Safety Critical Procedure Development
Requires High Level Multi-Disciplinary Knowledge

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Introduction

Relevant career highlights:

- Lt-Col ret. RNLAF
- USAF Test Pilot School (1985).
- 15 years experience in flight-testing many types of airplanes, simulators and helicopters.
- Following retirement founded: Avio*Consult.*

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Test Pilot School

- Training subjects:
  - Aircraft Performance;
  - Flying Qualities;
  - Airborne Systems;
  - Pilot-Vehicle Interface.
- Entry level is an MSc or BSc in engineering + entry exam.
- One-year course, 50% academic and 120 hours flying in 23 different types civil and military airplanes, helicopters, and simulators + reports writing.
- Graduates are qualified to conduct experimental flight-testing.

EMB-120ER, Darwin, Australia, 2010-03-22

Accident following an engine failure after takeoff

ATSB video

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Accidents after Engine Failure

- During past 25 years more than 400 of such accidents were reported on the Internet (i.e. Western World), 3600 casualties.
- Why do these accidents continue to happen?
  Airplanes are flight tested and certified, minimum speeds are determined and published, pilots are well trained.
- I decided to do something about this, and reviewed >400 accident investigation/ safety reports.
- These reports often list the cause as inappropriate crew response, blaming the pilots (often postmortem, which is unfair).

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Accidents after Engine Failure

- I noticed in the reports that pilots:
  - allowed (or could not prevent) their airplane to yaw and/or bank, or
  - intentionally initiated turns at low speed while at high asymmetrical power setting.

  But multi-engine airplanes are not designed and flight-tested to turn at low speed when the thrust is asymmetrical and high.
- After also reviewing many Flight Manuals and pilot text/ learning books, it became clear that engine emergency procedures and definitions of safety speeds in these manuals do not agree with airplane design and flight-test techniques.

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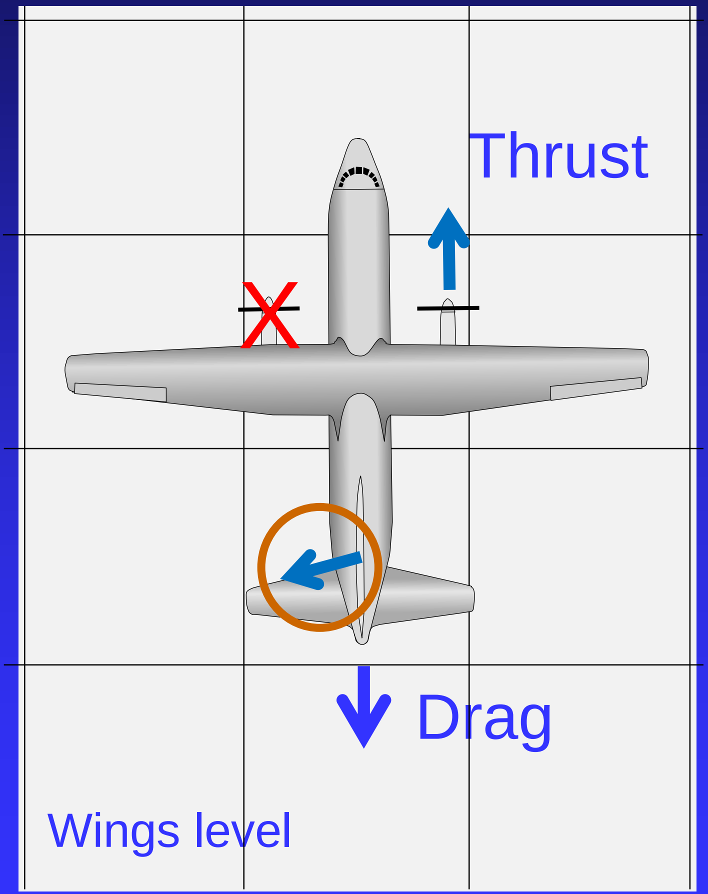
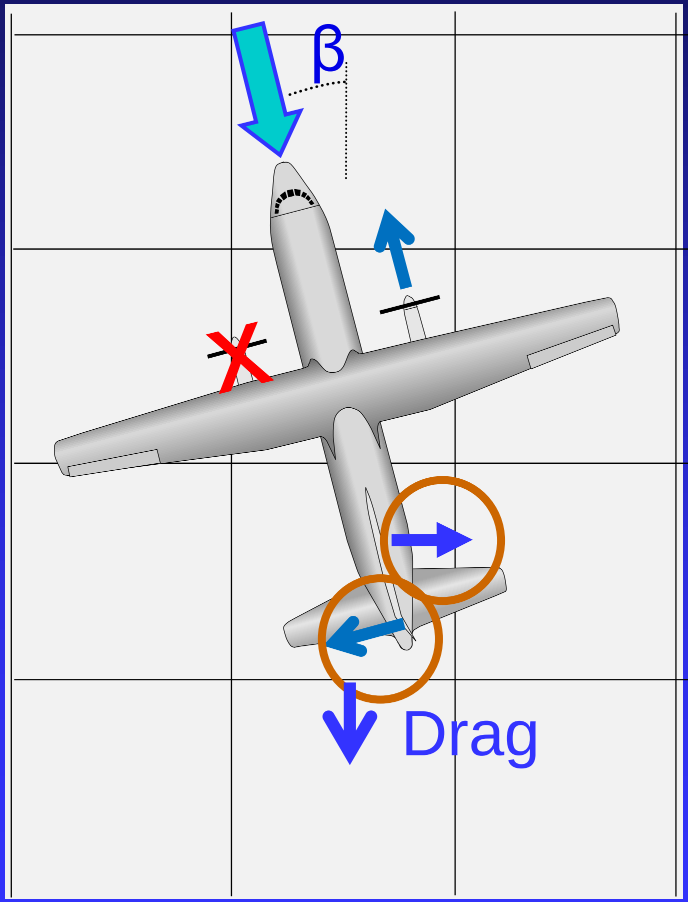
Directional Control after Engine Failure

- Yawing after engine failure continues until the side force due to sideslip balances the asymmetrical thrust.
- The resulting sideslip causes lots of drag: less remaining or no climb performance at all.
- Pilot needs to take action to avoid the loss of control and performance using the aerodynamic controls rudder and ailerons (or close the throttles and land).



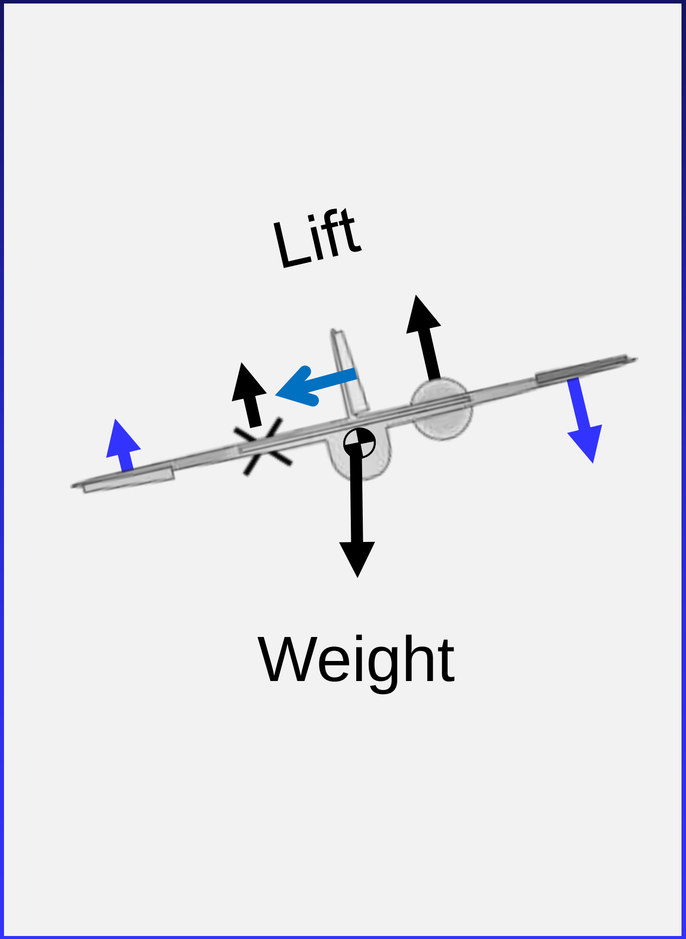
Directional Control after Engine Failure

- Rudder is the only control to recover and remains required to counteract the asymmetrical thrust.
- The rudder side force also causes sideward displacement: a sideslip.
- This sideslip, in turn, results in an opposite side force due to sideslip, requiring additional rudder.
- Sideslip β increases until balance of side forces is achieved.
- Result is lots of drag and hence, loss of climb performance.



Lateral Control after Engine Failure

- A side effect of yawing after engine failure is rolling due to:
  - Increased airspeed of 'good' wing.
  - Less propulsive lift, and blanked wing section due to sideslip on 'bad' wing.
- Aileron deflection is also required to recover and to maintain the desired bank angle.



Vertical fin with rudder and ailerons must be designed large enough for counteracting the yawing and rolling at a defined minimum control airspeed.

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Minimum Control Speed V_{MC} or V_{MCA}

Aviation Regulations require this Minimum Control Speed V_{MCA}:

V_{MC} is the calibrated airspeed at which, when the critical engine is suddenly made inoperative, it is possible to maintain control of the airplane with that engine still inoperative, and (thereafter) maintain straight flight at the same speed with an angle of bank of not more than 5 degrees.

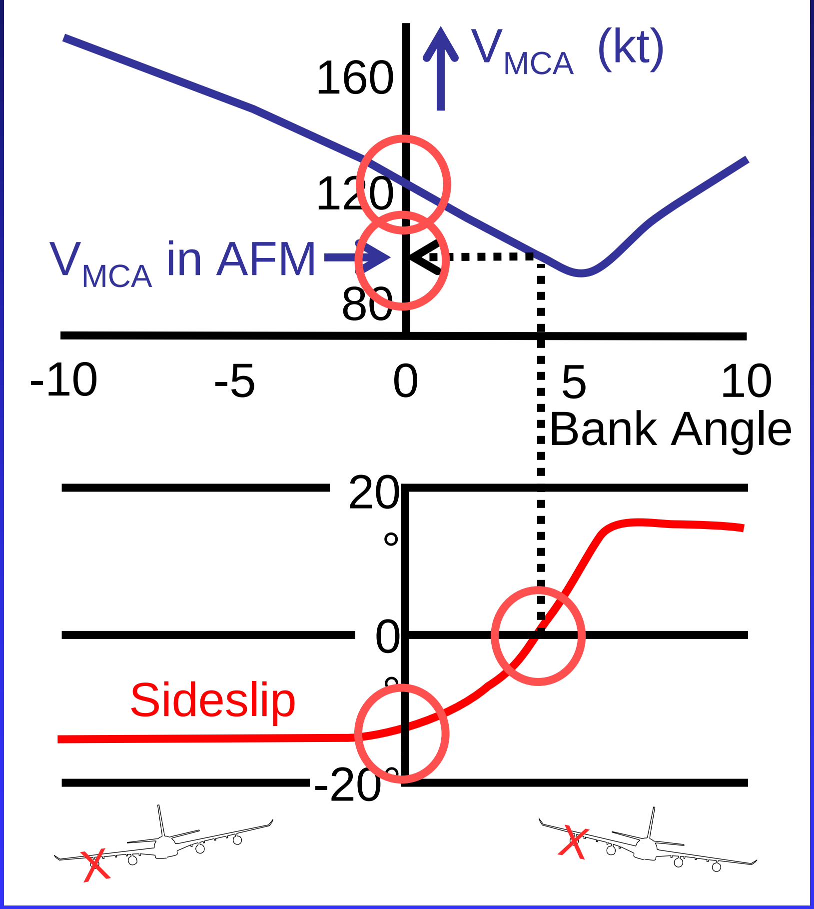
In the Regulations, two requirements for magnitude of V_{MC} (=V_{MCA}):

1. Maintain *control,* incl. recovery, following a sudden failure, and
2. Maintain ***straight flight*** *when the airspeed is as low as V_{MCA}* while one engine is inoperative and the opposite produces max. thrust.

Please notice that there is no requirement for maintaining control during turns, i.e. for maneuvering, at airspeeds as low as $V_{MC(A)}$.

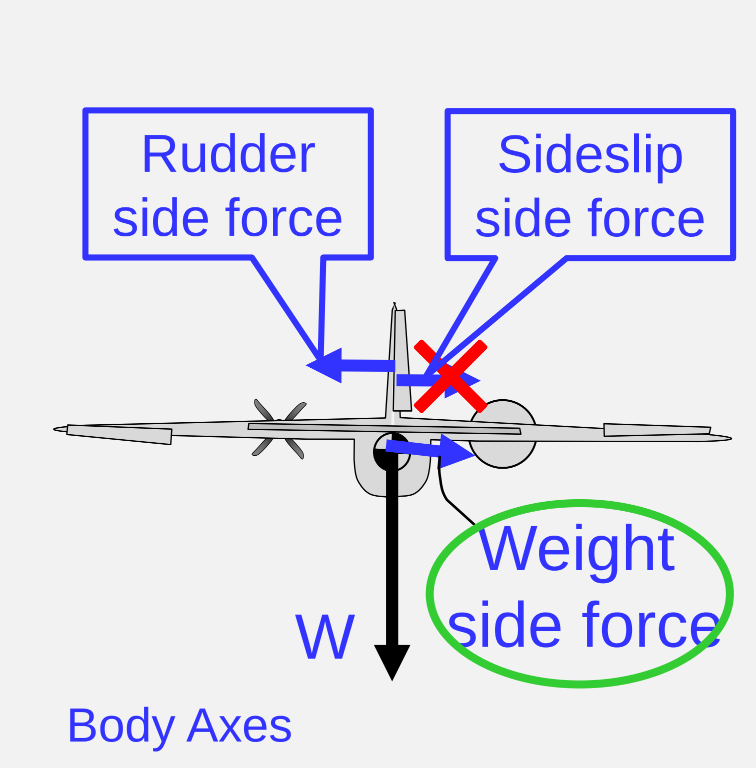
Effect of Bank Angle on V_{MCA} and Sideslip

- The design engineer calculates this graph with V_{MCA} and sideslip during sizing the vertical tail for engine out.
- When wings are level: V_{MCA} ≈120 kt, sideslip ≈14° - means lots of drag.
- For zero sideslip/ min. drag: bank angle needed is 4°: V_{MCA} ≈ 95 kt.
- 4° is less than 5° as required in the Regulations; hence 95 kt is the (design) V_{MCA} of the airplane.
  But this V_{MCA} is only valid for ϕ = 4°.
- At other bank angles, both V_{MCA} and sideslip are higher.



Effect of Bank Angle on V_{MCA} and Sideslip

- With wings level, balance of side forces only with sideslip: ➔ drag.
- When banking, a component of the weight generates a side force in the cg (body axis).
- The rudder doesn't have to counter-act the sideslip side force anymore, only the asymmetrical thrust: ➔ the airspeed (V_{MCA}) is lower.
- The side force due to banking replaces the side force due to sideslip and maximizes climb performance.



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Airplane Control after Engine Failure

Conclusions from the graphs shown:

- The standardized V_{MCA} is valid only if the bank angle is the same as used for designing the vertical tail (while the thrust setting is high, rudder max.) – i.e. only during straight flight while banking few degrees (5°) into the good engine!
- The *actual* V_{MCA}, i.e. the V_{MCA} that the pilot will experience in-flight, varies considerably with bank angle, and is definitely *not a constant value*.
- Climb performance is maximal only if a small bank angle is being maintained.
- *The requirement for pilots to maintain straight flight with a small bank angle at low speed (while thrust is high) is not adequately presented in definitions and engine emergency procedures!*

Flight-testing to determine V_{MCA}

- For V_{MCA} testing, the airplane is in the test configuration:
  Cg aft, low weight, critical engine inoperative, propeller as is (no feathering if manual), opposite engine at max. thrust.
  Safe altitude (5,000 ft).
- Then the airspeed is slowly decreased, while increasing rudder and aileron to maintain straight flight, until either the heading or bank angle can no longer be maintained, because the:
  - Rudder deflection is maximum, or pedal force is 150 lb (667 N), or
  - Aileron deflection is maximum.

  (The heading change is initially very slow)

The airspeed at which this occurs is the wings-level V_{MCA}.

Flight-testing to determine V_{MCA}

- Then, the bank angle is gradually increased to the bank angle for zero sideslip, as used for tail design, after which the airspeed can be further decreased until again one of the limitations is reached.
- This is the static V_{MCA} – for "thereafter". This static V_{MCA} is ≈ 8 kt (small twin) to 30 kt (DC-8) lower than wings-level V_{MCA}.
- Then, dynamic V_{MCA} tests are conducted during which the critical engine is suddenly made inop. at decreasing airspeeds.
- The deviations in roll and heading must stay within certain limits; an average pilot must be able to recover.

The highest of static and dynamic V_{MCA} will be published in the AFM as the (standardized) V_{MCA}. This V_{MCA} is always safe, provided straight flight with 5° into the good engine is maintained!

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V_{MCA} Definition in a Flight Manual

With this V_{MCA} knowledge, I'll review a V_{MCA} definition, which is in most manuals copied from FAR/ CS 23 or 25.149:

"*V_{MC} is the calibrated airspeed at which, when the critical engine is suddenly made inoperative, it is possible to maintain control of the airplane with that engine still inoperative and thereafter maintain straight flight with an angle of bank of not more than 5 degrees.*"

Correct? Yes, but only for tail sizing, certification and flight test, which is what FAR/CS 23 and 25 are for!

Definitely wrong for a Flight Manual or a multi-engine rating textbook! Several errors in this definition if used by pilots.

V_{MCA} Definition in a Flight Manual

... with an angle of bank of not more than 5 degrees.

Does this mean that pilots have to keep the wings level to within 5 degrees *either side* to maintain straight flight while an engine is inoperative and the airspeed is V_{MCA}?

No, definitely not. The vertical tail is designed, and V_{MCA} is determined and is valid only, with a fixed small bank angle of up to 5° away from the inoperative engine, i.e. during straight flight.

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V_{MCA} Definition in a Flight Manual

"V_{MC} is the calibrated airspeed at which, when the critical engine is suddenly made inoperative, it is possible to maintain control of the airplane with that engine still inoperative and thereafter maintain straight flight with an angle of bank of not more than 5 degrees"

Error: Critical engine.

The vertical tail is designed, and V_{MCA} is determined with the critical engine inoperative, because this results in the highest, safest V_{MCA}. But a V_{MCA} also applies after failure of any other engine (is then actually a few knots lower, though).

V_{MCA} Definition in a Flight Manual

- The word *critical* does therefore not belong in the definition of V_{MCA} for pilots, neither in Flight Manuals, nor in textbooks. It is for tail design and for defining worst-case V_{MCA} flight-test conditions only (for certification).
- If *critical engine* is mentioned, then other factors that affect V_{MCA} even more, like bank angle, weight, amount of rudder and thrust level should have been mentioned in the definition (for pilots) as well.

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V_{MCA} Definition in a Flight Manual

"V_{MC} is the calibrated airspeed at which, when the critical engine is suddenly made inoperative, it is possible to maintain control of the airplane with that engine still inoperative and thereafter maintain straight flight with an angle of bank of not more than 5 degrees"

- Last error: 'suddenly made'**.** This condition is also for tail design and flight test.
- A V_{MCA} also applies during the remainder of the flight, not only after a sudden failure. Many accidents happened during the turn to downwind or base leg, or during final turn for landing.
- 'Suddenly made' is misleading and does not belong in the V_{MCA} definition for pilots in Flight Manuals either.

A V_{MCA} applies also during final turn

This is illustrated with a video of a fatal accident on 10 Dec. 2011, Beech 65 Queen Air, Philippines

- After takeoff, the left engine failed.
- Airplane returned to the airport for landing.
- This is what happened:

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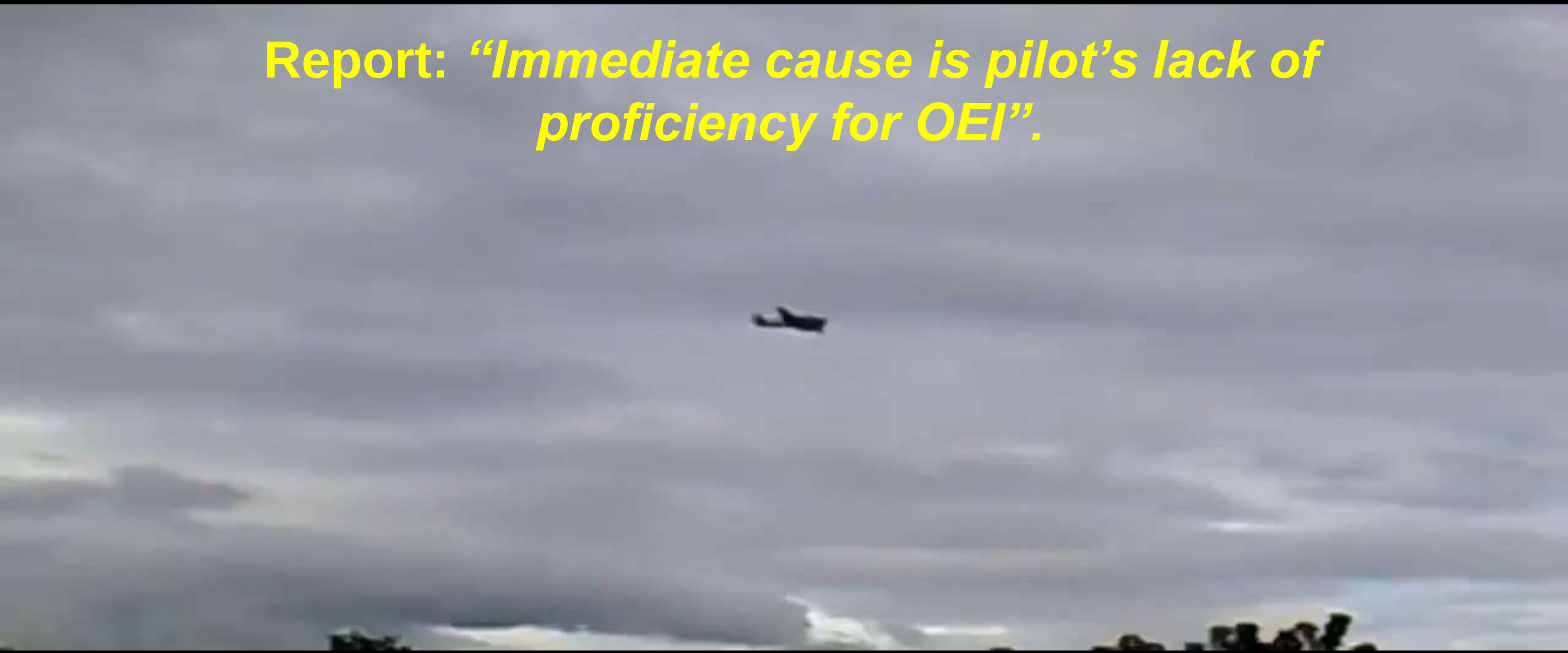
A V_{MCA} applies also during final turn

Report: ***"Immediate cause is pilot's lack of proficiency for OEI".***



A V_{MCA} applies also during final turn

- The pilot was regrettably not made aware of effect of bank angle on V_{MCA} (and on performance) when initiating the final turn at high asymmetrical thrust. Don't blame him, because
- The safety-critical V_{MCA} definition and the engine emergency procedure were obviously not properly developed and written for use by pilots.

- In the fully written paper more V_{MCA} definitions are reviewed: EMB-120, ATR-72, Wikipedia, SKYbrary.

Improved V_{MCA} Definition for Pilots

FAR/CS copied V_{MCA} definitions should be replaced with:

"V_{MCA} is the airspeed at which, when an engine fails or is inoperative, it is possible to maintain straight flight only, provided a small bank angle of 5° *[to be specified by the manufacturer]* is being maintained away from the inoperative engine when the thrust is maximal".

Add a:

WARNING

Do not turn at airspeeds near V_{MCA} while the thrust setting is high; performance will and control might be lost.

A V_{MCA} applies all the time while an engine is inoperative, including during the final turn for landing.

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Takeoff speeds

- Takeoff speed of small twins is required to be only 1.05 V_{MCA}.
- When an engine fails at liftoff, wings are level and the actual V_{MCA} is most often higher than IAS.

- Larger airplanes use takeoff safety speed V_2. This is not a much higher airspeed than V_{MCA} either.
- The EMB-120 of the video accelerated to V_2, but could not maintain control.
- These takeoff speeds are not high enough, the safety margin above (actual) V_{MCA} is too small when an engine really fails.

Engine Emergency Procedure

For instance PA-44 – used for twin rating training.

- *Maintain heading.*
- *Retract gear when climb established.*
- *Accelerate to 88 KIAS (Best ROC - V_{YSE}).*
- *Feather inoperative engine propeller.*

- Maintain heading is good, but no ref. to maintaining 5° bank for both minimizing V_{MCA} and maximizing climb performance.
- Bank angle appears only in the legend of the OEI Climb data: "3 – 5 deg bank toward operative engine" (at 88 KIAS).
- Performance is covered, but maintaining control seems forgotten.

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Safety Critical Procedure Development

- Why do engine failures continue to result in fatal accidents so often? My answer is:
- The safety speed definitions and emergency procedures in Airplane Flight Manuals and in pilot training books:
  - do not agree (anymore) with airplane design methods and flight test techniques (of FAA and EASA), and
  - the conditions for the safety procedures and definitions to be valid, are not included with these anymore.
- Pilots are not made familiar with the real value of V_{MCA} and with the flight restrictions that come with it (and with takeoff speeds).

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Safety Critical Procedure Development

- Pilots don’t want to get killed for whatever reason.
- Pilots have the right to be protected with safe and well-developed procedures, as have their passengers.
- Copied text, whatever the source, must be properly amended for use by pilots.

Safety Critical Procedure Development

- To achieve this, high level multi-disciplinary knowledge is required for safety-critical procedure development.
  Not only experienced operators, but also:
  - Engineers who designed the airplane and/or well understand the limitations of the airplane design and control,
  - Test pilots who conduct experimental flight test, and
  - Pilots who use the procedures to ensure they'll understand.

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Finally

- Hippocrates said long time ago:

  "There are in fact two things, science and opinion.
  The former begets knowledge, the latter ignorance".

- Use science in safety-critical procedure development, not opinion.

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References

- Engine-out flight test training: USAF Test Pilot School. http://www.dtic.mil/dtic/tr/fulltext/u2/a319982.pdf.
- Tail design theory: University of Kansas/ Airplane Design by Dr. Jan Roskam.
- FAR Regulations and EASA Cert. Specifications, Parts 23/ 25.
- FAA and EASA Flight Test Guides (AC 23-8C and 25-7C, resp. CS 23 Book 2, AMC).
- *On-line Engine-out Trainer*, University of North Dakota, USA.
- EMB-120 accident: https://www.atsb.gov.au/media/3546615/ao-2010-019.pdf.
- Philippines accident report: http://www.caap.gov.ph/?download=3353, video: https://www.youtube.com/watch?v=vTQwkKameLg.
- Papers on the subject, a video lecture and links to these references on the downloads page of my website: www.avioconsult.com.

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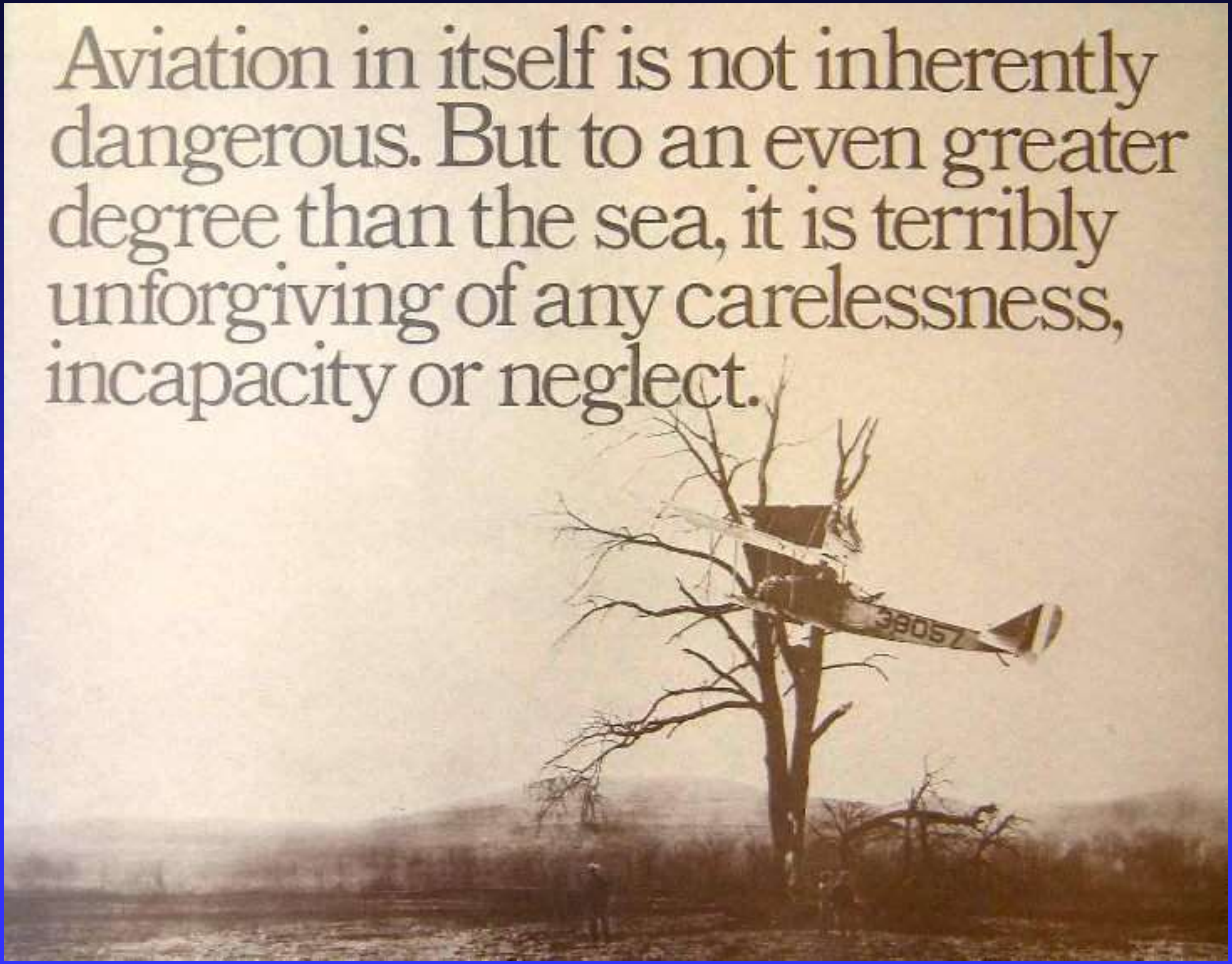

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Some additional slides for Q&A

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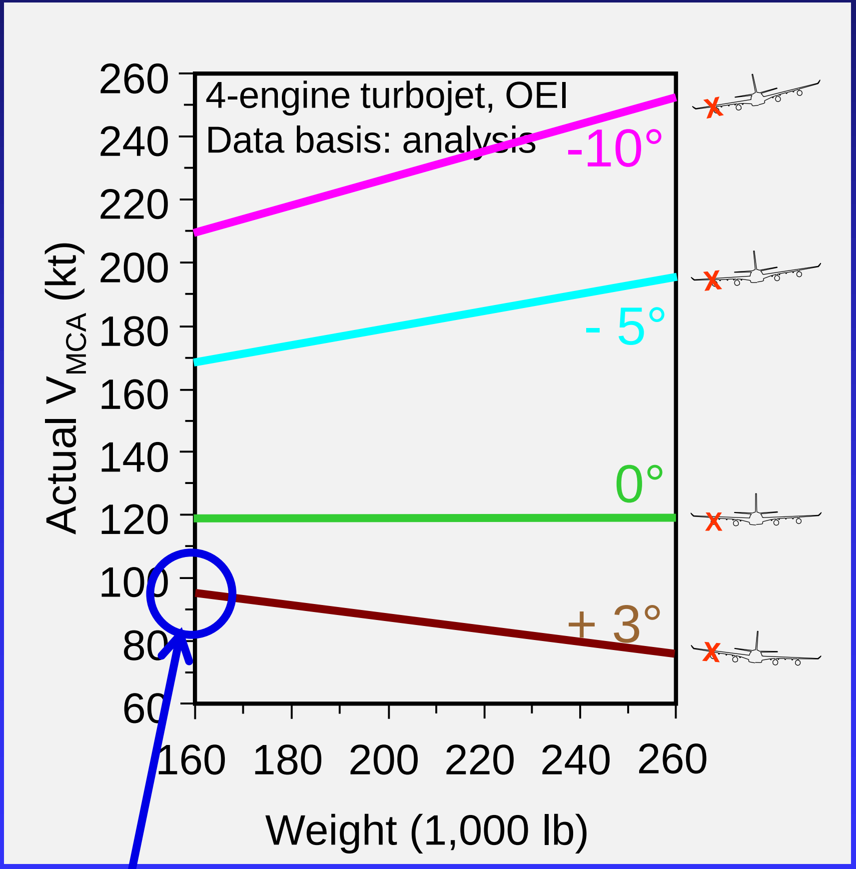
Effect of Bank Angle & Weight on V_{MCA}

C-130 pilots will recognize this graph (SMP777 page 3-18).

Graph shows *actual V_{MCA}* as both weight and bank angle ϕ are changed (effect of $W \cdot \sin \phi$):

10° bank into inop. engine
5° bank into inop. engine
0° bank (wings level)
3° away from inop. engine



V_{MCA} in AFM

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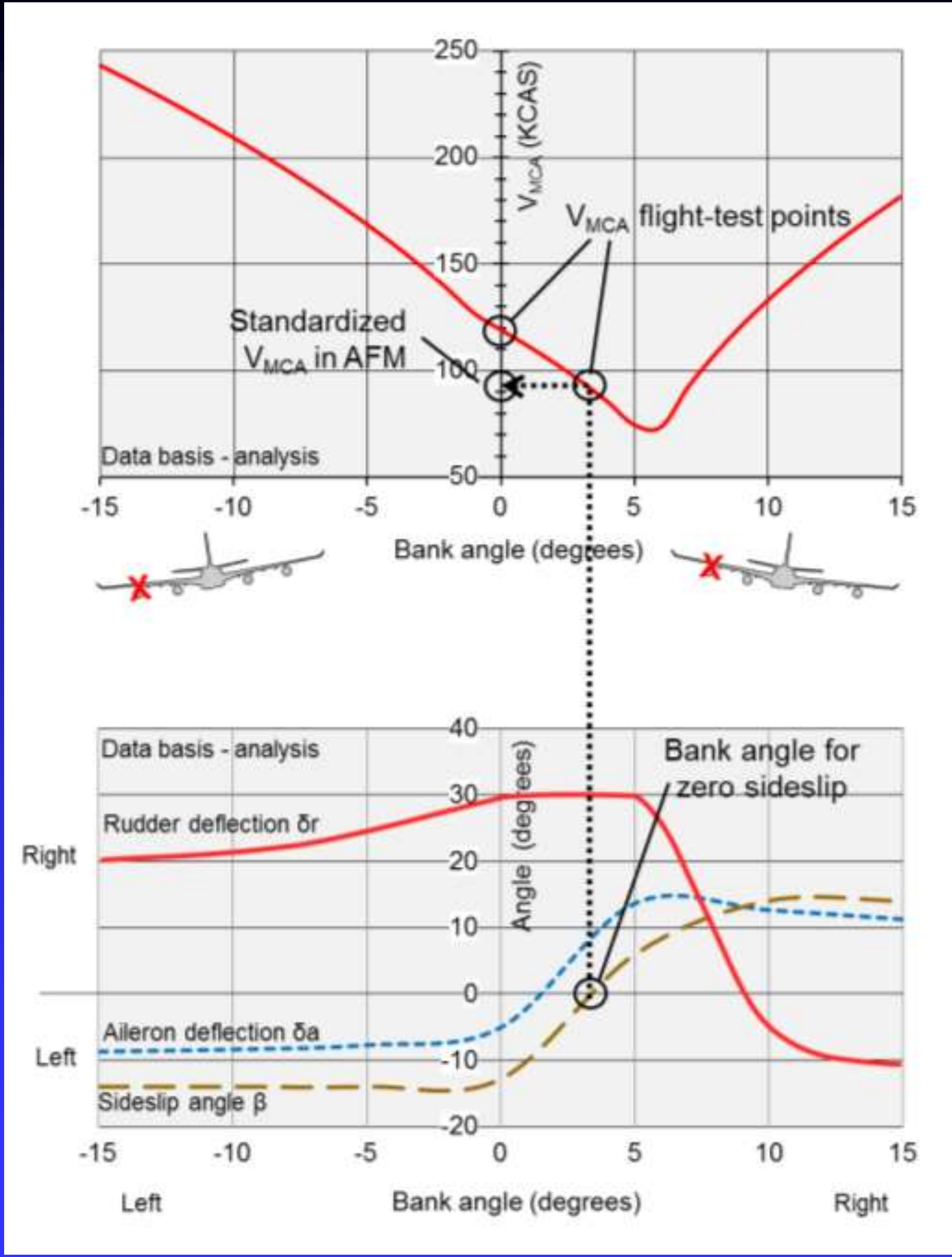
Effect of Bank Angle on V_{MCA}



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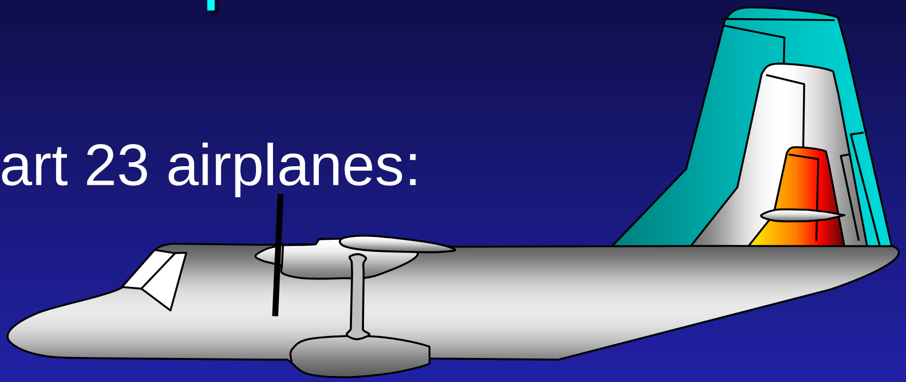
Tail Design Multi-Engine Airplane



- Regulations also require, for Part 23 airplanes:
  - V_{MCA} <= 1.2 V_S (lowest V_S)
    ➔ tail not too small.
  - Takeoff speed must be >= 1.05 V_{MCA}
- Operators want a low takeoff speed, i.e. a low V_{MCA}, to be able to operate from short runways – resulting in a large tail.
- A large vertical tail does decrease V_{MCA} but increases both weight and manufacturing cost – not liked very much.
- The Regulations offer one more option for a smaller tail, a lower V_{MCA}: a small bank angle of max. 5° (into good engine).

Other effects on actual V_{MCA}

- Many more factors have influence on V_{MCA} – see my papers.
- In general, anything that affects thrust or drag symmetry, i.e. for which the balance of forces and moments acting on the airplane changes, has influence on V_{MCA}. Examples:
  - Idling engine, not set at thrust for zero drag – V_{MCA} higher;
  - Cargo hatch opens in-flight – the asym. drag affects V_{MCA};
  - Forward Center of Gravity decreases V_{MCA}, longer rudder arm.
  - Cross feed, transfer of fuel and/or pax to good engine side – shifts lateral cg, thrust moment arm smaller, V_{MCA} lower;
  - Increased engine thrust rating, or new propellers – V_{MCA} up;
  - If camera installed (for fun) on wing tip – affects V_{MCA};

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V_{MCA} Definition in AFM EMB-120

"V_{MCA} is the minimum flight speed at which the aircraft is controllable with a maximum 5° bank [toward the operative engine] when one engine [critical engine] suddenly becomes inoperative with the remaining engine operating at takeoff power. The value presented represents the most critical combination of power, weight, and centre of gravity. In aircraft with auto-feathering, V_{MCA} is calculated with a feathered propeller".

- Many errors in this definition in the AFM, for pilots. This definition does not prevent accidents.

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V_{MCA} Definition in AFM EMB-120

"V_{MCA} is the minimum flight speed at which the aircraft is controllable with a maximum 5° bank [toward the operative engine] when one engine [critical engine] suddenly becomes inoperative with the remaining engine operating at takeoff power. The value presented represents the most critical combination of power, weight, and centre of gravity. In aircraft with auto-feathering, V_{MCA} is calculated with a feathered propeller".

- Several items already discussed.
- Indeed, the value presented is the worst case, but this sentence adds unnecessary complicating topics – no need for pilot to analyze these after engine failure – don't mention.

V_{MCA} Definition in AFM EMB-120

"V_{MCA} is the minimum flight speed at which the aircraft is controllable with a maximum 5° bank [toward the operative engine] when one engine [critical engine] suddenly becomes inoperative with the remaining engine operating at takeoff power. The value presented represents the most critical combination of power, weight, and centre of gravity. In aircraft with auto-feathering, V_{MCA} is calculated with a feathered propeller".

- Do not all EMB-120 airplanes have an auto-feather system?
- Better: If auto-feather fails, V_{MCA} is x kt higher than the presented value.
- This definition is just copy-work, not well-written for pilots.

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V_{MCA} Definition in AFM ATR-72

"Minimum control speed in flight at which aircraft can be controlled with 5° bank, in case of failure of the critical engine the other being set at RTO power (take off flaps setting and gear retracted)".

- What does it mean: Controlled with 5° bank? Must be: can maintain straight flight while maintaining 5° of bank into the operating engine.
- V_{MCA} applies in case of failure of any engine, not only the critical.
- RTO power = Reserve Takeoff Power (is 100% TQ), seems max. TO power (max. 5 min, OEI max. 10 min), but is it?
  Should be the power level the pilot can set with max. throttles.
- Take off flaps? What V_{MCA} applies during final turn?
- Definition is not in Limitations Chapter 2, but in Performance Section; the writer was not concerned with airplane control after engine failure.

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Engine flame out in AFM ATR-72

- At VR rotate to the safe pitch attitude.
- With a positive vertical speed
  - LDG GEAR … RETRACT
  - Use rudder and control wheel to control aircraft heading maintaining aircraft wings essentially levelled
- CLIMB AT V2
- At accel alt.: ACCELERATE UP TO 1.18 VsR FLAPS 0°

- Presume that V_2 used by manufacturer is V_{2MIN}, no safety increment; the safety margin of V_2 above V_{MCA} is very small.
- No advice for straight flight with small bank angle.

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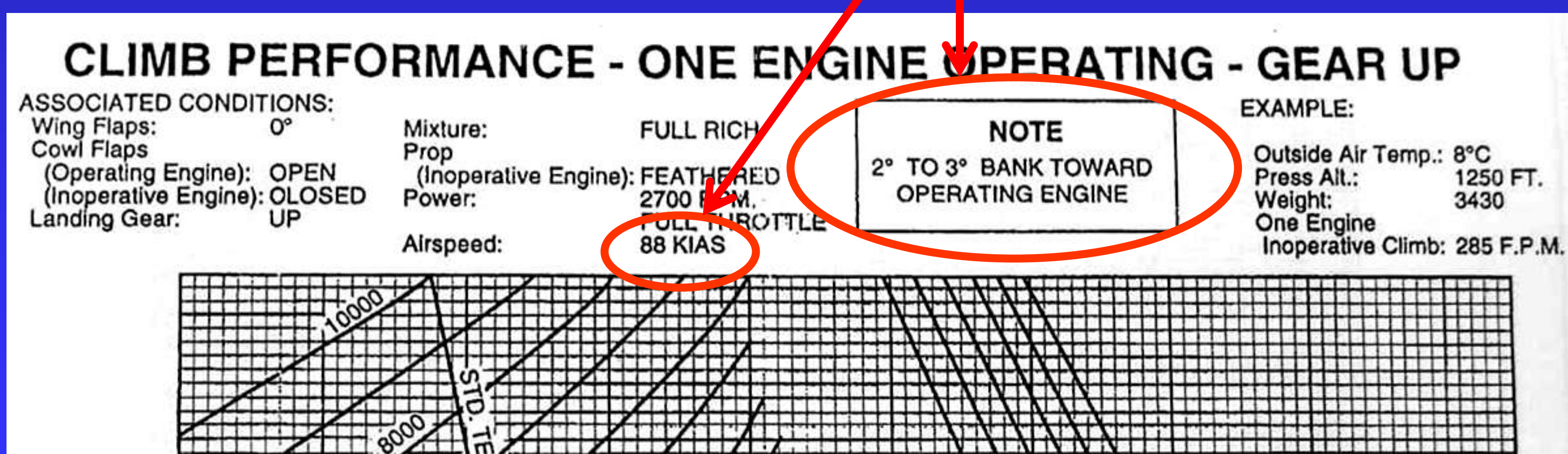
Single Engine V_{YSE} in PA44-180 Manual

- In Performance data PA44-180, there is a bank angle requirement in the one-engine operating performance chart.
- Pilots regrettably do not understand the value of a bank angle; they turn ASAP after engine failure, and loose altitude.
- Performance data is only valid at V_{YSE} 88 KIAS (blue line speed), with 2° to 3° bank (V_{MCA} = 56 KIAS).



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Beech B55 Baron Engine Failure

- Landing gear and flaps – up
- Throttle (inop engine) – CLOSED
- Propeller (inop engine) – Feather
- Power (operative engine) – AS REQUIRED
- Airspeed - Maintain speed at failure – 100 kt max. until obstacles are cleared
- After positive control established: clean-up steps, like mixture, fuel, etc.
- NOTE: If airspeed < 78kt (=V_{MCA}) reduce power operating engine as required to maintain control.
- Nothing on maintaining both straight flight and small bank angle.

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Beech King Air 100 Engine Failure

Affected Engine:

1. Power Lever – IDLE
2. Propeller – FEATHER
3. Condition Lever – CUT-OFF
4. Fuel Firewall Valve – CLOSED
5. Bleed Air Valve – AS REQUIRED
6. Fire Extinguisher – ACTUATE (as required)
7. Clean-up (inoperative engine): 6 steps

Nothing on maintaining straight flight and on small bank angle for reducing V_{MCA} and increasing performance, which would be the most important, lifesaving steps.

Wikipedia

- I wrote the article Minimum Control Speeds on Wikipedia using academic and Test Pilot School knowledge.
- Completely ruined by incompetent editors within a few years.

Don’t use Wikipedia as source of knowledge

SKYbrary

Two articles on Minimum Control Speeds, not correct either:

- **#1: Vmca** is defined as the minimum speed, whilst in the air, that directional control can be maintained with one engine inoperative (critical engine on two engine aeroplanes), operating engine(s) at takeoff power and a maximum of 5 degrees of bank towards the good engine(s).

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SKYbrary

- **#2. Light Twin: V_{mca}** - Airborne minimum control speed - this is the minimum airspeed at which directional control can be maintained under the following conditions: maximum gross weight, center of gravity [C of G] at the maximum aft position, sea level, flaps set to the takeoff position, landing gear retracted, operating engine developing maximum power, critical engine failed and windmilling, a maximum of 5 degrees of bank towards the good engine.

- New error, often made: maximum gross weight, because V_{MCA} is determined at minimum gross weight, which is the worst case weight for published V_{MCA}.