Why do airplanes crash after engine failure?

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Worldwide, accidents involving multi-engine airplanes following an engine failure still occur monthly. In the past 30 years, more than 4,200 people died in over 500 such accidents with, amongst other types, a Boeing 747 in Amsterdam, a Beech 350 in the USA, a Twin Otter in Thailand, a Beech 200 at Southend Airport in London, an MD-11 in Louisville, and a Diamond DA-42 in Australia. The questions of why such accidents occur and whether they can be prevented have not been answered adequately and with expertise until now.

If an engine on one of the wings of a multi-engine airplane fails, the airplane will yaw and subsequently move slightly sideways through the air in a sideslip, which causes high drag and severely reduces climb capability. The airplane also rolls around its longitudinal axis in the direction of the failed engine. The yaw can be counteracted with the rudder and the roll with the ailerons, provided the speed is high enough. The aerodynamic control forces generated by these control surfaces are proportional to the square of the airspeed (V^2). At low speeds, maximum control deflection may be necessary to maintain the balance of forces and moments.
Drag with the wings level is not yet minimal at that point, and a heavily loaded airplane may consequently be unable to climb immediately after takeoff. The sideslip angle, and thus the drag, can be reduced by maintaining a small bank angle of not more than 5° in the direction of the still-operating engine. Due to this small bank angle, a small side force is generated at the airplane's center of gravity, which counteracts the side forces resulting from the sideslip and hence, minimizes the sideslip angle, thereby maximizing climb performance after an engine failure. With the rudder, the pilot now only needs to counteract the engine yawing moment. The consequence of this distribution of forces and moments is that the rudder is no longer fully deflected, and there is therefore room to reduce the speed until the rudder is fully deflected again. This speed is defined in airworthiness regulations (FAR/CS 23.149) as minimum control speed (V_{MC} or V_{MCA}). V_{MC} therefore varies with the bank angle and must be measured during flight tests in straight-line flight, while maintaining a small bank angle − but not exceeding 5° − in the direction of the engine operating at maximum power. A larger bank angle than 5° increases the side force in the center of gravity and requires rudder reduction or even reversal.

The required dimensions of the control surfaces are determined during the airplane design phase, partly based on the then still theoretical V_{MC}. If the airspeed is lower than V_{MC}, or the bank angle is different from 5° in the direction of the operating engine at maximum asymmetrical power, the maximum deflected aerodynamic control surfaces can no longer generate sufficiently large control forces to prevent further yaw and roll, and control is lost. Larger control surfaces result in a lower V_{MC}, but small control surfaces are cheaper, and the airplane weight is lower. The regulations therefore also impose requirements on minimum dimensions, by limiting the maximum permissible V_{MC} during straight flight at maximum asymmetrical power and with the small 5° bank angle to 1.2 or 1.13 times the stall speed V_S (FAR/CS 23.149(b) and FAR/CS 25.149(c) respectively). However, V_{MC} varies with more variables than just the bank angle and the throttle of the operating engine; during the remainder of the flight, the actual V_{MC} can become much larger.

To make a turn, a bank angle other than the 5° is required which changes the lateral force at or near the center of gravity; this is often referred to as centripetal force. The side force creates a small sideslip angle, causing the vertical tail to yaw the nose of the airplane in the direction of the bank angle; the airplane is in a turn. If one of the engines is inoperative, rudder deflection or a sideslip is necessary to counteract the engine yawing moment. The side or lateral force generated by the rudder or sideslip influences the sum of the centripetal and other lateral forces, causing the airplane to make a turn by skidding or slipping. The flight is no longer coordinated; the controls are no longer approximately centered.
The larger the bank angle, the greater that lateral force. Such a lateral force causes the sideslip angle to increase enormously, and with it the airplane's drag, which significantly reduces climb rate. The pilot must therefore try to keep that sideslip angle as small as possible, but is dependent on the airspeed to do so. At too low speeds, the sideslip angle can no longer be counteracted by the rudder, which is too small for the purpose, and control is therefore lost. An airplane is not designed, nor needs to be, to be able to make a turn at maximum asymmetrical engine power. The saved hardware weight must be replaced by a 'heavy' procedure on paper for reducing asymmetrical power a little during a turn.

Regrettably, airplane manuals and training books do no longer inform pilots about the limitations associated with flying while an engine is inoperative. The definition of minimum control speed V_{MC} in most airplane manuals is that the airplane is still controllable at that speed. If the airplane continues to yaw and roll in the direction of the failed engine, despite fully deflected rudder, then surely one cannot say that the airplane is controllable.

The Airworthiness Regulations (FAR/CS 23/25.149) require that only straight flight be possible at the published V_{MC}, while maintaining a small bank angle of no more than 5°. This is therefore not a requirement to be able to make turns with maximum power on the operating engine, neither during takeoff, during cruising, nor during the approach for landing. If a turn is initiated with less than full throttle, and full throttle is applied during the turn, the sum of the lateral forces and the sum of the yawing moments of the engine, sideslip angle, and rudder increase, and a much higher speed is required to maintain the balance of forces and moments, which is proportional to V^2. Consequently, the actual V_{MC} increases significantly, and there is a high probability that the airplane will become uncontrollable even if the airspeed is well above the AFM-published V_{MC}.
Fifty years ago, the conditions associated with V_{MC} were still listed in airplane handbooks, but those limitations were removed by handbook and textbook writers who obviously did not understand flying with an inoperative engine very well. Accident investigators no longer know this either, and authorities did not intervene. Fortunately, this is still taught and demonstrated at test pilot schools.

Following an engine failure, the pilot will climb at the 'best rate of climb speed single engine' (V_{YSE}). For a minimal sideslip angle and thus the lowest possible drag at V_{YSE}, a bank angle slightly smaller than 5° is required − typically 3° in the direction of the good engine − because V_{YSE} is somewhat higher than V_{MC}. This bank angle should be stated in the legend of the 'One Engine Inoperative performance' charts in the AFM/POH.

The one V_{MC} published in airplane manuals is the V_{MC} measured with an aft center of gravity, the lowest possible airplane weight, a bank angle of 5° away from the failed engine, a specific flap position (usually the takeoff position), and maximum asymmetrical power. The variables mentioned represent the 'worst-cases' for V_{MC}; they result in the highest value of V_{MC} for the given configuration. Any change in these variables alters the actual V_{MC}. A more forward center of gravity lengthens the moment arm of the rudder and lowers the actual V_{MC}. A higher weight lowers V_{MC}, but only if a small bank angle is being maintained away from the failed engine. At a low weight and a bank angle of 5°, V_{MC} is highest; consequently, a low weight is the 'worst-case weight '. At this bank angle, V_{MC} decreases with higher weight, but at a bank angle other than the aforementioned 5° away from the failed engine, the sum of the side forces and yawing moments changes, and the actual V_{MC} actually increases. An airplane therefore has many V_{MC}'s, even though only one of them is published in the airplane flight manual. With that V_{MC}, it should be indicated that it applies only during straight flight at maximum power, with maximum rudder deflection, and while maintaining a bank angle of 5° in the direction away from the failed engine. Regulations do not require these 'associated conditions', being vital conditions, to be furnished with V_{MC}, which is why they are not included in most airplane flight manuals and multi-engine course books. If the throttle is reduced, V_{MC} decreases, but if full throttle is applied again during a turn, e.g., the last turn before landing (to maintain the glide path), the actual V_{MC} increases significantly and the risk of Loss of Control is extremely high, with a minimum chance of survival.

The 'critical engine' is often mentioned in airplane manuals. If the 'critical engine' fails, the corresponding V_{MC} is slightly higher than when another engine fails. However, during flight tests, it is investigated which engine is the 'critical engine', and that engine is shut down to determine the V_{MC}, which is therefore the highest − the 'worst-case' V_{MC} after either engine failure. If the or another engine, a 'non-critical engine', fails, the actual V_{MC} is slightly lower and hence, safer. Therefore, pilots do not need to analyze whether the failing engine is the 'critical engine'; there is, after all, only one engine failure procedure. 'Critical engine' should not be mentioned in an airplane flight manual.
Most AFM/POH's contain more errors regarding flying with an inoperative engine. The books are written by people who, unfortunately, do not exactly know what V_{MC} is and what the associated conditions are for the furnished V_{MC} to be valid, even though all of this can be found in the public-accessible aviation regulations.

In airspeeds listed in AFM/POH, also errors are included. V_{MC} and other speed limits are measured and published as Calibrated Airspeed (CAS). The limits published in CAS are the same for all airplanes of the same type or series. However, the Airspeed Indicators (ASI) in the different airplanes are not identical because manufacturing defects cannot be prevented during the production process, which is the reason why not only the pitot-static system must be calibrated, but also all ASIs individually (FAR/CS 23.1323). The Indicated Airspeeds (IAS) can therefore vary per airplane, even on multiple ASIs in the same cockpit. If the calibration data were applied correctly, the red radial V_{MC} line on the ASIs indicates V_{MC} in knots Indicated Airspeed KIAS). Consequently, the red V_{MC} line will appear at different speeds on airspeed indicators in airplanes of the same type/series, or even in the same cockpit if more than one ASI is installed. Therefore, reliable IAS values can never be provided in an AFM/POH applicable to all airplane of that type/series, because they are inaccurate by definition. The allowed errors may total up to as much as 9 knots! IAS is also the abbreviation for 'Inaccurate Air Speed'.

A computerized Air Data System also has errors. Besides the position error of the pitot-static system, there are also conversion errors from the measured air pressures to digital data. It should not be difficult to be able to enter the calibration data of the pitot-static system and the pressure conversion into the air data computer so that the cockpit displays show all speeds in CAS. Calibrated Airspeeds are reliable and accurate speeds also used in the AFM/POH for operational limits and performance data. The pilot no longer needs to make corrections when he sees CAS on his display; with IAS, this is still always required.

The V_{MC} furnished in AFM/POH is usually for the takeoff configuration. This V_{MC}, among other speeds, is used to calculate the takeoff rotation (V_R) and takeoff safety (V_2) speeds which are at least 1.05 and 1.1 times V_{MC}, respectively. This is not a large safety margin above $V_{MC,}$ because if the pilot keeps the wings level after liftoff, the actual V_{MC} for a small twin is already approximately 6 kt higher than the V_{MC} published in the AFM/POH. The safety margin is then already nearly consumed. The takeoff speeds are only safe when maintaining straight flight with a small 5° bank angle and at maximum power.

Accidents following engine failure occur because pilots no longer properly learn how to handle an airplane with one or more engines inoperative, and no longer are made aware of the limitations of V_{MC} and of the 'associated conditions' that apply with V_{MC}. The airplane flight manuals and textbooks, which will often have been written by pilots whose engineering knowledge extends no further than high school level, fall woefully short nowadays, a fact that was unfortunately never discovered during authoritative inspections and accident investigations. A Master's Degree is not required to learn to fly, but it is common practice to demand a higher level for teaching than that of the students. In the past 50 years, much of the knowledge relevant to safety has been lost or scrapped (due to incompetence), but fortunately not yet at test pilot schools, which were established in major aviation nations as early as the Second World War because many prototypes and their crews were lost due to a lack of engineering knowledge among the pilots operating them.

How do I prevent an accident after an engine failure?

Upon noticing a sometimes slow 'uncontrolled' yaw, immediately counter-steer with up to maximum rudder to maintain straight flight, and simultaneously bank 5° towards the good engine, to the same side as the rudder pedal. Do not allow a turn to keep V_{MC} low. If maximum rudder control is required, the speed is close to the current V_{MC} and Loss of Control is imminent. With a half-deflected rudder, V_{MC} is higher. If the airplane does not respond or does not respond adequately, the pilot has no other option than to slightly reduce the throttle of the operating engine (temporarily), which reduces the engine yawing moment. Once straight flight with the small bank angle is achieved, and the speed is higher than V_{MC}, the throttle can be fully opened again. Climb at V_{YSE} to a safe altitude, which can take a very long time. A small bank angle (3° at V_{YSE}) guarantees minimum drag and maximum Rate of Climb (ROC). Never turn at low speed and maximum asymmetrical power; climb to a safe altitude and accelerate first and/or reduce power a little before the turn (sacrificing some altitude).

Airplane also crash after engine failure because the pilots are not properly prepared for an engine failure during takeoff. They rotate at a too low Calibrated Air Speed, or allow or cannot prevent the airplane from yawing and rolling because it is not counteracted with full rudder and/or roll control, resulting in a loss of control. It cannot be repeated often enough: the V_{MC} published in the AFM/POH (in KCAS) is only valid during straight flight when also a small bank angle, but not exceeding 5°, is maintained in the direction of the good engine, that is, to the same side as the rudder. Then the actual V_{MC} is lowest and the sideslip angle is also smallest, and thus the ROC is maximum. Consequently, a climb to a safe altitude should be possible, provided the airplane is not too heavy. If a turn is necessary, accelerate to at least 20 kt (for a small twin engine airplane) above V_{MC}, or reduce the power of the operating engine slightly so that less rudder control is required, and also limit the bank angle. Flight with an engine failure is not coordinated; rudder control remains necessary because of the asymmetrical engine power. If the bank angle during a turn towards the good engine exceeds approximately 8°, the rudder must be released, and with a larger bank angle, it must even be deflected to the other side to maintain the balance of forces and moments. Therefore, ensure sufficient speed (and altitude). After a turn, and after maintaining a small bank angle again, the throttle can be opened fully again, if necessary.
V_{MC} remains a factor throughout the entire flight with an inoperative engine. Turns with full asymmetrical engine power are discouraged; during the final turn before landing, this is even fatal.
This procedure should be repeated during every takeoff briefing so that it is fresh in mind.

See the Downloads, V_{MCA}, Accident, and Links pages on the website https://www.avioconsult.com for much more data, papers, and reviews on the subject. Fly safely.

List For Further Reading

1. This paper can be downloaded here: https://www.avioconsult.com/downloads/Why do airplanes crash after engine failure.pdf.
2. V_{MCA} in Regulations and Flight Test, a summary. https://www.avioconsult.com/downloads/Background VMC(A) Regulations and Flight Test.pdf.
3. TAS, CAS, IAS, and V_{MC} explained. https://www.avioconsult.com/downloads/Airspeeds TAS, CAS, IAS, VMC Explained.pdf.
4. A 42 min. video lecture on V_{MC}, including two accidents. https://youtu.be/Wbu6X0hSnBY. The slides and script: https://www.avioconsult.com/downloads/Vmca slides + script YouTube video AvioConsult.pdf.
5. The effect of Bank Angle and Weight on V_{MCA}. https://www.avioconsult.com/downloads/Effect of Bank Angle and Weight on Vmca.pdf.
6. Airplane Control and Analysis of Accidents after Engine Failure. https://www.avioconsult.com/downloads/Airplane Control and Analysis of Accidents after Engine Failure.pdf.
7. Download suggestions for adding pen and ink changes to your AFM and/or checklist. https://www.avioconsult.com/downloads/Pen and Ink changes to AFM or POH.pdf.
8. Limited Review DA 42 Airplane Flight Manual. https://www.avioconsult.com/downloads/Review DA 42 Airplane Flight Manual.pdf.
9. Limited Review Pilot Operating Handbook/AFM DHC-6. https://www.avioconsult.com/downloads/DHC-6 POH - AFM Limited review.pdf.
10. Limited Review Pilot Operating Handbook Beechcraft Super King Air B200(C). https://www.avioconsult.com/downloads/Beechcraft SKA B200 & B200C POH review.pdf.
11. Pitot-Statics and the Standard Atmosphere, 4th edition (Jul 2020). https://apps.dtic.mil/sti/pdfs/AD1115005.pdf.
12. Flying Qualities Textbook, Volume II, Part 2, 1986. USAF Test Pilot School. (Chapter 11 = Asymmetrical power). https://ia801001.us.archive.org/17/items/DTIC_ADA170960/DTIC_ADA170960.pdf.
13. FAA Flight Test Guide AC 23-8C Part 23 Airplanes (Controllability and Maneuverability, including VMCA testing, in Section 4.4 § 23.149). https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_23-8C.pdf.

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