Safety-Critical Procedure Development Requires High Level Multi-Disciplinary Knowledge

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References

A – *Engine-out theory,* Chapter 11. Flying Qualities Flight-test, Aug. 1992, USAF Test Pilot School. Download: https://apps.dtic.mil/dtic/tr/fulltext/u2/a319982.pdf

B – *Fixed Wing Stability and Control*, Chapter 6 Asymmetric Power. US Naval Test Pilot School. Download: http://www.usntpsalumni.com/Resources/Documents/USNTPS_FTM_103.pdf or an older version: https://apps.dtic.mil/dtic/tr/fulltext/u2/a124610.pdf

C – Video lecture *Accidents after Engine Failure, the real value of* V_{MCA}. Avio*Consult*, Nov. 2014. Start the video here: https://youtu.be/Wbu6X0hSnBY. The slides with full script can be downloaded: https://www.avioconsult.com/downloads/Slides + script of YouTube video on Vmca.pdf

D – *Airplane Control and Performance during Asymmetrical Powered Flight*, Avio*Consult*, June 2005. Download: https://www.avioconsult.com/downloads/Control and Performance During Asymmetrical Powered Flight.pdf.

1. Introduction

1.1. Aviation has achieved the highest level of safety of all means of transportation. Nevertheless, during the past 25 years, more than 400 engine failure related accidents with small and bigger transport category multi-engine airplanes were reported on the Internet (in the Western world) causing more than 3,600 casualties. Airplanes are meticulously designed, thoroughly flight-tested and certified airworthy. Minimum safety speeds during takeoff, climb and flight are determined and published in Airplane Flight Manuals. Procedures are developed and published, and pilots are well-trained and qualified. So, the question is why do engine failures lead to catastrophes so often? This paper provides the answer and recommends improvements.

1.2. The NTSB already stated in 2013 and continues to do so this year: "*Engine failures and subsequent loss of control are the No. 1 of Top 10 causes of General Aviation Accidents*". Accident investigation or safety reports often conclude the cause of engine failure related accidents as inappropriate crew response, blaming the pilots (often postmortem, which is unfair). While reviewing investigation and safety reports, I noticed in that pilots either allowed or could not prevent their airplane to yaw and/or bank, or intentionally turned their airplane at low speed while at a high asymmetrical thrust or power setting for which airplanes are definitely **not** designed to be able to do, as is taught by Aeronautical Universities and Test Pilot Schools (ref. A, B).

1.3. After including many Airplane Flight Manuals (AFM) and student pilot text/ learning books in my review, it became clear that the real cause of these accidents was an incorrect definition of the minimum control speed and an incomplete engine emergency procedure in these manuals. In this paper, the inappropriate definition and procedure are discussed, and improved alternatives are presented. But first, in order to better understand the errors and recommended improvements, airplane control after engine failure and the safety speeds are discussed briefly.

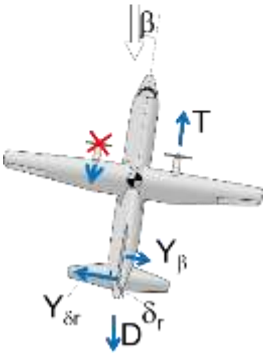
1.4. The knowledge used for writing this paper can be found in the course books of the USAF Test Pilot School (ref. A) and US Naval Test Pilot School (ref. B), both downloadable from the Internet using the URL's provided in the list of references above. The Test Pilot Schools in the UK and France present similar courses. A YouTube video lecture on the subject is presented in Ref. C. The video of the fatal accident with an EMB-120, as shown during the paper presented in Brussels, is included in Ref. C. The video also describes the real cause of the accident as seen through the eyes of a Test Pilot School graduate.

1.5. US Federal Aviation Regulations (FAR) Part 23 and 25, FAA Flight Test Guides in Advisory Circulars AC23-8C and AC25-7C, as well as the equivalent EASA Certification Specifications (CS) 23 and 25, that contain the requirements for flight with a failed engine, can be downloaded from the respective formal websites of FAA and EASA. Abbreviated and clarified versions of these regulations can be found here, which is on the Downloads page of website www.avioconsult.com.

2. Airplane Control Multi-Engine Airplane When One Engine Inoperative

2.1. When one engine fails, the airplane yaws into the failed engine. A side effect of yawing after engine failure is rolling due to the increased airspeed of the 'good' wing, and less propulsive lift as well as a blanked wing section due to sideslip on the affected wing. The resulting sideslip causes lots of drag, meaning less or no remaining climb performance at all. The yawing continues until the side force due to sideslip balances the asymmetrical thrust of the operating engine, if at all possible, or until the pilot takes action by using the aerodynamic controls rudder and ailerons, or by closing the throttles and land, either of which is required to avoid the Loss of Control. Recovery to controlled flight might not be possible if the airspeed is too low, causing the controls to be ineffective.

2.2. Besides aileron to level the wings, rudder (δ_r) is required to recover and to counteract the asymmetrical thrust (T) during the remainder of the flight. The rudder generated side force ($Y_{\delta r}$) also causes sideward displacement, resulting in a sideslip (β). This sideslip, in turn, results in an opposite side force due to sideslip (Y_β). When balance of these forces is achieved, sideslip β increases no more. On a DHC-6 Twin Otter, β is up to 14°. This means lots of drag (D) and hence, loss of climb performance.



2.3. Both the vertical fin with rudder and the ailerons need to be designed large enough for counteracting the yawing and rolling at a defined minimum control speed. This minimum control speed in the air (V_{MC}, today mostly called V_{MCA}), is defined by authorities in the aviation regulations mentioned in § 1.5 above, and is explained in the next paragraph.

Ref. D presents a more detailed description of airplane control after engine failure.

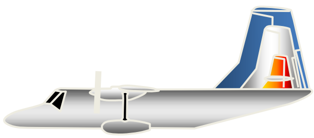
3. Minimum Control Speed and Tail Size Multi-Engine Airplane

3.1. FAR & CS 23/25.149 require a Minimum Control speed to be determined for all multi-engine airplanes:

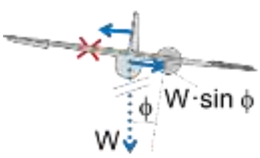
"V_{MC} is the calibrated airspeed at which, when the critical engine is suddenly made inoperative, it is possible to maintain control of the airplane with that engine still inoperative, and (thereafter) maintain straight flight at the same speed with an angle of bank of not more than 5 degrees".

3.2. There are two requirements for the magnitude of V_{MC} (=V_{MCA}) in this Regulation. Maintain control, i.e. recover, following a sudden failure, and (thereafter) maintain straight flight when the airspeed is as low as V_{MCA} while an engine is inoperative. Please notice that there is no requirement for maintaining control during turns, for maneuvering, at airspeeds as low as V_{MCA}, only for recovery immediately following the failure and for straight flight!

3.3. Regulations for small Part 23 airplanes also require that $V_{MCA} \leq 1.2\ V_S$ (lowest stall speed), and that the takeoff speed is equal to or larger than 1.05 V_{MCA}. Operators want a low takeoff speed, i.e. a low V_{MCA}, to be able to operate from short runways or, with higher payload, from long runways, resulting in a large tail. A small tail requires a higher speed for counteracting the asymmetrical thrust; V_{MCA} is higher. A large vertical tail decreases V_{MCA} but increases both weight and manufacturing cost, which is not liked very much. FAR and CS 23 and 25 offer an option for a smaller tail, a lower, safer V_{MCA} and zero-sideslip for increased climb performance, which is applying a small *"angle of bank of not more than 5° "*.



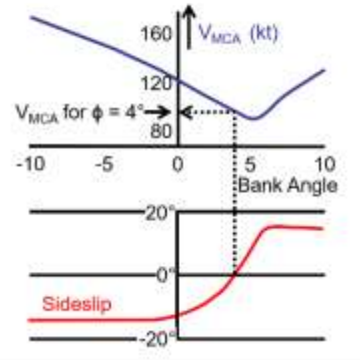
3.4. When the wings are kept level, an equilibrium of side forces and yawing moments is only possible with a sideslip, which results in drag and less climb performance (figure adjacent to § 2.2 above). When banking into the good engine, as shown in the adjacent figure, a component of the weight generates a side force (W·sin φ – Weight times the sine of bank angle φ) in the center of gravity. In the adjacent figure, the body axes system is used; the lateral body axis runs from wing tip to wing tip through the cg. The lift generated by the wings has no side force component in this lateral axis and is therefore not shown.



The $V_{MC(A)}$ definition in the regulations (§ 3.1 above) allow the design engineer to use maximum 5° of bank (which is of course into the good engine for the balance of forces). This side force due to bank angle can replace the side force due to sideslip (Y_β). The bank angle is limited to 5° because a larger bank angle increases the sideslip to the same side, which might cause the vertical fin (with deflected rudder) to stall.

Hence, a small bank reduces the sideslip; the drag becomes lowest possible maximizing the remaining climb performance. But there is another effect of bank, which is discussed next. Of course, there are many more forces and moments acting on the airplane, but the ones mentioned here are the most important.

3.5. A small bank angle into the good engine decreases the drag, as was shown above. The bank angle however, also has effect on the magnitude of V_{MCA}. The airplane design engineer calculates the adjacent graphs (of a sample airplane) during sizing the vertical tail. The graph shows both V_{MCA} and sideslip angle versus bank angle when the left engine #1 is inoperative. When the wings are level, V_{MCA} for this sample airplane is calculated to be ≈120 kt, the sideslip is ≈14°, which means a lot of drag. For zero sideslip, i.e. minimum drag, as shown in the lower graph, a bank angle of 4° is needed: V_{MCA} will then be ≈95 kt. This is the (design) V_{MCA} of the airplane that will be verified during flight-test. Hence, this V_{MCA} is only valid for bank angle φ = 4°. The blue V_{MCA} line shows the actual V_{MCA}, being the V_{MCA} that the pilot would experience in-flight, for changing bank angles. The actual V_{MCA} increases when the bank angle is smaller than the favorable 4° bank angle for this sample airplane or into the dead engine. If banked further than 4° into the good engine, the sideslip also increases and can lead to a fin stall, because the rudder is deflected into the good engine as well; a higher airspeed is required to avoid the fin to stall. If the Indicated Air Speed is lower than the actual V_{MCA}, i.e. anywhere below the blue V_{MCA} line, control will be lost (when the asymmetrical thrust is maximal). Dr. Jan Roskam of Kansas University wrote in his Airplane Design book on tail design: "*V_{MC} and sideslip are tied together by bank angle*".



3.6. *Conclusion from the graphs shown*: The actual V_{MCA}, that is the V_{MCA} that the pilot would experience in-flight, and the sideslip angle vary considerably with bank angle when an engine is inoperative. V_{MCA} is definitely *not* a constant value as suggested in most flight and pilot manuals. The pilot 'controls' the *actual V_{MCA}* with bank angle, rudder and thrust settings (and by propeller feathering if manual when no auto-feather is installed). The standardized V_{MCA} presented in Flight Manuals is always safe, but is valid only if the bank angle is the same as used for designing the vertical tail (while the thrust setting is high and the rudder is maximum) – i.e. during straight flight only! The bank angle for the published standardized V_{MCA} to be valid is regrettably not (yet) presented in the V_{MCA} definition and with V_{MCA} data in most Airplane Flight Manuals, although some manufacturers do present a bank angle for zero drag at the blue line V_{YSE} in one-engine performance tables or graphs (like in the PA-44 manual).

4. Flight-testing to determine V_{MCA}

4.1. All factors that have influence on V_{MCA} are set at their worst-case value (two of which are lowest weight, and the center of gravity max. aft and laterally into the inoperative engine (fuel imbalance)), because this results in the highest, worst case V_{MCA} that a pilot would ever experience in-flight, and is therefore the safest for publishing in the Airplane Flight Manual. Tests are conducted at a safe altitude (5,000 ft) and begin at an airspeed higher than the expected V_{MCA}. For new airplanes, the crew has parachutes in the seats. The fuel to the critical engine is cut. The propeller, if applicable, feathered if automatic, otherwise wind milling; the opposite engine is set at maximum thrust; both also being worst cases. Then the airspeed is slowly decreased (at a rate of 1 kt/sec), while increasing rudder and aileron to maintain straight flight, until the heading or bank angle can no longer be maintained, because either the rudder deflection is maximum, the pedal force is 150 lb (667 N), the aileron deflection is maximum, or the roll control force is the maximum, as specified in the FAR/ CS 23 and 25. The heading change is initially very slow. The airspeed at which the heading begins to change and cannot be counteracted with rudder and/or aileron is the wings-level V_{MCA} of the airplane. The test continues.

4.2. Then the bank angle is gradually increased to the bank angle for zero sideslip as used for tail design while decreasing the airspeed until again one of the rudder or aileron limitations is reached and the heading starts changing. The airspeed at which this occurs is the static V_{MCA} (for *"thereafter"* as was specified in the V_{MC} definition in Aviation Regulations, § 3.1 above). This static V_{MCA} is approximately 8 kt lower than wings-level V_{MCA} for a small twin, and up to 30 kt (!) lower for a 4-engine turbofan.
The Aviation Regulations require another test to be conducted: the dynamic V_{MCA} test, during which the critical engine is suddenly made inoperative at decreasing airspeed test points. The Aviation Regulations require that the deviations from the flight path in yaw and roll must stay within certain limits; an average pilot must be able to recover the airplane. When the deviations at the decreasing speeds reach the limitations, dynamic V_{MCA} is reached.

4.3. The highest of static and dynamic V_{MCA} (which is usually the static) will, extrapolated to sea level, be published in the Airplane Flight Manual as the (standardized) V_{MCA} of the airplane. This V_{MCA} is always safe, even when the thrust is, or is increased to maximum, provided straight flight with (usually) 5° of bank into the good engine is maintained! Remember though that flight-tests prove that the actual V_{MCA}, i.e. the V_{MCA} that the pilot experiences in-flight, increases 8 – 30 kt (depending on the type of airplane) above the published standardized V_{MCA} if the wings are returned to or kept level, and increases even further at other bank angles. If the indicated airspeed is, or decreases below the actual V_{MCA}, control will be lost; the vertical tail with rudder is simply not designed large enough to be able to maintain control.

5. V_{MCA} Definitions in Airplane Flight Manuals and flying handbooks

5.1. The V_{MCA} definition in most AFMs and pilot learning books is simply copied from FAR/ CS 23.149 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".

Is this definition correct? Yes, but only for tail sizing, flight test and certification, which is what Aviation Regulations 23 and 25 are for! This definition is definitely incorrect for an Airplane Flight Manual, a flying handbook or a multi-engine rating coursebook! There are several errors in this definition, if used for pilots, which will be briefly discussed below.

5.2. *"…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 for, and V_{MCA} is determined and is only valid with, a fixed small bank angle of 5° away from the inoperative engine. The number of degrees depend on the airplane type. The not more than 5° restriction is for the tail design engineer, for sizing the tail large enough to achieve zero sideslip for max. climb performance and limit V_{MCA} to less than 1.2 V_S. A pilot has to maintain straight flight while banking 5° into the good engine when the airspeed is as low as V_{MCA} (and the asymmetrical thrust or power is maximal), otherwise control will be lost, as was explained above.

5.3. *"Critical engine"*. V_{MCA} is determined while the critical engine is inoperative, which leads to the highest, the worst case V_{MCA}. Yet V_{MCA} definitely also applies after failure of any other engine, but is then actually a few knots lower though. *"Critical engine"* never shows up in engine emergency procedures either; there is only one such procedure. A pilot does not have to analyze the criticality of a failing engine before taking action. The word *"critical"* does therefore not belong in the definition of V_{MCA} in Airplane Flight Manuals, nor in textbooks for pilots. It is for tail design and for defining worst-case V_{MCA} flight-test conditions only (for certification). If *"critical engine"* is mentioned in a V_{MCA} definition for pilots, then other factors that affect V_{MCA} even more, like bank angle, weight, amount of rudder deflection and thrust level should be mentioned in the definition as well.

5.4. *"Suddenly made"*. An engine fails or is inoperative. A pilot never 'makes' an engine inoperative during normal operations (unless for training purposes). This condition is also for tail design and flight test for a large enough tail to recover from a sudden failure and prevent too large deviations. The published and indicated V_{MCA} applies always, not only immediately after the failure, but also during the remainder of the flight. Many accidents happen during the turn to downwind or base leg, or during final turn for landing, when the thrust is increased to maintain the glidepath. *"Suddenly made"* does not belong in the V_{MCA} definition for pilots in Flight Manuals and handbooks.

5.5. Good in this definition is: *"(thereafter) maintain straight flight"*, but this was regrettably not noticed by many mishap pilots and accident investigators, because these pilots did not maintain straight flight with 5° of favorable bank away from the inoperative engine at airspeeds near or as low as V_{MCA} while the thrust setting was high, and got killed. They turned to downwind for landing too early at too low a speed, or increased the thrust during the final turn for landing. The definition obviously did not make them well enough aware of the flight and airplane limitations or restrictions that come with V_{MCA}.

5.6. *Conclusion on this $V_{MC(A)}$ definition*. This definition is for design, flight-test and certification. This definition is inadequate for use by pilots, is even deficient for use in a Flight Manual and in airplane flying handbooks. Pilots are not made aware of the flight limitations that come with V_{MCA} and hence, use the wrong technique to fly with an inoperative engine at low speed and high thrust setting. The definition is copied inappropriately, i.e. unamended, from design and certification Aviation Regulations (which are not for pilots) and led to many catastrophic accidents following the loss of control or performance after engine failure. Two more examples follow.

5.7. **The V_{MCA} definition in AFM EMB-120** (ref. C)

"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".

5.8. The airplane is not *"controllable"* at V_{MCA} with a maximum 5° bank angle, but can only maintain straight flight at maximum power setting and at a bank angle of 5° into the good engine, because the rudder and/ or ailerons are fully deflected. V_{MCA} is not for when one engine, the *"critical engine"*, *"suddenly becomes inoperative"*, but V_{MCA} applies after failure of anyone of the engines, critical or non-critical and also applies during the remainder of a flight, not only immediately following a sudden failure. V_{MCA} is measured with the propeller in the position it automatically assumes after engine failure. If equipped with auto-feather, that system is allowed to be used, if not, the propeller is left wind milling.

5.9. *"…takeoff power"* is not the correct term either. Takeoff power might be lower than maximum power. If power is mentioned in the definition, it should be the maximum power the pilot can set when moving the throttles fully forward, which is the worst-case power for determining V_{MCA} and for maintaining control. The safety report of this accident seems to include that the original engines were replaced with more powerful ones, which would have required a larger fin or a higher V_{MCA}. This might be inappropriately solved by mentioning a (lower) takeoff power.

5.10. "*In aircraft with auto-feathering, V_{MCA} is calculated with a feathered propeller*". Why is this line added? Do not all EMB-120 versions have an auto-feather system? This line might confuse pilots and is not required. Better would be to replace with: If auto-feather fails, V_{MCA} is x kt higher than the published value.

5.11. Good seems *"The value presented represents the most critical combination of power, weight, and center of gravity",* but this list is incomplete, since there are more important variables (amount of rudder, bank angle, etc.).

5.12. *Conclusion.* This definition is definitely not correct and not well-written for an Airplane Flight Manual, for pilots. This definition is not in agreement with design and flight-test methods and conditions, and did not contribute to preventing the catastrophic accident that was discussed in Ref. C.

5.13. **The 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)".

5.14. 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 engine". "RTO power"* (= Reserve Takeoff Power, 100% TQ) seems to be maximum takeoff power (max. 5 min, OEI max. 10 min). This should be the maximum power level the pilot can set with fully advanced throttles.
Another remark is that the definition is not in Limitations Chapter 2, but in the Performance Section. V_{MCA} however, is a very important airspeed limitation for both performance and control (§ 3.5 above).

5.15. **An improved common V_{MCA} definition** for pilots in Airplane Flight Manuals and course books would be:

"V_{MCA} is the lowest calibrated airspeed at which, when an engine fails or is inoperative, it is possible to maintain straight flight only, provided a small bank angle of 3° – 5° [to be specified by manufacturer] is maintained away from the inoperative engine when the thrust is maximal".

5.16. Ii is recommended to add a **WARNING**: *"Do not turn away from the favorable bank angle at airspeeds near V_{MCA} while the thrust setting is high; performance will, and control is very likely to be lost"*, because some (actual) V_{MCA} applies all the time while an engine is inoperative, including during the final turn for landing when an engine already failed during takeoff. The requirement to add this warning is very obvious after viewing the video of the accident with a Beech Queen Air that returned for landing after failure of the left engine: https://www.youtube.com/watch?v=vTQwkKameLg. The actual V_{MCA} increased above the IAS due to the large bank angle into the dead, left engine: control was lost.

6. Takeoff speeds

6.1. *Small twins*. As discussed above, keeping the wings level increases V_{MCA} to a higher actual value; the increase is approximately 8 kt for a small twin. The takeoff speed of small twins is required (by FAR/ CS 23.51) to be 1.05 times V_{MCA} (§ 3.3 above). If V_{MCA} is 80 kt, the takeoff speed will be 84 kt. The actual V_{MCA} when the wings are level (at lift-off) will however be approximately 8 kt higher than the published V_{MCA}, ≈ 88 kt, which is even higher (!) than the takeoff speed. Refer to the second accident discussed in Ref. C where control was lost at lift-off. The 5% safety margin above V_{MCA} is obviously not large enough. Since the wings are level at liftoff, it is recommended to use at least 1.05 V_{MCA} +10 kt as a safe takeoff speed for a small twin for the case an engine might fail at lift-off. Ask the manufacturer of your airplane for the wings-level V_{MCA}, so that you can add a 5% safety margin to that speed. Following engine failure, attaining a bank angle 5° away from the inoperative engine should never be delayed, because a small bank angle is required for maintaining both performance and control (§ 3.5 above).
This bank angle requirement should be included early in engine emergency procedures as a life-saving reminder for pilots.

6.2. *Takeoff safety speed V_2*. Many airline pilots don't care about V_{MCA} anymore; V_2 is the procedural takeoff safety speed after engine failure on Part 25 transport airplanes. V_2 is supposed to be a safe speed after engine failure, but is it? Unconditionally? Let's take a look.

6.3. FAR/ EASA CS 25.107: V_2 provides a positive rate of climb and may not be less than:

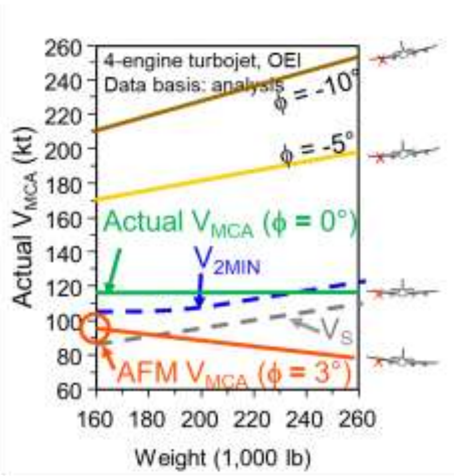
- Minimum V_2 (V_{2MIN});
- V_R + speed increment attained before reaching 35 ft; etc.

V_{2MIN} may not be less than:

- 1.10 V_{MCA} for all airplanes, and
- 1.08 stall speed (V_S) or 1.13 V_S, depending on the airplane type.

Consequently, V_{2MIN} depends on both V_S and V_{MCA}. V_S increases with weight (and a little with bank angle). The V_{MCA} used in the calculation of V_2 is a constant, is the standardized V_{MCA} published in the Flight Manual that is determined using a small bank angle and lowest weight. However, we now know that *actual* V_{MCA} varies a lot with bank angle (§ 3.5). The question can be asked whether V_2 is still a safe takeoff speed while banking, i.e. whether the applied speed increment is large enough.

6.4. To answer this question, a different V_{MCA} graph than presented in § 3.5 above is required. The graph below presents the effect of both weight and bank angle on V_{MCA}. While maintaining a small bank angle (φ = 3°) for minimizing the sideslip, the V_{MCA} increases with decreasing weight. This shows that V_{MCA} at the lowest weight, in this case 95 kt, is the worst case V_{MCA} for all weights, reason for this V_{MCA} to be published in the Airplane Flight Manual. The graph also shows the effect of weight when the airplane is banked into the dead engine. Pilots of Lockheed Hercules, Orion and Electra know a similar graph from their Performance Manual SMP-777.



6.5. As shown in the adjacent chart, actual V_{MCA} increases above V_{2MIN}, if the favorable bank (for this sample airplane 3°) is not maintained and the wings are kept level, except at weights above 240,000 lb.
Loss of control at lower weights might occur even while maintaining V_{2MIN} (of course when at max. thrust). Hence, V_2 is only a safe takeoff speed when an adequate speed increment is added above V_{2MIN} for keeping the wings level or for turning – which is up to the manufacturer or operator. Some engine failure procedures allow bank angles of 15° at V_2, other require the wings to be maintained level. This might not be a problem when the asymmetrical thrust is less than maximum and/or the speed increment is indeed large enough. For the EMB-120 (ref. C) the increment was too small.
This figure is for one engine inoperative. The actual V_{MCA} increases considerable if two engines on the same wing are inoperative.

6.6. Boeing writes in their AFM's: *"V_{MCA}'s are below V_R and V_{REF}"*, but does not specify for which bank angles. They also recommend to *"use rudder to center wheel"* after engine failure. The prime reason must that the roll assisting spoilers deploy if the flaps are down and the control wheel is turned >7°. The consequence is the increase of drag due to sideslip though, and may be also an increase of V_{MCA}. The safety margin between the actual V_{MCA} and the indicated airspeed might become very small. Also, the performance decreases due to the sideslip when the wings are kept (near) level.

6.7. *Conclusion*: The V_2 that the EMB-120 (ref. C) maintained after takeoff was definitely not high enough, was not a safe takeoff safety speed. Pilots of large Part 25 airplanes obviously also need to be (made) aware of sideslip, loss of performance and increase of V_{MCA}, not only during takeoff, but during the remainder of the flight as well.

7. Engine Emergency Procedures

Three examples of emergency procedures of different airplane types are presented below:

7.1. *Piper PA-44* engine emergency procedure. Standardized V_{MCA} = 56 KIAS, takeoff speed ≥ 59 KIAS.

Below 75 KIAS: Abort takeoff.
At 75 KIAS or above:

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

A warning is included: *"In certain combinations of aircraft weight, configuration, ambient conditions and speed, negative climb performance may result. Refer to One Engine Inoperative Climb Performance chart, Figure 5-25"*.

However, no guidance is included in this emergency procedure to maintain 5° into the good engine for both maintaining control and best climb performance. Only in the legend of the OEI Climb Performance chart the following requirement is included: "*3 – 5 deg bank toward operative engine*" (at 88 KIAS). Airplane control at V_{MCA} was obviously not a concern of the procedure writer.

7.2. *Beech 55 Baron* engine emergency procedure. Standardized V_{MCA} = 78 kt.

- 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.

Although the NOTE shows consideration with the effect of thrust on the magnitude of V_{MCA} for maintaining control, the procedure should have included the requirement for a small bank angle into the good engine to reduce the actual V_{MCA} that might be 8 kt higher than 78 kt when the wings are kept level. Nothing on maintaining straight flight in this procedure either.

7.3. *Beech King Air 100* engine failure procedure.

Affected Engine:

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

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

7.4. *Conclusion on engine emergency procedures*. Many procedures out there are inappropriate, written by people who do their best, but who are not aware of flight limitations that come with the (limited) size of the vertical tail with rudder, of the flight test techniques to determine V_{MCA} and of the effect of bank angle on V_{MCA} and the engine-out climb performance. Accident/ safety investigators didn't notice, are not aware either.
Pilots don't want to get killed for whatever reason and have the right to be protected with safe and well-developed procedures, as have their passengers.
Hence, for writing appropriate and safe procedures, not only pilots are required, but also airplane design and/or flight test engineers, together constituting a multi-disciplinary team of experts. The same of course, is applicable to writing learning books and reference manuals.

8. Mistakes in Other Publications

8.1. *Wikipedia*. I wrote the article *Minimum Control Speeds* on Wikipedia using my academic and Test Pilot School knowledge. The article was completely ruined by incompetent editors, by people *who do not know what they do not know* (is quote of FAASafety.gov). Improvements I tried to make were undone within minutes; I gave up. Don't use Wikipedia as source of knowledge.

8.2. *SKYbrary* publishes two articles on Minimum Control Speeds, neither is fully correct:

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"*) (https://www.skybrary.aero/index.php/Velocity_-_Minimum_Control_(air)_(Vmca)).

   The (underlined) errors were already discussed in § 5 above. This article requires improvement to match with airplane design and flight-test techniques.

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 wind milling, a maximum of 5 degrees of*

bank towards the good engine" (https://www.skybrary.aero/index.php/Engine_Failure_After_TakeOff_-_Light_Twin_Engine_Aircraft).

An often-made error is *"maximum gross weight"*, because V_{MCA} is determined at minimum gross weight, which is the worst-case weight for V_{MCA} through the term W·sin φ (refer to § 6.4 above). The other (underlined) errors were already discussed in § 5 above.
This article also requires improvement to match with airplane design and flight-test techniques.

9. Airport ATC Emergency Aircraft Procedures

9.1. ATC controllers usually have emergency procedures for cases when they receive emergency reports from pilots. For instance, when an engine failure is reported, the controller in his procedure is advised to expect course deviations, level-off, aircraft losing height and aircraft not being able to turn over the dead engine. The latter expectation is supported by the engine-out theory presented above in this paper because of the increase of actual V_{MCA} when banking into the dead engine. ATC should recommend and/ or approve a long straight out climb path for the airplane to gain altitude and airspeed first, before turning (to either side). Approving a turn to immediately return to the runway for landing is asking for big trouble, as accident statistics prove. When approaching with a failed engine, is it also safer to recommend a long straight-in approach and with that avoid a tight final turn during which the actual V_{MCA} may increase with power adjustments for maintaining the glide path.

9.2. Bird ingestion after lift-off in one of the engines of a Boeing 737 at Schiphol airport on 6 June 2010 for instance, became a nightmare for the pilots and controllers because the airplane turned too early and never climbed above 740 ft AGL. It was said in the newspapers that the airplane flew through the backyards of the houses on the downwind leg. Fortunately, the airplane landed safely.
For a small twin-engine airplane with one engine inoperative, it can take up to 10 to 20 minutes to reach the traffic pattern altitude, or even longer to reach a safe altitude to allow for turns.

10. Conclusions and recommendations

10.1. The question why engine failures lead to catastrophes so often can now be answered. The definition of the minimum control speed V_{MCA} and the engine emergency procedures as published in Airplane Flight Manuals and in pilot course books:

- do neither agree with airplane design methods for sizing the vertical tail, nor with the flight test techniques that are required to be used to determine V_{MCA} (flight test guides, see § 1.5), and
- the conditions/ limitations for V_{MCA} and the derived safety speeds to be valid, are not included with these speeds in most, if not all Airplane Flight Manuals and pilot course books.

It appears that the definition of V_{MCA} is simply being copied from Aviation Regulations that are for the design and certification of airplanes, and were not properly amended before publishing in Airplane Flight Manuals for use by pilots. Engine emergency procedures do not present the most important and lifesaving requirement for preventing the loss of control after engine failure, which is maintaining straight flight only while maintaining a small bank angle away from the inoperative engine while at takeoff speed. The obviously existing knowledge gap between airplane design and operations must be bridged as soon as possible to avoid any more unnecessary accidents and to further improve aviation safety.

10.2. It is recommended for the development of safety-critical procedures to make use of high level multi-disciplinary knowledge. Not only experienced operators should be involved, but also:

- Engineers who designed the airplane and/or well understand airplane design and control,
- Test pilots and/ or flight test engineers who conduct experimental flight test, and
- Less experienced pilots who are going to use the procedures.

Procedures should represent worst case conditions and be simple to comprehend while in emergency conditions. If texts are copied from text that is intended for one trade (engineers), it should be amended to the target trade (pilots), the future users.
General, world-wide accepted and understood terminology, abbreviations and acronyms in safety-critical procedures should be the same for pilots from twin engine rating training to transport category airplanes, and not include type-specific or manufacturer specific terminology, because pilots frequently transition to different airplane types during their career.

10.3. Hippocrates said long time ago: "*There are in fact two things, science and opinion. The former begets knowledge, the latter ignorance*".
It is strongly recommended to use science in safety-critical procedure development, not only opinion. Procedure writers should not believe they are right, they must ensure they are. ■