degree bank angle
  - Airspeed 1.05 $v_{accelerated\text{-}stall}$ in turn
- Post-turn glide:
  - Airspeed best glide ($v_{L/Dmax}$)
- Transitions are assumed instantaneous
- No delay between engine failure and turn initiation

reproduced from Rogers

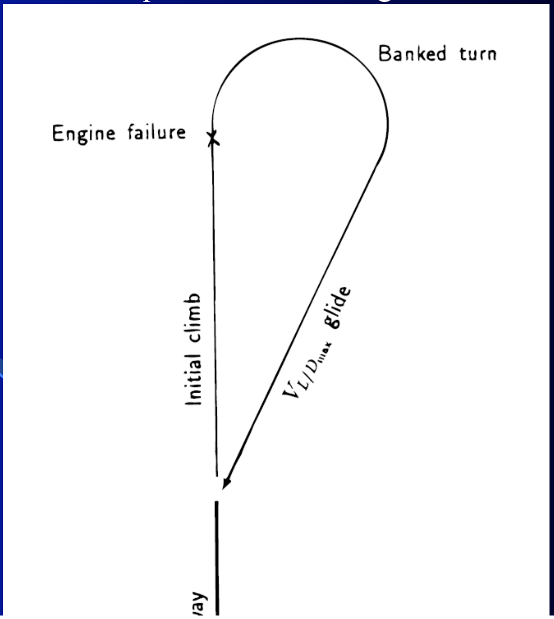


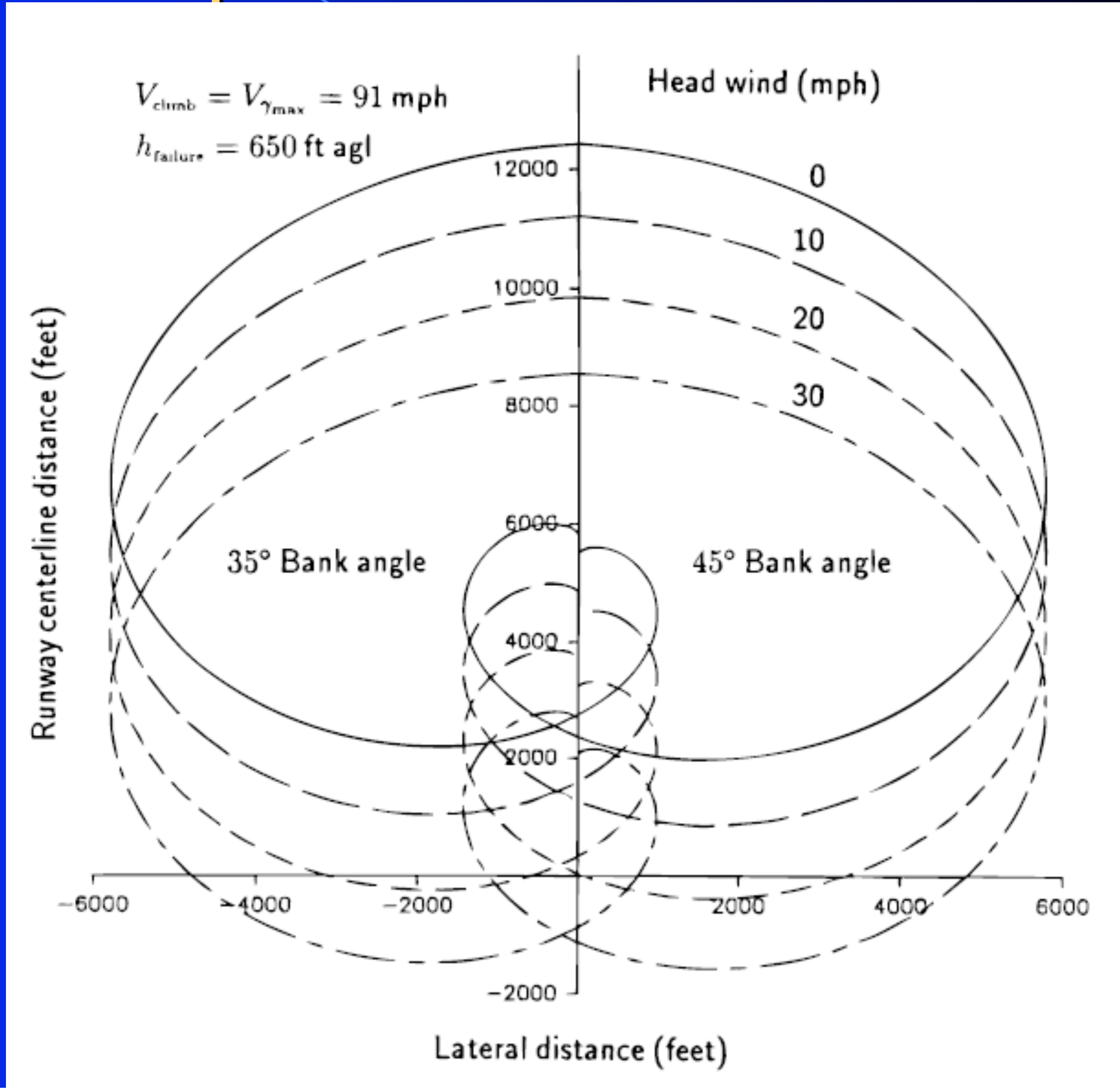
Table 1 Aircraft Characteristics
Beech Bonanza Model 33A

Gross weight	3300 lbs
Wing Area	181 ft^2
$L/D_{\max}$	10.56
Power	285 bhp
Propeller	Constant Speed
	3-blade
V_{cruise} @ 65%	190 mph
$V_{\text{stall (clean)}}$ Power off	72 mph
$V_{\text{stall (dirty)}}$ Power off	61 mph
$V_{L/D_{\max}}$	122 mph
$V_{\gamma_{\max}}$ @ SL	91 mph
$V_{R/C_{\max}}$ @ SL	112.5 mph
R/C @ SL & 3300 lbs	1200 fpm

Bank angle and headwind impact turnback performance

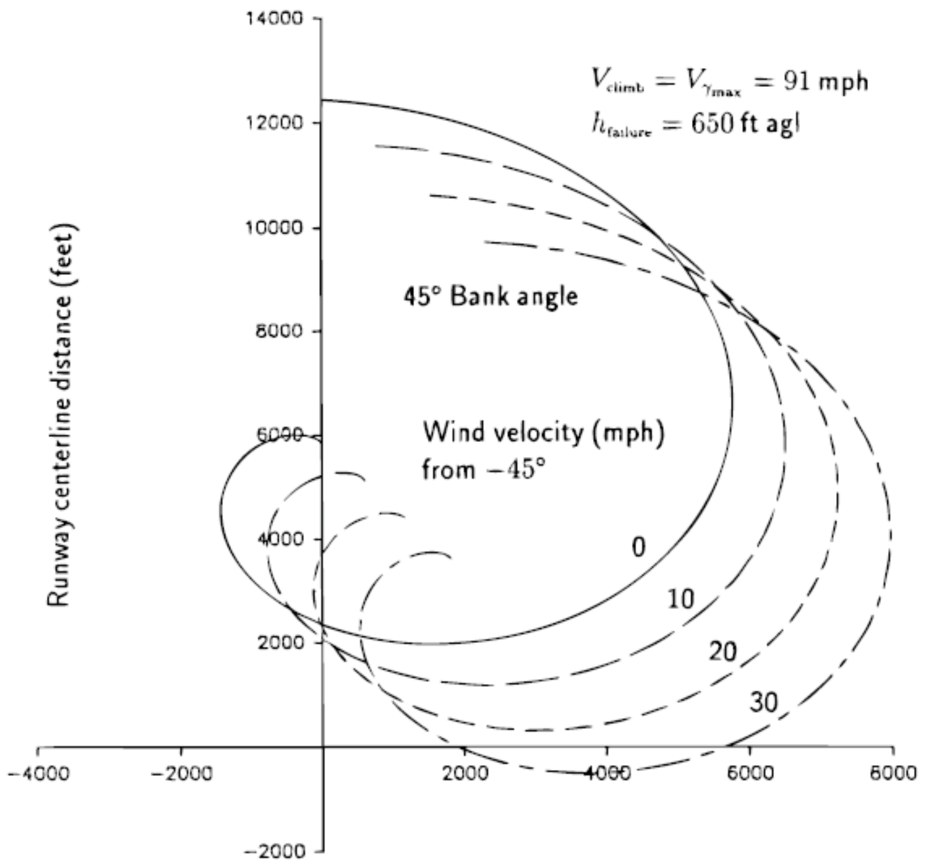
reproduced from Rogers

- 45 degrees of bank yields gets you closer to your starting point, but 35 degrees is not much worse
- Overrun of runway during teardrop is possible for strong headwinds

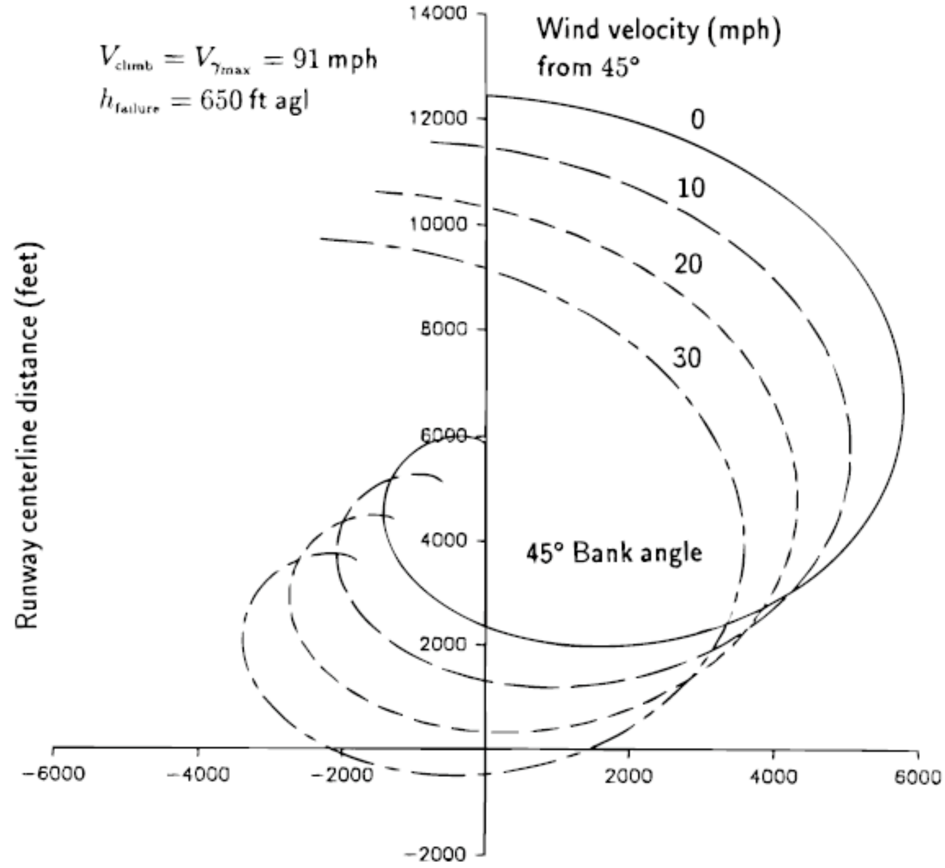


Turning into a crosswind results is shorter runway length requirement

Turn away from crosswind



Turn into crosswind



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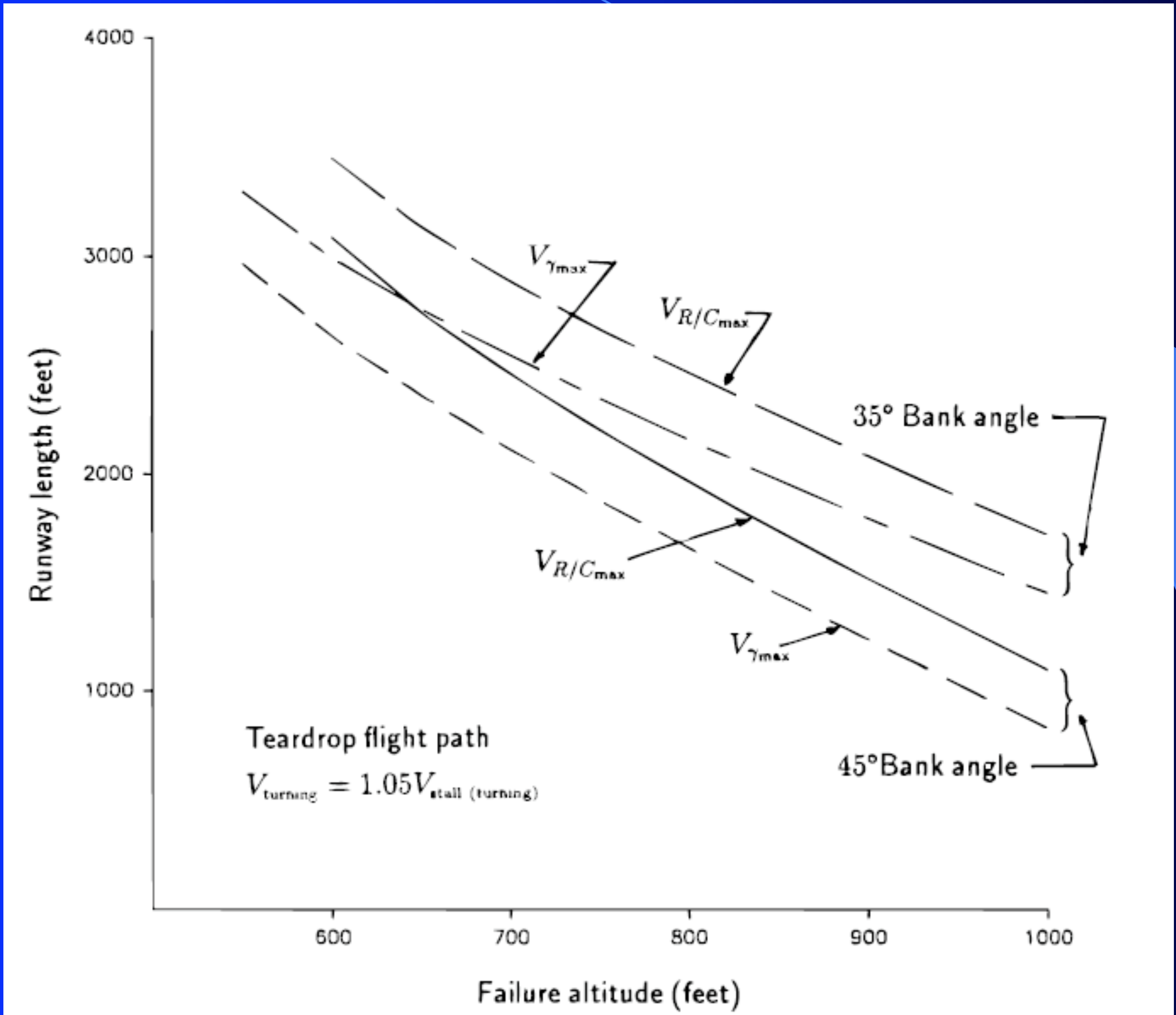
45 degrees of bank and climbing at best angle require least runway length



reproduced from Rogers

Rogers analysis summary

- Max probability of successful turnback involves (in theory):
  - Initial climb at best angle speed
  - 45 degree bank during turn
  - Airspeed near stall in turn
- Human factors and broader risk mitigation strategies are neglected in this analysis
  - Successful completion of this maneuver may require practice
  - Climbing at best angle introduces new risks
  - Turning near stall speed at low altitude introduces new risks

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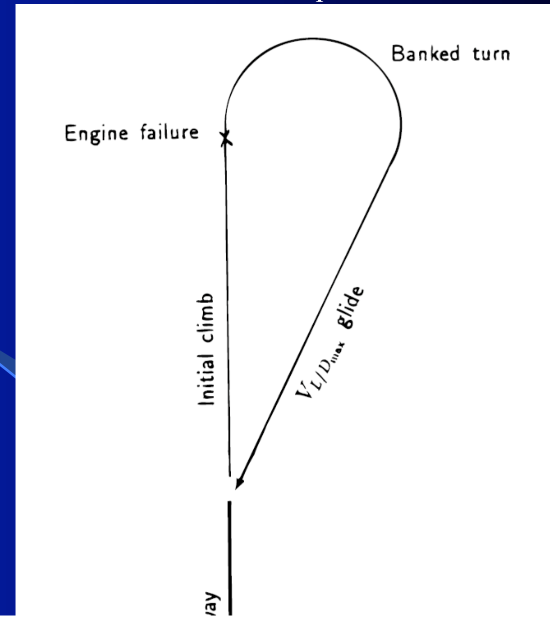

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Human factors: Simulator study by Jett

- B. W. Jett, Proc. AIAA 20th Aerospace Sciences Meeting, AIAA-82-0406 (1982).
- 28 pilots experience engine failure on takeoff at 500’ AGL in simulator representative of a “single-engined, light utility/sport aircraft”
  - Simulator exhibits partial motion
  - Early 1980s technology probably lacks realistic graphics, terrain, obstacles to crash into, etc.
- Experience ranges from 40 hour pilots to CFIs and 5000+ hour military pilots

Success criterion for landing off-airport:

- <2500 fpm max descent rate
- <500 fpm descent at touchdown
- wings within 5 degrees of level below 100’ AGL

Success criterion for turnbacks are the above plus:

- turn >175 degrees above 100’ AGL
- maximum bank angle less than 55 degrees*

*Remember this one

Jett study: Flights #1 and #2

- Flight#1: Pilots were told to climb to 3,000’ AGL and await further instruction
  - Pilots were told to expect an emergency at some point during flight
  - Engine failed at 500’ AGL
- 85% of pilots landed straight ahead, no crashes
- Of the 15% that attempted a turn back, 2/3 crashed from steep bank/stall

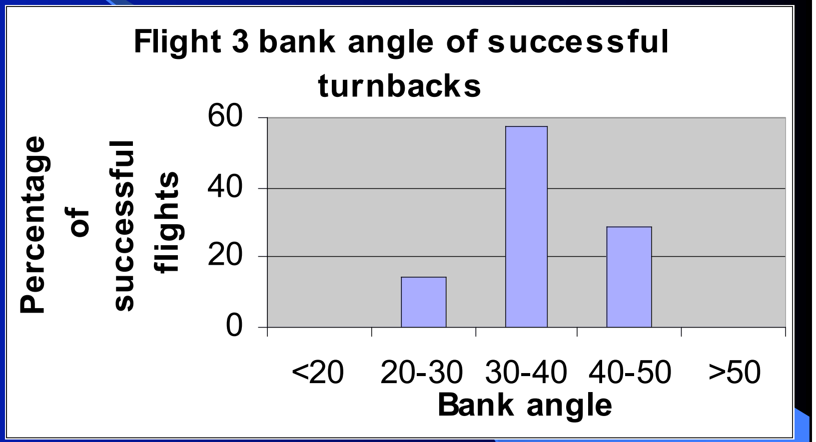
- Flight #2: Pilots were told to expect engine failure at 500’ AGL
  - Pilots were told to handle it any way they wish
- – 90% pilots landed straight ahead, no crashes
- – Of the 10% that turned back, 50% crashed

100% of straight ahead landing attempts were successful.
>50% of turnbacks were considered crashes.

Jett study: Flights #3 and #4

- Flight 3:
  - Pilots were told to attempt 180 turn upon engine failure
  - 43% success rate
  - 85% of failures involved bank exceeding 55 degrees
- Flight 4:
  - Same as flight 3 but pilots directed to use 45 degrees of bank and airspeed just above stall
  - Overall success rate 75%
  - 10% unable to turnback successfully after 3 attempts

These flights suggest that success chance is improved by:
1) Experience with turnbacks and/or optimal technique use
2) Total flight time



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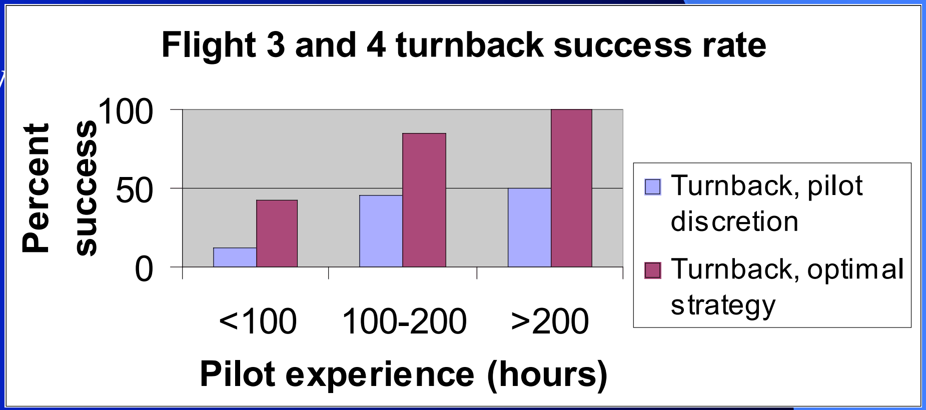
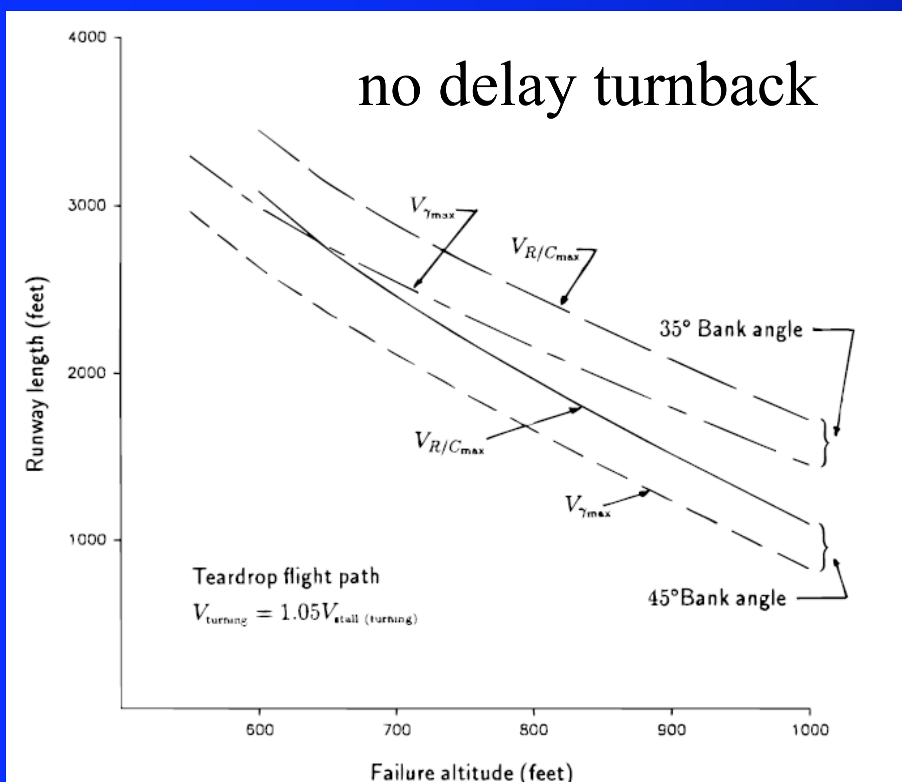


Jett study: Caveats to consider

- The scenario studied here was on the ragged edge of feasibility
  - This study involved turnbacks from 500’ AGL with an airplane that required about 340’ to do a 180 using optimal technique
  - These statistics are not likely to hold for turnbacks from higher or lower altitudes
- 100% of straight ahead landings were successful, but there were no terrain/obstacle issues in this study
- Bank angles greater than 55 degrees were defined as crashes
  - We know that there is no advantage to using more than 45 degrees of bank, but it would have been nice to see this demonstrated by this study rather than assumed

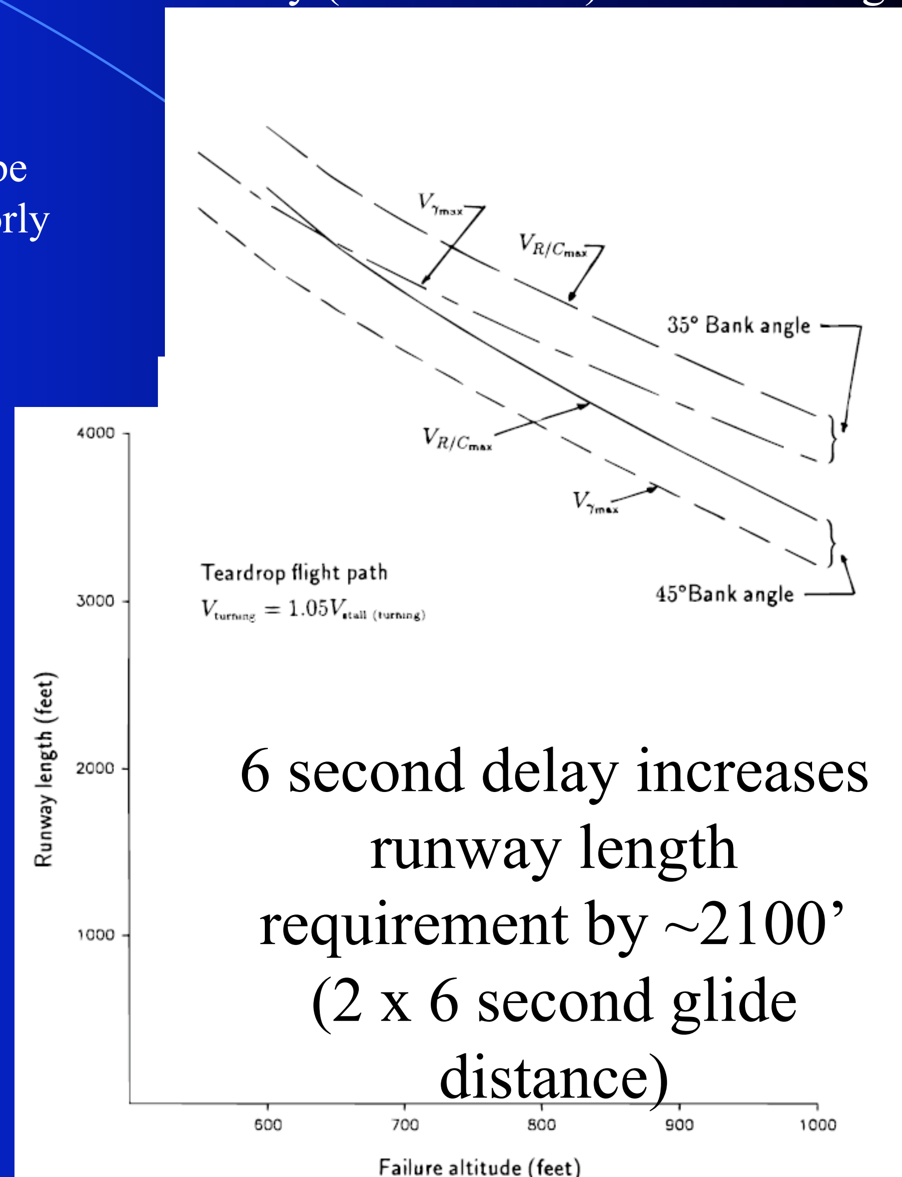
Effect of delayed turnback

- Unless you're expecting it, there will be some time delay between engine failure and initiation of turnback maneuver
- The delay time can impact probability of success
- The advantages of minimizing the delay should be weighed against disadvantages of impulsive, poorly planned behavior



reproduced from Rogers

Rogers data transformed by ~6 second delay (100' descent) before turning



Lowering the psychological barrier to off-airpot landings: What's really going to happen after a successful off-airport landing?

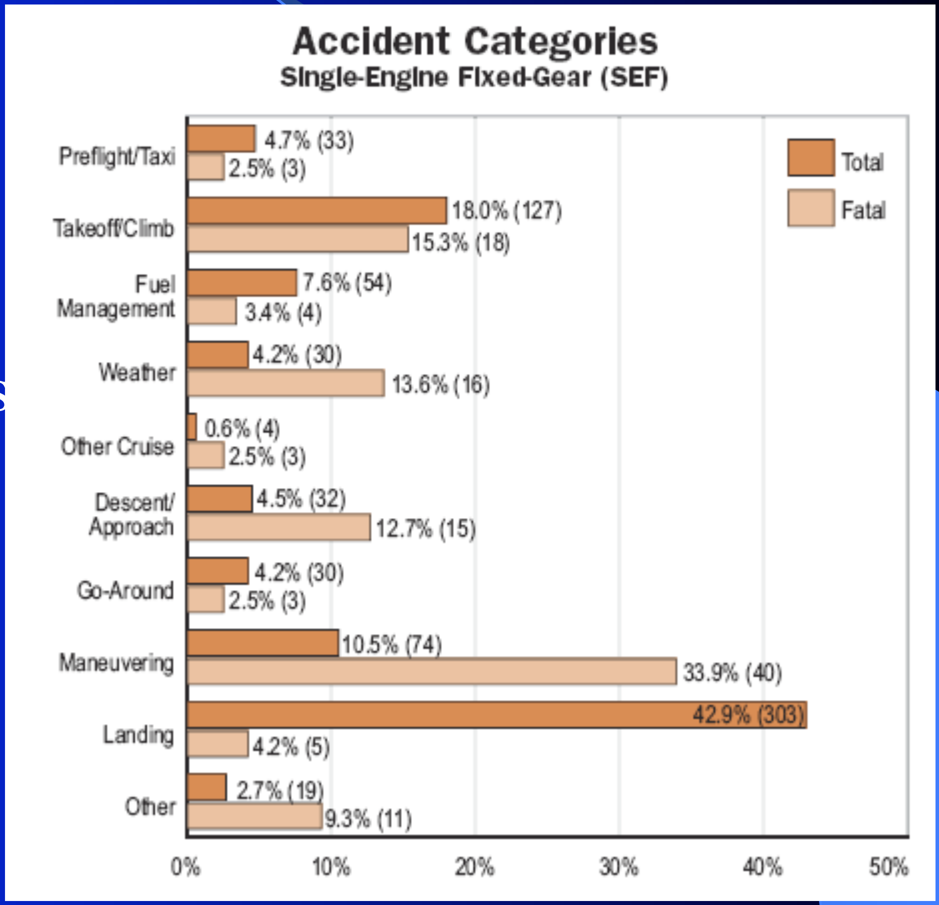
- May attract attention from FAA, FPI
- Most likely, nothing bad will happen
  - May be responsible for club's damage deductible
  - No one will criticize your decision to land straight ahead
- Worst case scenario (highly unlikely):
  - License suspended for some time period
  - Find another flying club

Ensuring that you and the plane are legal and insured before flying can minimize your hesitancy to land straight ahead.

Nall statistics

- Turnbacks are included in maneuvering category, with other types of accidents
- Maneuvering accidents are comparable to some other categories
- High fatality rate for maneuvering accidents reflects high danger level of this kind of accident
- A comparative turnback study between glider and power pilots may shed light on the role of the turnback training that glider pilots receive

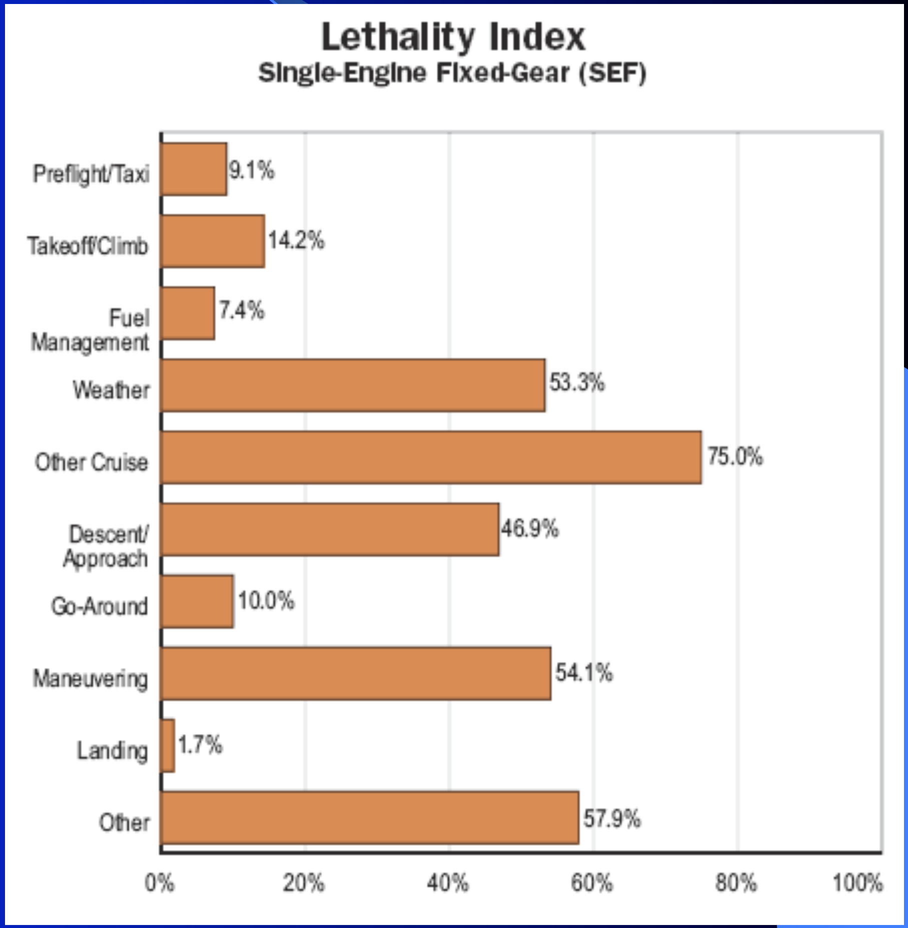
2007 Nall report



Statistics

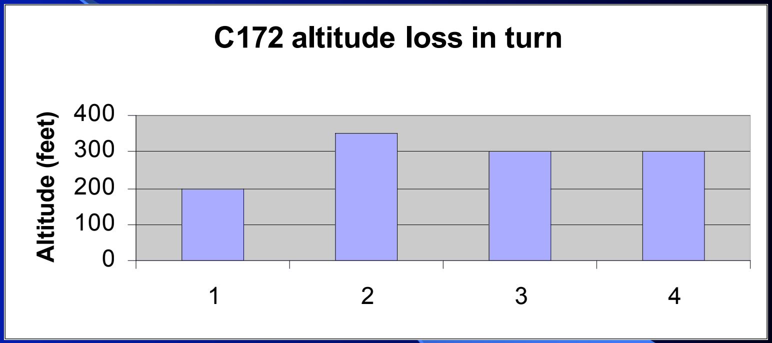
- Turnbacks are included in maneuvering category, with other types of accidents
- While turnbacks do not dominate GA accident statistics, they get much attention in part due to their high fatality rate

2007 Nall report



Turnbacks in C172 N73857

- All tests done at 3700’ DA, except 6000’ DA for #4
- All turns done with ~45 degrees bank
- Wind effects removed from data
- Test 1:
  - Climb vx, no delay before turn, near stall speed in turn
- Test 2:
  - Climb vy, 6 sec. delay before turn, 80 kts in turn
- Test 3:
  - Climb vy, 6 sec. delay before turn, 70 kts in turn
- Test 4:
  - Climb vy, 6 sec. delay before turn, 70 kts in turn, ~6000’ density altitude

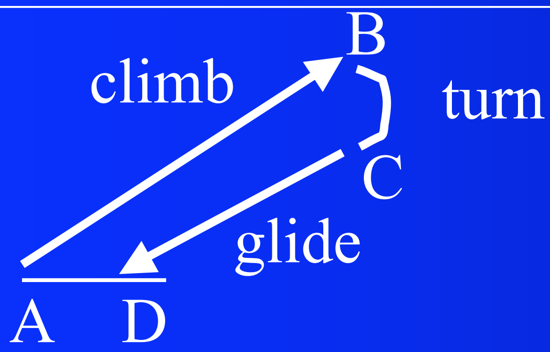


Altitude loss ranges from 200-350’ for max performance to “safe” turns.

200’ altitude loss for maximum performance case (test 1) is close to theoretical prediction.

Some details about the data and extrapolations that follow

The time, altitude, and distance from the GPS "takeoff rotation" fix were recorded at points B, C, and D. Altitude of A and D are equal.

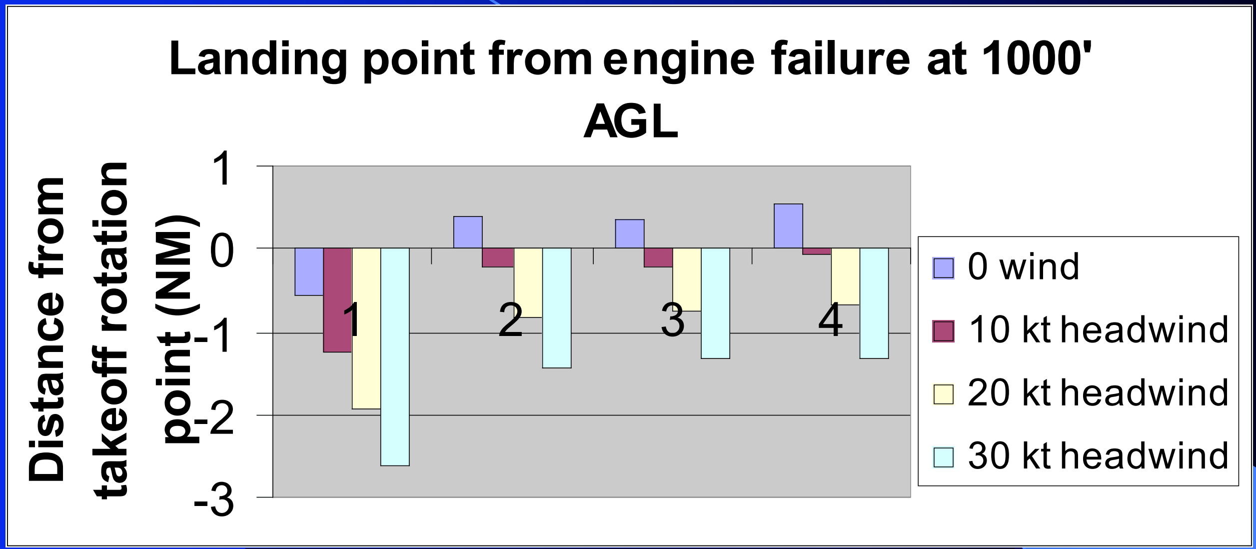


		1	2	3	4
	pressure altitude	3000	3000	3000	6000
	temperature C	15	15	15	
	wind speed (headwind)	18	18	18	25
engine failure	distance (nm)	1.36	1.54	1.48	1.51
	time (sec)	110	97	91	100
	altitude	4000	4000	4000	7000
	delay		6	6	7
turn complete	distance	1.26	1.53	1.52	1.52
	time	133	145	118	130
	altitude	3800	3650	3700	6700
	altitude loss in turn	200	350	300	300
ground elevation	distance	-1.8	-0.7	-0.65	-1
	time	245	218	202	223
	climb speed	vx (59)	vy (76)	vy (76)	vy (76)
	turn airspeed	near stall	80	70	70

The maneuver was done into the wind. The time to arrive at point D enabled calculation of wind speed effects on point D location. Extrapolations to failure altitudes other than those flown were accomplished assuming the altitude change is compensated by the climb and glide segments, i.e., the altitude required for the turn is independent of failure altitude.

Turnbacks from 1000' AGL in C172 N73857

Negative values correspond to overshooting the runway.



Return possible for all wind speeds. S-turns required in many cases. Most challenging for high density altitude case.

- Test 1: Climb vx, no delay before turn, near stall speed in turn
- Test 2: Climb vy, 6 sec. delay before turn, 80 kts in turn
- Test 3: Climb vy, 6 sec. delay before turn, 70 kts in turn
- Test 4: Climb vy, 6 sec. Delay before turn, 70 kts in turn, ~6000' density altitude

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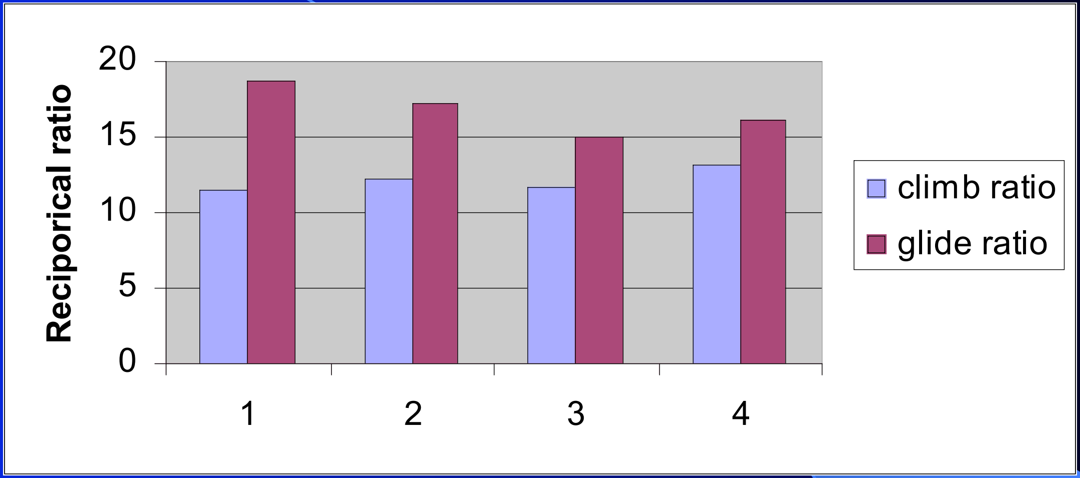
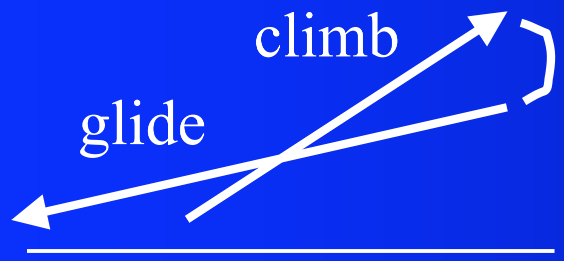


Glide ratios measured are substantially lower than POH value of 1/9. Reason for this is unclear.



Glide ratios are all greater than climb ratios for all test cases => climb angle is greater than glide angle.

- Test 1: Climb vx, no delay before turn, near stall speed in turn
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- Test 3: Climb vy, 6 sec. delay before turn, 70 kts in turn
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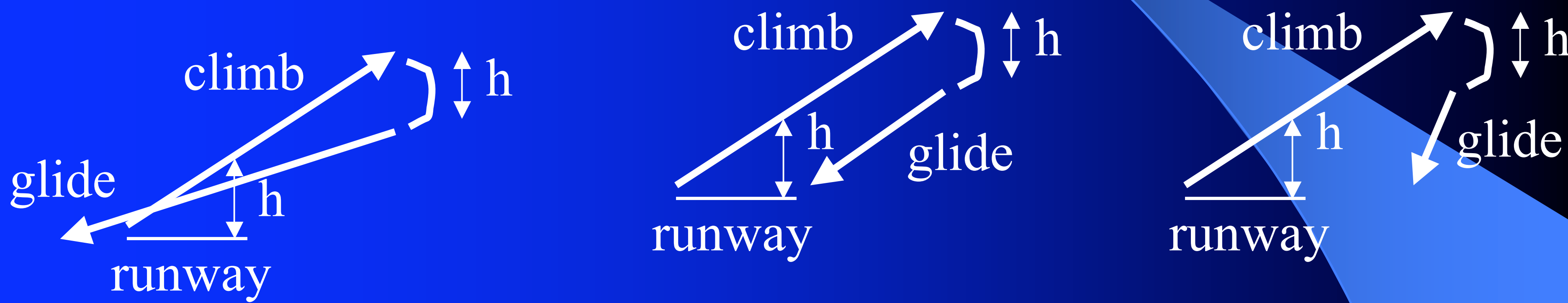
Successful turnback rule of thumb

Climb ratio > glide ratio. Success	Climb ratio = glide ratio.	Climb ratio < glide ratio. Failure



You can turnback if: 1) you height when crossing the departure end of the runway exceeds the altitude required to make the turn, AND 2) Climb ratio is more than glide ratio.

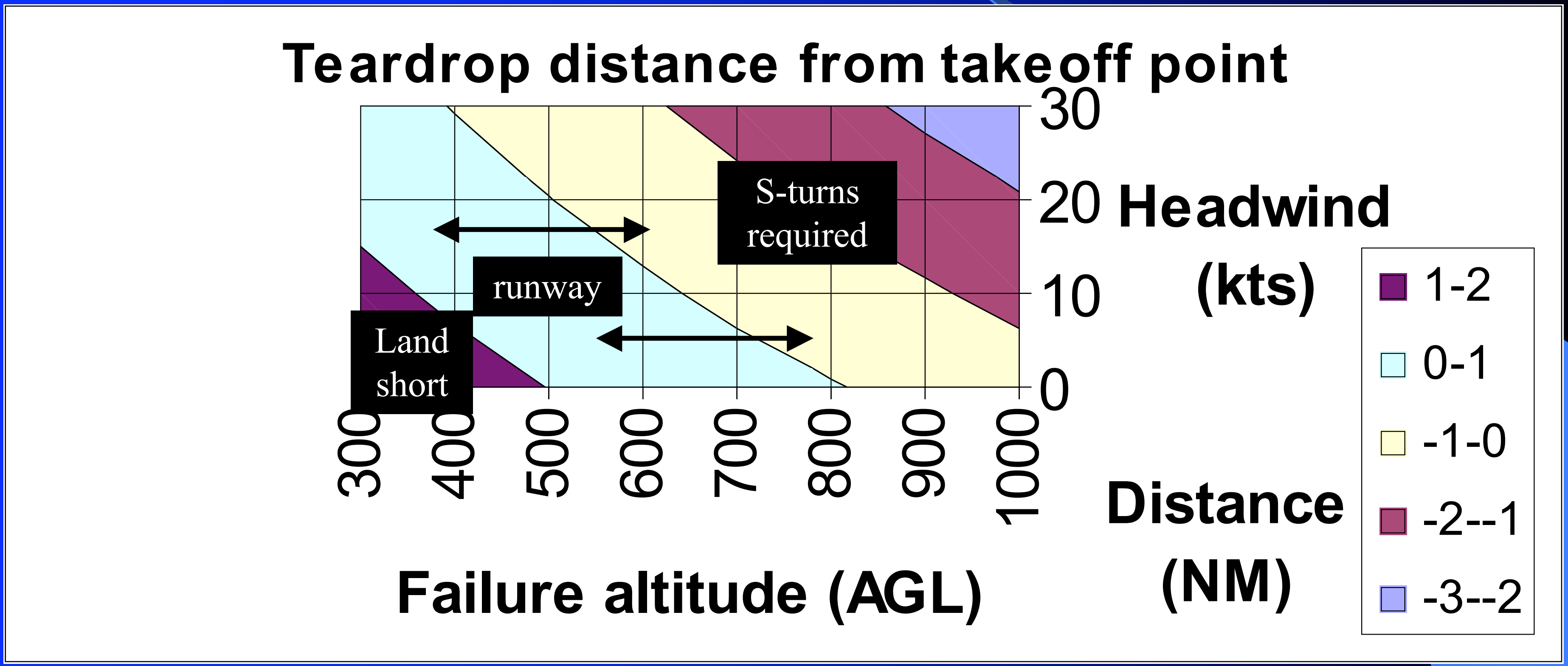
For 10:1 glide ratio airplane, the latter condition can be determined by comparing airspeed (kts) to vertical speed/10 (fpm).

E.G., turnback can be made if vertical speed/10 (fpm) > airspeed (kts).

Turning back becomes impossible as climb ratio decreases (e.g. density altitude) => turning back may be impossible regardless of altitude for high density altitude.

Extrapolated return point from C172 N73857 data, test 1: maximum performance

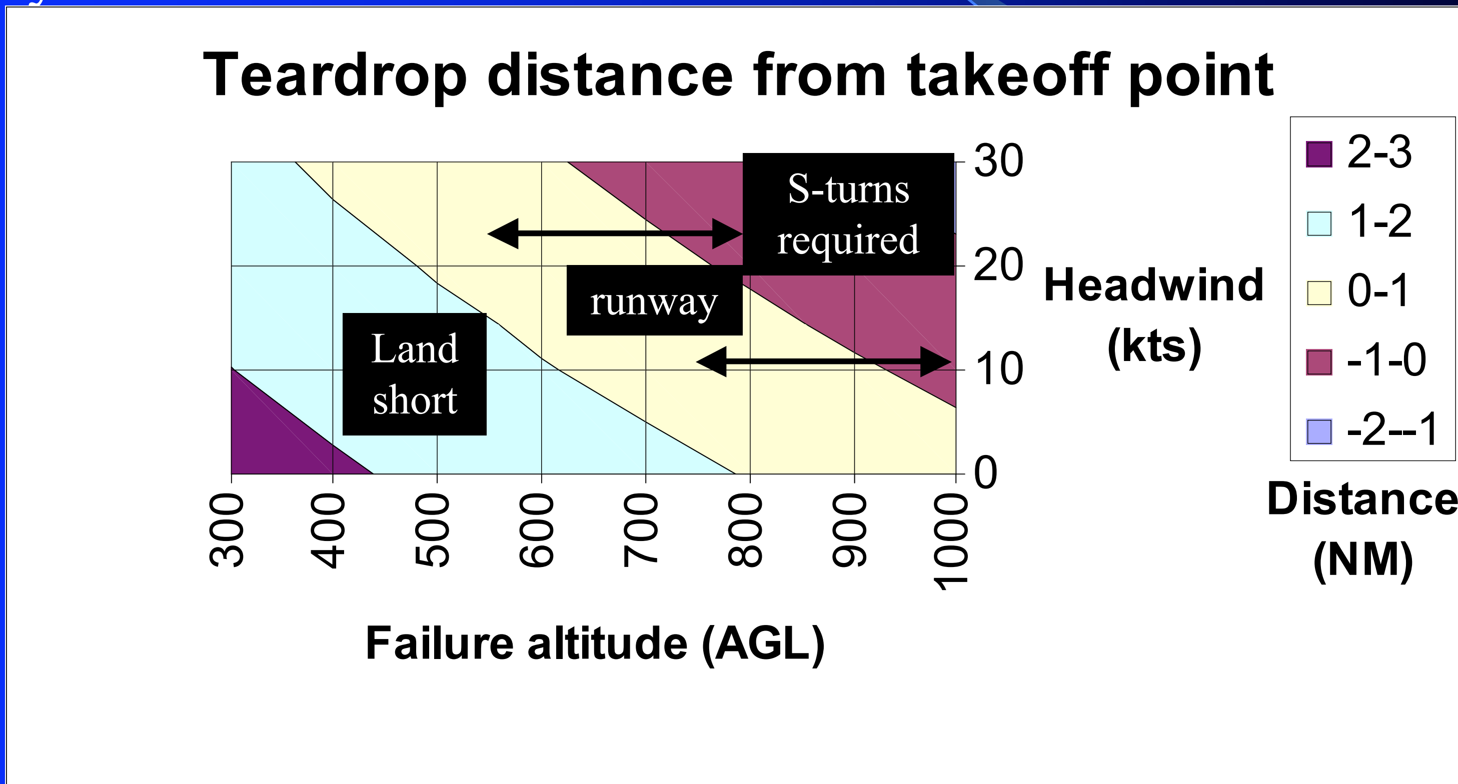
- Test 1: Climb vx, no delay before turn, near stall speed in turn



For this MAXIMUM PERFORMANCE case, 600’ AGL is minimum turnback altitude for most runways with no wind (3700’ density altitude).

Extrapolated return point from C172 N73857 data, test 2: sloppy performance

- Test 2: Climb vy, 6 sec. delay before turn, 80 kts in turn, 3700' density altitude



For this relatively sloppy case, 900' AGL is minimum turnback altitude for most runways with no wind (3700' density altitude.)

Turnback video in C172 N73857

- See it at: http://www.youtube.com/watch?v=SNgoOFq87aY
- Climb at best rate (76 kts)
- Engine fail at 800’AGL, ~1000 density altitude
- 6 second delay before turn initiated
- 40-45 degrees bank with 75 kts airspeed (no buzzer)
- 7 kt headwind on surface, probably 10-20 kts aloft
- Return to runway possible, s-turns required to avoid overrun
- Results of this flight are in reasonable agreement with extrapolated results

Practical tips

- Turn crosswind at 500'
  - You probably can't turn back before this and if you need to on crosswind, you'll already be halfway through the turn
- Decide on a personal strategy while on the ground
  - Consider the number of different models of aircraft you fly and your knowledge of the critical altitudes for those aircraft
  - Your experience with the turnback maneuver
  - Your overall experience level (remember Jett study)
- If you decide to turn back:
  - Keep bank angle 35-45 degrees
    - Theory and Jett simulator study show that 45 degrees or less is both safest and most effective
  - A 10-20 kt airspeed safety margin over stall speed can be purchased with a 100-150' increase in turn altitude for a C172
  - Be prepared for possible s-turns and potential overrun