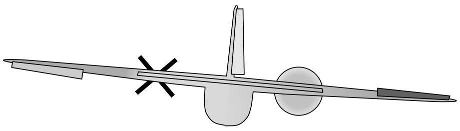

# Airplane Control

# and

# Analysis of Accidents

# after

# Engine Failure

Multi-Engine Airplanes

**Harry Horlings**

Avio*Consult*

The Report Documentation Form 298 is on the last page.

## Airplane Control and Analysis of Accidents after Engine Failure

This report is an initiative of and is written by Harry Horlings, Avio*Consult*. An oral presentation to accompany this report is available as well. The first report on this subject originates from Nov. 1999; accident analyses were added May 2012.
Please check the downloads page of website https://www.avioconsult.com for the most recent version.

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## LIST OF ABBREVIATIONS AND SYMBOLS

| | |
|---|---|
| $\alpha$ | Angle of attack |
| $\beta$ | Sideslip angle |
| $\rho$ | Air density |
| $\phi$ | Bank angle |
| $\theta$ | Pitch angle |
| $\delta_a$ | Aileron deflection angle |
| $\alpha_b$ | Angle of attack propeller blade |
| $\delta_r$ | Rudder deflection angle |
| AC | Advisory Circular |
| ADI | Attitude & Direction Indicator |
| AFM | Airplane Flight Manual |
| AGL | Above Ground Level |
| ATPL | Airline Transport Pilot License |
| $C_{L\alpha}$ | Lift coefficient due to angle of attack $\alpha$ |
| CPL | Commercial Pilot License |
| CS | Certification Specification (EASA) |
| D | Drag |
| EASA | European Aviation Safety Agency |
| FAA | Federal Aviation Administration |
| FAR | Federal Aviation Regulation |
| FD | Flight Director |
| fpm | feet per minute |
| ft | foot, or feet |
| FCOM | Flight Crew Operating Manual |
| FCTM | Flight Crew Training Manual |
| FTG | Flight Test Guide |
| ICR | Inappropriate Crew Response |
| IFR | Instrument Flight Rules |
| IMC | Instrument Meteorological Conditions |
| JAR | Joint Airworthiness Requirements |
| KCAS | Knots Calibrated Airspeed |
| kg | kilogram |
| KIAS | Knots Indicated Airspeed |
| kt | knot or knots |
| L | Lift |
| L | Rolling moment |
| $L_\beta$ | Rolling moment due to sideslip angle $\beta$ |
| $L_{\delta a}$ | Rolling moment due to aileron deflection $\delta_a$ |
| lb | Pound or pounds |
| $L_T$ | Rolling moment due to (asymmetric) thrust T |
| MCT | Maximum Continuous Thrust |
| MTOW | Maximum Take Off Weight |
| N | Yawing moment |
| N | Newton |
| $N_\beta$ | Yawing moment due to sideslip angle $\beta$ |
| $N_{\delta a}$ | Yawing moment due to aileron deflection $\delta a$ |
| $N_{\delta r}$ | Yawing moment due to rudder deflection $\delta_r$ |
| $N_T$ | Yawing moment due to (asymmetric) thrust T |
| NTS | Negative Torque Sensing System |
| OEI | One Engine Inoperative |
| PFD | Primary Flight Display |
| POH | Pilot Operating Handbook |
| PSM | Propulsion System Malfunction |
| QRH | Quick Reference Handbook (checklist) |
| RNLAF | Royal Netherlands Air Force |
| S | Surface area |
| SID | Standard Instrument Departure |
| SL | Sea Level |
| T(#) | Thrust of propeller or turbofan/-jet (engine No. #) |
| $T \cdot \sin\beta$ | Thrust bending side force due to sideslip |
| TEI | Two Engines Inoperative |
| TPS | Test Pilot School |
| USAF | United States Air Force |
| V | Velocity or speed |
| $V_1$ | Decision speed |
| $V_2$ | Takeoff Safety Speed |
| $V_{2MIN}$ | Minimum Takeoff Safety Speed |
| $V_{EF}$ | Engine Failure Speed |
| $V_{MC}$ | Minimum Control Speed |
| $V_{MCA}$ | Minimum Control Speed in the Air (or Airborne) |
| $V_{MCA1}$ | Minimum Control Speed in the Air, OEI |
| $V_{MCA2}$ | Minimum Control Speed in the Air, TEI |
| $V_{MCG}$ | Minimum Control Speed on the Ground |
| $V_{MCL}$ | Minimum Control Speed Landing configuration |
| $V_{MCL1}$ | Minimum Control Speed Landing config., OEI |
| $V_{MCL2}$ | Minimum Control Speed Landing config., TEI |
| $V_R$ | Rotation speed |
| $V_S$ | Stall speed |
| $V_{S0}$ | Stall speed, landing configuration |
| $V_{S1}$ | Stall speed, specified configuration |
| $V_{SR}$ | Reference stall speed |
| $V_{SSE}$ | Safe intentional OEI speed (FAR/ CS 23.149) |
| $V_{XSE}$ | Speed for best single engine angle of climb/ range |
| $V_{YSE}$ | Speed for best single engine rate of climb |
| W | Weight |
| $W \cdot \sin\phi$ | Side force due to Weight W and bank angle $\phi$ |
| $Y_\beta$ | Side force due to sideslip angle $\beta$ |
| $Y_{\delta r}$ | Side force due to rudder deflection $\delta_r$ |
| x | x body axis (to front and aft, thru cg) |
| y | y body axis (out wings, thru cg) |
| z | z body axis (down out of bottom, thru cg) |

# 1. INTRODUCTION

1.1. Engine failures or, in general, propulsion system malfunctions of multi-engine airplanes continue to result in serious incidents and fatal accidents all across the globe quite frequently, although the airplanes were designed, flight tested and certificated to continue to fly safely, both immediately following such a malfunction as well as during the remainder of the flight while an engine is inoperative. Between January 1996 and 2015, more than 400 accidents were reported on the Internet (by only a few Western countries) causing more than 3,500 casualties (ref. 1). After reviewing many accident investigation reports, it was noticed that most flight instructors, (airline) pilots and accident investigators explain the minimum control speed ($V_{MC}$), today mostly abbreviated $V_{MCA}$ ($V_{MC}$ in the Air), and the remaining performance after engine failure of multi-engine airplanes in a different way than airplane design engineers, experimental test pilots and flight test engineers do. This difference in interpretation has, to the opinion of the author of this report, resulted in many incidents and catastrophic accidents because of the loss of control and/or decrease of performance following a propulsion system malfunction or while an engine was inoperative, and in incorrect and incomplete conclusions and recommendations in accident investigation reports. A separate, less scientific paper (ref. 2) was written for CPL and ATPL pilots and student pilots on Control and Performance during Asymmetrical Powered Flight that complies with published Learning Objectives. For viewing, rather than reading, a video is published on YouTube, ref. 3. Reports and video assume the readers and viewers have a basic understanding of airplane control and performance.

1.2. The objective of this report is to bridge the obviously existing knowledge gap on the subject of airplane control after engine failure between the design engineers, experimental test pilots and flight-test engineers – supported by aviation regulations – on one side, and other pilots, flight instructors as well as airplane accident investigators on the other side. This report briefly describes almost all that pilots and accident investigators should know about the controllability of an airplane after engine failure or while an engine is inoperative, on the ground and in the air. Included are brief descriptions of the design methods of the vertical tail and of the experimental flight-tests to determine the minimum control speeds in the air and on the ground to be able to improve the understanding of the controllability of an engine-out multi-engine airplane and the limiting airspeeds. Some imperfections in Airplane Flight Manuals (AFM) and on required placards in cockpits of Part 23 airplanes, that relate to controllability and performance after engine failure, are discussed as well, as are the real values of rotation speed $V_R$ and takeoff safety speed $V_2$ of Part 23 Commuter and Part 25 airplanes. In § 8 and § 9, flight-test knowledge-based analyses of six accidents after engine failure are presented using data out of accident and incident investigation reports, both with and without available data of Flight Data Recorders.

1.3. The author of this report is a graduate Fight Test Engineer of the USAF Test Pilot School (TPS), Edwards Air Force Base, CA, Class 85A. During the one-year course, all aspects of experimental flight-testing and evaluation of aircraft and its systems are taught to the students (pilots and engineers) for obtaining the qualification/ endorsement to prepare and conduct experimental flight-testing of all types of airplanes (and simulators), military or civil, single, or multi-engine during first flights, qualitative evaluations and flight-test programs following alterations or modifications of airplanes. The TPS entry level in 1985 was a Master of Science degree in engineering or a Bachelor and an entrance exam, and for pilots also 1,000 flight hours. About 50% of the time were academic hours, the remaining time was for actual flight-test training and gaining flight-test experience in over 25 different types of aircraft and simulators, and of course for preparing test-flights, and study for 32 exams and many check rides throughout the year.
The training included the theory and actual engine-out flight-testing of propeller and turbojet/ fan airplanes during and following the intentional shut down in the air of one engine on two-engine airplanes (n-1), and of one and two engines on the same wing on four-engine airplanes (n-1 resp. n-2). The acquired flight-test data of such flight-tests are used to calculate the dynamic and static Minimum Control speeds in the Air ($V_{MCA}$) for publishing in the limitations section of AFM’s.

1.4. This report was written using Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA) Flight Test Guides (FTG), ref.'s 3, 5, 6, Federal Aviation Regulations (FAR), ref. 7 and EASA Certification Specifications (CS), ref. 6, aeronautical university series of books by Dr. Jan Roskam, University of Kansas, ref. 8, course books of USAF TPS, ref. 9, Empire TPS, UK, ref. 10, and US Naval TPS, ref. 11. More and alternate links can be found on the Links page of the website of Avio*Consult*: https://www.avioconsult.com.

1.5. This report does not include the methods for the actual investigation of the wreckage debris, but only analyses FDR and other data of investigations. The data that should be available and used for analyzing control and performance of airplanes following propulsion system malfunction related incidents or accidents will also be discussed. Although text and figures mainly present propeller airplanes, the theory applies to turbojet- and turbofan-equipped airplanes as well.

1.6. After reading this report, pilots will improve airplane control after engine failure, and airplane accident or air safety investigators will be able to improve the analysis of airplane accidents following a propulsion system malfunction. The engine-out performance and the real value of the $V_{MC}$'s, that are published in the AFMs of multi-engine airplanes, as well as the conditions for which $V_{MCA}$ is valid, will be understood much better, which is of vital importance for including appropriate conclusions and recommendations in the accident investigation/ safety reports. These reports will become much more valuable for preventing propulsion system malfunction related accidents and incidents in the future.

## 2. AIRPLANE CONTROL WHILE AN ENGINE IS INOPERATIVE

### 2.1. Forces and moments acting on an airplane

2.1.1. An airplane in-flight has six degrees of freedom, it can accelerate and move forward and aft, sideways left and right, up, and down and also rotate about three axes. The translational and rotational motions are not only caused by external forces that act on the airplane, but also due to aerodynamic forces and moments caused by control inputs of rudder, aileron, and elevator in the three axes and by the propulsion systems and its malfunctions or other failures of the airplane itself. These forces and moments are vector quantities that have a direction and a magnitude. A *force* moves a body in the direction of the force, a *moment* (is a force × its perpendicular distance – called arm – from the center of gravity) produces a rotation of a body about an axis. It is unavoidable to mention forces and moments when analyzing airplane control when an engine fails or is inoperative.

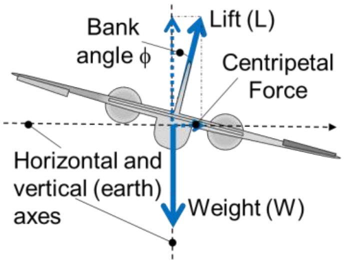

Figure 1. Centripetal force as component of Lift in flat earth referenced coordinate system.

2.1.2. There are several coordinate systems in use to describe forces and moments that act on an airplane. Pilots are used to explain turns using the centripetal force, which is the horizontal component of the lift generated by the wings in the flat earth referenced coordinate system (that is fixed to the aircraft's center of mass – center of gravity), as shown in Figure 1, which is similar to the inertial system. The lift of the wings and the drag are, by definition, perpendicular resp. parallel to the velocity vector. As shown in Figure 1, the weight of the airplane acts along the vertical axis (towards the center of the earth) and hence has no side force (lateral) component in this axis system. The vertical component of the lift ($L \cdot \cos \phi$) must equal the weight to maintain level flight. There is nothing wrong with using this axis system for calculating turns, as long as the airplane is healthy and the flight is coordinated. But in this coordinate system, the lateral-directional forces, and the rolling and yawing moments about the horizontal and vertical (earth) axes cannot easily be expressed and analyzed. These forces and the resulting moments though, are needed during the analysis of the controllability after engine failure, which is the subject of this report. Therefore, in order to describe and explain the controllability of an airplane after a propulsion system malfunction, another coordinate system is a lot easier to use: the *body-fixed coordinate system* (Figure 2).

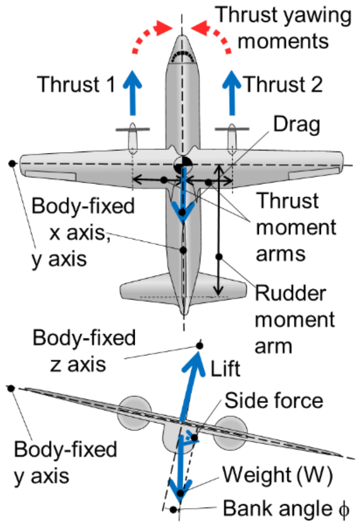

Figure 2. Forces and moments, including side force as component of weight, in the body-fixed axis system.

2.1.3. As shown in Figure 2, the three body axes are fixed to the airframe, hence move with it and originate also in the center of gravity; the positive x-axis points toward the front, the positive z-axis points down the bottom and the positive y-axis points to the right, parallel to the wings; all three axes are perpendicular to each other.

Figure 2 shows that the lift of the wings acts along the z-body axis and therefore has no side force, no lateral component in this axis system. The weight acts towards the center of the earth and has components in the z and y body axes. The lift must equal the z-axis component of the weight ($W \cdot \cos \phi$) to be able to maintain level flight. The component $W \cdot \sin \phi$ of the weight provides for a side force in the direction of the y-body axis.

The body-axis system allows the fairly easy analysis of the effects of rudder and aileron inputs, of sideslip angle $\beta$, of weight W and bank angle $\phi$ and of asymmetrical thrust T on the lateral and directional forces and moments that act on the airplane, reason why this coordinate system is also used by aeronautical engineers during designing the airplane and by experimental test pilots to prepare (engine-out) flight testing.

2.1.4. In this report, only the most relevant forces and moments, that act in the body-fixed axes on an airplane and that play a significant role for controlling an airplane laterally and directionally before and after engine failure, will be discussed.

## 2.2. Equilibrium of forces and moments

Required for equilibrium (trimmed) flight condition:
Sum of all forces = 0
AND
Sum of all moments = 0

2.2.1. For *equilibrium* during straight flight, i.e. for steady straight trimmed flight (trims + manual control inputs), balance is required of all forces and of all moments that act on an airplane; both the sum of all forces and the sum of all moments (in their respective axis) need to be zero, not only when all engines are operative, but also if one or more engines are inoperative. A change in any force will change the sum of forces and moments and hence, results in an acceleration in the direction of the new resultant force that only ends when both the sum of all forces and the sum of all moments are again zero. Only then, a new equilibrium, a new balance of forces and moments, is achieved. If the sum of all forces and the sum of all moments cannot become zero anymore, then the airplane continues to accelerate and/ or rotate; the airplane is *out of control*.

Below, first the forces, moments and motions after engine failure are briefly explained, then the tail design considerations of the engineer responsible for designing and sizing the vertical tail at the drawing board, followed by several options for maintaining equilibrium and safe flight with an inoperative engine.

In the figures presented in this report, not all of the forces and moments that act on an airplane are shown; the ones shown are not to scale.

## 2.3. Forces, moments, and motions after engine failure in-flight

2.3.1. At the instant an engine fails, the sum of the forces and the sum of the moments are no longer zero. In general, if one or more of the forces or moments that act on an airplane change after engine failure, the airplane starts accelerating and/ or rotating in the direction of the resultant force and moment. The motions continue until both the sum of the forces and the sum of the moments that act on the airplane are again zero and some kind of balance/ equilibrium is established, which might not be the balance, i.e. the attitude or flight path that the pilot wants (Figure 3). The pilot has influence on the motions by using the aerodynamic controls in the three axes (as long as the airspeed is high enough) and by changing the thrust of the engine opposite of the failed engine.

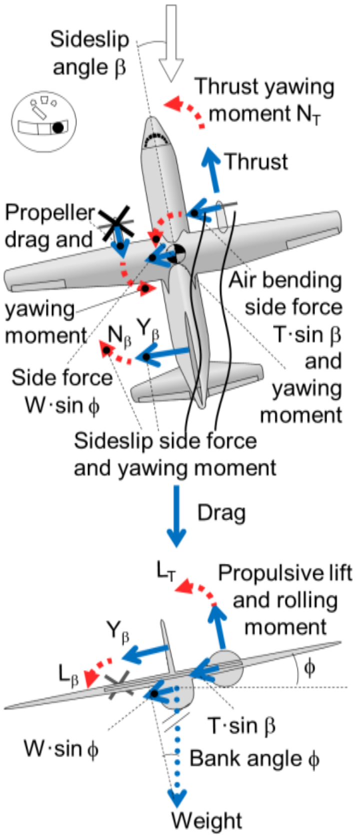

Figure 3. Lateral forces and moments (in the y body axis) immediately after engine failure – propeller airplane.

2.3.2. After engine failure, the power or thrust distribution on the airplane is no longer symmetrical. The asymmetrical thrust of engine #2 in this case (Figure 3) generates a yawing moment ($N_T$) that, if the airspeed is low and the thrust is high, yaws the airplane through a large angle in the direction of the failed or inoperative engine. The yaw rate is not always large and might, in the dark or while in IMC, be undetected for a while. The drag of the propeller of the failed engine, unless feathered, adds to the asymmetrical thrust T, as does the *spillage drag* of a turbojet or -fan engine, and generate destabilizing yawing moments (increases the yawing moment, makes it worse). A sideslip $\beta$ develops, which instantaneously increases the drag (D) and hence decreases (climb) performance and airspeed. Due to sideslip $\beta$, the vertical tail generates side force $Y_\beta$ that is stabilizing because the moment $N_\beta$ that this force generates, limits the sideslip to a certain value (weathercock stability).

The sideslip also generates a destabilizing side force $T \cdot \sin \beta$ (in front of the center of gravity) generated by airflow bending of all (operative) propeller discs or turbojet/fan inlets, as long as the thrust setting is high.

2.3.3. Not only yawing moments act on the airplane after engine failure. On propeller airplanes, the blown wing section(s) behind the propeller(s) of the operative engine(s) produce more propulsive lift than the other wing. This generates a rolling moment ($L_T$) into the failed or inoperative engine. Sideslip also generates a rolling moment $L_\beta$ caused by blanking of a wing from the free airstream, in this case the left wing, and by the relative wind blowing under the high wing, called the dihedral effect (upward angle of the wings). The asymmetrical slipstream of the propeller will also have effect on the vertical tail or fin as sideslip β increases. The last (but not least) side force discussed here is the side force due to banking. While banking with bank angle ϕ, a component of the weight W of the airplane acts as side force $W\cdot\sin\phi$ in the center of gravity of the airplane in the direction of banking (in the body-fixed y axis). As mentioned before, the wing lift has no lateral component in the body axis system.

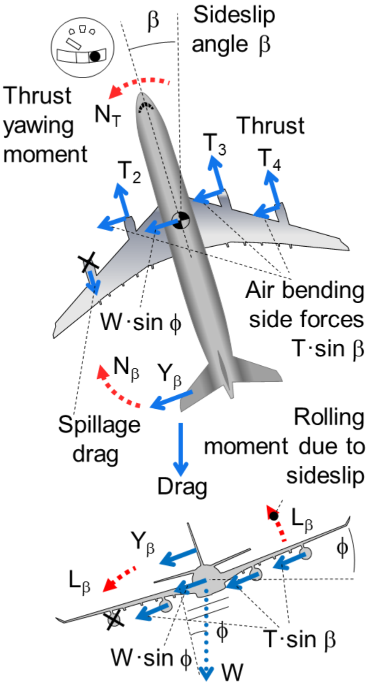

Figure 4. Lateral forces and moments immediately after engine #1 failure – turbofan, in the y body axis.

2.3.4. Turbofans mounted underneath the wings (Figure 4) do not produce propulsive lift. The swept wings of these types of airplane however, generate a larger rolling moment $L_\beta$ due to sideslip and the resulting larger frontal area of the upwind swept wing and the reduced frontal area and blanking by the fuselage of the downwind wing.

2.3.5. The sum, the resultant of the side forces will start accelerating and consequently displacing the airplane sideward to the dead engine side. The flight path will be less climbing or even descending because of the increase of the drag. The sideward acceleration causes the relative wind and sideslip angle β to reverse to the other side and the weathercock stability $N_\beta$ will start to turn the nose of the airplane to the ground. This of course is just one possible scenario; nevertheless, this actually took place following several engine failures, including a Boeing 747 in Amsterdam in 1992. The crews could not put an end to this out-of-control situation because the aerodynamic control power of the lateral and directional control surfaces was not large enough due to a too low airspeed. The control power that the vertical tail with rudder can develop is not unlimited, as will be discussed below.

2.3.6. Without appropriate crew response to a propulsion system malfunction, the rolling will also continue under influence of the dihedral of the wings or, on propeller airplanes, under influence of the asymmetrical propulsive lift despite opposite aileron control input. Ailerons might not be effective enough to counteract the rolling moment if the airspeed is low and the sideslip angle is large. On some airplanes, *spoilers* might kick in to assist the roll control as soon as the aileron control wheel is exceeding a fixed control wheel angle (often 7 degrees). Although this generates a stabilizing yawing moment, it increases the drag as well, and deteriorates the already reduced climb performance even further.
Most takeoff engine failures regrettably end with a collision with the ground (unless the pilots did read this report).

2.3.7. The pitching moment change caused by engine failure is usually small and the horizontal tail and elevator are dimensioned to be able to handle the change easily and maintain control of the airspeed. Furthermore, the airspeed is always to be higher than a factor 1.13 to 1.3 times the stall speed (depending on the flight phase), so the probability of an aerodynamic stall and loss of pitch control is small. Therefore, pitch control is not further discussed.

2.3.8. ***Summary***. After an engine failure during takeoff or go-around, large changes in lateral and directional forces and moments occur due to the high asymmetrical engine thrust and the limited control power of the aerodynamic control surfaces at low speed. The resulting dynamics and motions can be very slow, but also more violent. Motions will continue until a new balance of forces and moments is established. If both the airspeed and the altitude are low, this might never happen while the airplane is still in the air. Turbofans, after failure, take longer to spool down, so the dynamics of an engine failure might not be as violent as the dynamics after an engine failure on turboprop airplanes. In any engine failure case, the crew response to a propulsion system malfunction must be rapid and appropriate.

## 2.4. Tail design and birth of minimum control speed $V_{MCA}$

2.4.1. The vertical tail with rudder is the only aerodynamic control surface available to a pilot to counteract asymmetrical thrust. Closing the throttles also removes the thrust asymmetry, but then no performance is left. During the design phase of a multi-engine airplane, the design engineer faces the challenge of designing a vertical tail with rudder that will be able to generate the aerodynamic force required to counteract the large asymmetrical yawing moment caused by the remaining engine(s) after failure of one or more engine(s) and by other forces. The vertical tail should be as small as possible to save cost and materiel (weight).

The power or thrust (T) of engines (and propellers) varies with the engine characteristics and mostly also with air temperature and pressure altitude (density). The maximum asymmetrical thrust yawing moment ($N_T$) that is to be counteracted by the vertical tail with rudder ($N_{\delta r}$) is, on two-engine airplanes, the yawing moment after the failure of the critical engine and, on four or more engine airplanes, the yawing moment after the failure of two engines, the critical engine as well as the engine inboard of it on the same wing. Other yawing moments such as caused by sideslip ($T \cdot \sin \beta$) and aileron deflection ($\delta_a$) should be included as well. The remaining engine(s) is/ are assumed to produce the maximum thrust the pilot can set from the cockpit. The failure of the critical engine leads to the largest yawing moments as compared to the other engine(s). Critical engine is further explained in § 4.5 below.

The lift or force that an aerodynamic airfoil produces can be determined with the *lift equation* $\frac{1}{2}\rho V^2 S C_{L\alpha}$ in which $\rho$ is the air density, V is the airspeed and S is the surface area of the aerodynamic airfoil. The lift coefficient $C_{L\alpha}$ does not only depend on the shape and other characteristics of the aerodynamic airfoil, but also on its angle of attack $\alpha$ to the incoming free air stream. The lift equation does not only apply to 'horizontal' airfoils, but to the vertical tail with rudder as well. Airspeed V has a significant (quadratic) influence on the generated lift or force.

2.4.2. When the airspeed decreases or is low, the rudder deflection has to increase to continue to balance the asymmetrical engine thrust, because the thrust itself does not change if temperature and altitude do not change. However, the rudder has a maximum mechanical deflection angle and the vertical tail has a fixed size. In addition, FAR and CS 23 and 25 (ref.'s 6, 7) present control force limits for both rudder (civil 150 lb, military 180 lb) and ailerons (25 lb); these will be used in § 5.2.4 below.

Consequently, there must be a lowest speed at which the fuselage, vertical tail and rudder generate a side force that is just high enough to counteract the asymmetrical thrust. This lowest airspeed at which straight flight can just be maintained, or at which either the lateral or the directional control deflection or force limit is reached, is the *minimum control speed airborne*, or 'in the air', abbreviated $V_{MCA}$. This is only a *general definition* of $V_{MCA}$, because there are many variables that have influence on $V_{MCA}$. This report explains that almost any configuration of an airplane has its own $V_{MCA}$. On some airplanes, the maximum aileron deflection or control force is reached before the rudder deflection is maximum. Other airplanes might stall before $V_{MCA}$ is reached (during deceleration). Contrary to civil airplanes, for military airplanes an aileron control power limit (75%) does exist besides an aileron control force limit (25 lb). On some airplanes, a rudder boosting system is used to increase the rudder deflection per pound (unit) of pedal pressure (§ 4.12).

2.4.3. Operators would like the airplane to have a takeoff speed as low as possible to enable operations from short runways or with higher payloads from longer runways. The takeoff speed of Part 23 airplanes and the rotation speed $V_R$ of Part 23 Commuter and Part 25 airplanes is equal to or greater than 1.05 $V_{MCA}$ (or 1.10 $V_S$, FAR/ CS 23/25.107). $V_{MCA}$ should therefore be as low as possible, hence the vertical tail large, i.e. heavy and more expensive (Figure 5).

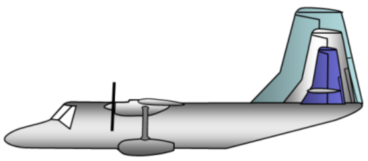

Figure 5. How large should the vertical tail be made?

2.4.4. There is also a requirement for a minimum tail (fin) size. The smaller the vertical tail, the higher the airspeed will have to be to continue to provide a large enough yawing moment for counteracting the asymmetrical thrust and other adverse yawing moments, such as *spillage drag* of a turbofan engine (with a stuck fan), drag of a non-feathered propeller, sideslip, etc. Therefore, a maximum allowable $V_{MCA}$ exists: FAR/ CS 23 and 25 require that $V_{MCA}$ must be lower than 1.2 $V_S$ resp. 1.13 $V_S$, $V_S$ being the lowest stall speed.

For designing the smallest possible tail while $V_{MCA}$ stays below that speed limit, the design engineer has to reduce the required rudder generated side force as much as possible. This can easily be achieved by intentionally using a bank angle of a few degrees away from the inoperative engine. This small bank angle adds a component of the airplane gross weight (W·sin ϕ) as a side force to the other side forces that act on the airplane in the direction of banking (refer to Figure 3 and Figure 4). FAR/CS 23.149, 25.149 and equivalent allow the design engineer to use a bank angle of maximum 5 degrees for sizing the vertical tail with rudder. Because the design engineer would like a vertical tail as small as possible to save manufacturing cost and weight, the bank angle related side force W·sin ϕ is always used during sizing the vertical tail.

**CAUTION**
**FROM THE AIRPLANE DESIGNERS DRAWING BOARD**
The published and indicated standardized $V_{MCA}$ is valid only while maintaining a small bank angle away from the inoperative engine, i.e. during straight flight only, while the thrust is maximal, definitely not during turns.

2.4.5. This design technique, i.e. the use of side force W·sin ϕ for balancing the side forces while an engine is inoperative, has consequences for pilots for maintaining control after engine failure. The vertical tail including rudder of a multi-engine airplane is designed and built to a size that generates just a large enough side force for maintaining straight flight after engine failure, while banking a few, up to a maximum of 5° away from the inoperative engine. The design engineer most often opts for a fixed bank angle between 3° and 5° away from the inoperative engine for the sideslip angle β to be zero, and hence for maximum remaining climb performance. Dr. J. Roskam (KU) discusses this design process in detail in ref. 8.
It is important to remember that tail design engineers assume straight flight at airspeed $V_{MCA}$ i.a.w. FAR/CS 23.149 and 25.149, and apply a small bank angle during the tail design process, because this reduces the required size of the vertical tail with rudder (saving money and weight), and reduces the sideslip, hence drag, for maximum remaining rate of climb.

2.4.6. The exact bank angle to be used during tail design can be analyzed and calculated using the equations of motion with the stability derivatives of the airplane. For flight test purposes the equations can be simplified by assuming small angles, and unaccelerated, 1 g, constant heading flight and then used to predict $V_{MCA}$, β, $\delta_a$ and $\delta_r$ for varying weight (mg) and bank angle (ϕ). Inertia terms are constant and the aerodynamic forces and moments depend only upon the relative orientation angles α and β. These simplified lateral-directional equations are shown (for information only) in Figure 6 below, but were solved to calculate the figures below for a turbojet/fan airplane (ref. 13). The equations are not valid for a propeller airplane because a propulsive lift term is not included.

$$C_{y_\beta}\beta_{trim} + C_{y_{\delta_a}}\delta_{a_{trim}} + C_{y_{\delta_r}}\delta_{r_{trim}} = \frac{-F_y}{\bar{q}S} - \frac{mg\Phi}{\bar{q}S} - C_{y_0}$$

$$C_{l_\beta}\beta_{trim} + C_{l_{\delta_a}}\delta_{a_{trim}} + C_{l_{\delta_r}}\delta_{r_{trim}} = \frac{-L_T}{\bar{q}Sb} - C_{l_0}$$

$$C_{n_\beta}\beta_{trim} + C_{n_{\delta_a}}\delta_{a_{trim}} + C_{n_{\delta_r}}\delta_{r_{trim}} = \frac{-N_T}{\bar{q}Sb} - C_{n_0}$$

Figure 6. The three simplified linear simultaneous lateral-directional equations.

The term mgϕ, for small bank angles in radians, in the first, the side force, equation ($F_Y$ – right hand side) is the same as W·sin ϕ with ϕ in degrees. Noteworthy is that the airspeed (dynamic pressure q), wing area (S), wingspan (b), aileron ($\delta_a$) and rudder ($\delta_r$) deflections and sideslip (β) not only have effect in the side force equation, but also in the roll (2nd) and yaw (3rd) equations, of which the magnitudes are determined by the C-coefficients, that the manufacturer knows or that can be determined during flight-testing. $L_T$ is the aerodynamic rolling moment about the x-axis and $N_T$ is the aerodynamic yawing moment about the z-axis, both due to Thrust (T). Suffix trim means the variable is for equilibrium, steady state trimmed flight.

2.4.7. These simultaneous linear equations should not be solved individually. Since there are four variables in these three equations (ϕ, δa, δr and β), many states of equilibrium are possible, but only the cases in which ϕ = 0° and β = 0° are of most interest. Zero bank angle is easy to fly (IMC) and zero sideslip causes the total drag of the airplane to be minimal, which is favorable to the remaining climb performance after engine failure.

2.4.8. Figure 7 below shows the results of solving the three equations with the coefficients of a sample 4-engine swept wing airplane, which is described in detail in ref.'s 12 and 13. The top graph presents the actual minimum speeds (i.e. actual $V_{MCA}$'s) at which equilibrium of forces and moments is possible for bank angles into and away from the inoperative engine. The bottom graph presents, besides aileron ($\delta_a$) and rudder deflection ($\delta_r$), also sideslip angle β. The design engineer selects the exact bank angle for which the sideslip angle is as small as possible, therewith reducing the *drag* and maximizing the remaining climb performance when an engine is inoperative. For this example, a bank angle of 4° was chosen; sideslip β will then be zero. The expected $V_{MCA}$ with that bank angle will be approximately 85 kt, which is lower than 1.2 $V_S$ as required by Regulations.

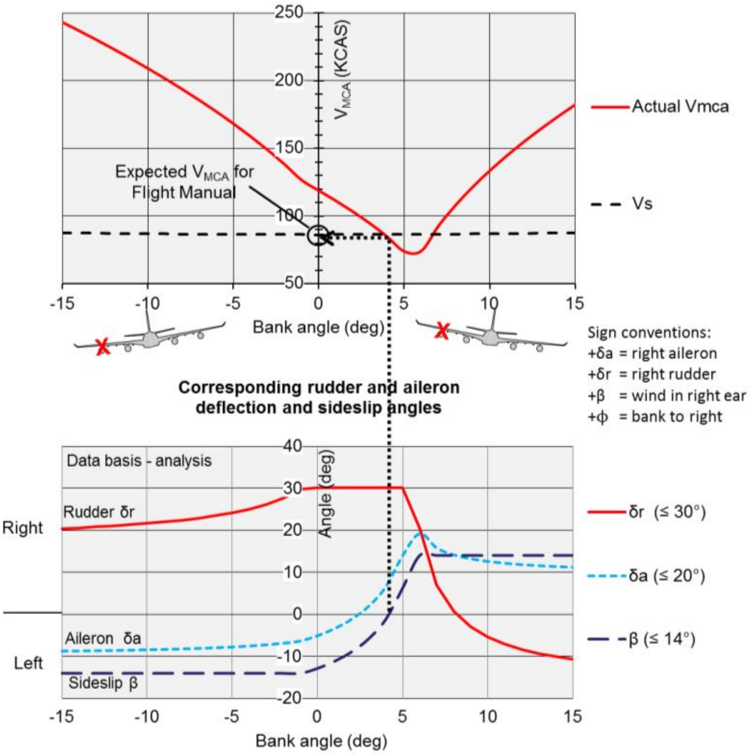

Figure 7. Analyzing the required bank angle for smallest tail size and expected $V_{MCA}$ on a sample 4-engine airplane.

$V_{MCA}$ is always determined at the lowest weight, being the worst-case weight for $V_{MCA}$, because then side force W·sin ϕ is smallest and $V_{MCA}$ highest. This weight effect on $V_{MCA}$ and also Figure 7 will be discussed in detail in § 4.3 below.

2.4.9. From the engineering or hardware point of view, there is nothing wrong with this tail design approach at the drawing board; it is in accordance with the applicable Aviation Regulations FAR/CS 23 and 25. During actual flight however, the lowest airspeed for maintaining straight flight ($V_{MCA}$) can deviate from the value that was used for designing the vertical tail. Therefore, Regulations require flight-tests to be conducted to determine the airspeed below which straight flight can no longer be maintained after both a sudden engine failure (*dynamic* $V_{MCA}$), and while an engine is inoperative (*static* $V_{MCA}$). During these flight-tests, the flight-test crew would normally use the same bank angle (ϕ) that was used to design the vertical tail, which is also the bank angle at which the sideslip angle (β) is as small as possible for the test-weight (Figure 7). The flight-test measured lowest speed at which straight flight can be maintained, while banking the same bank angle that was used to design the vertical tail and while the airplane is in the flight-test configuration, is the *standardized minimum control speed in the air* ($V_{MCA}$) of the airplane that is published in the AFM as an operational limitation. The dynamic and static $V_{MCA}$ flight-tests will be explained in § 5.2 below.

2.4.10. Figure 7 also shows the required rudder reversal for this sample airplane at bank angles larger than 5° into the good engine. This is caused by the increase of side force W·sin ϕ with increasing bank angle ϕ and hence increasing sideslip into the good engine side. This increasing sideslip increases the opposite side force due to sideslip ($Y_\beta$) after which less or even opposite rudder is required for maintaining the equilibrium of forces and moments. In § 2.10.3 below, on turns, this effect is further discussed.

2.4.11. Review of many accident investigation reports revealed that pilots are not (made) aware of the tail design-imposed limitations, which are in fact hardware limitations, and of the bank angle that needs to be applied for the AFM-published $V_{MCA}$ to be valid. Hence, many pilots do not know that they should maintain straight flight only while also maintaining a small bank angle away from the inoperative engine for the vertical fin to be able to maintain the equilibrium of side forces and yawing moments when the airspeed is low and the asymmetrical thrust is high. This is neither prescribed in the AFM, nor included in the engine emergency procedures of most multi-engine airplanes, except in the AFM and Performance Manuals of Lockheed airplanes. This is, to the opinion of the author, why accidents after engine failure happen. Pilots of Part 23 Commuter and Part 25 airplanes use rotation speed $V_R$ and takeoff safety speed $V_2$ and not $V_{MCA}$ anymore. However, $V_R$ is derived from $V_{MCA}$ and $V_2$ from both $V_{MCA}$ and the stall speed $V_S$, making $V_{MCA}$ important to pilots of all multi-engine airplanes. $V_R$ and $V_2$ are explained in § 6.4 resp. § 6.5 below.

2.4.12. $V_{MCA}$ is in fact a procedural or software fix (on paper) for a hardware shortcoming (too small a vertical tail). The significance of $V_{MCA}$ for the controllability of a multi-engine airplane after engine failure seems well documented in FAR, EASA CS, AFMs and textbooks, but – in fact – it is not. If the applicable $V_{MCA}$ and/ or $V_R$ and $V_2$ are readily available to pilots before every takeoff or go-around, why do engine failures, or in-flight simulation or demonstration of engine failures during training, still turn into catastrophes so often? Many publications were written to answer this question, but most reports and papers only discuss the early recognition of engine problems, incorrectly conclude a stall, or simply conclude 'inappropriate crew response to propulsion system malfunction' (ICR/PSM). $V_{MCA}$ is defined in FAR/CS 23.149 and 25.149; its definition is further discussed in § 5.5 below.

2.4.13. ***Summary***. The vertical tail with rudder of multi-engine airplanes is designed to be just large enough for *maintaining straight flight* while an engine is inoperative, while the thrust on the remaining engines is at maximum takeoff setting and the airspeed is as low as $V_{MCA}$, provided a bank angle of a fixed number of degrees, as determined by the tail design engineer (usually between 3º and 5º) away from the inoperative engine, is being maintained. Vertical tail and rudder are definitely not large enough for maintaining control during turns at low speed and high-power settings.

### 2.5. Recovery after engine failure in flight

2.5.1. To recover to steady straight and controlled flight, first the airplane motion must be arrested as soon as possible to prevent an uncontrollable attitude from developing. The controls available to the pilots are the aerodynamic controls: rudder, ailerons and elevator, and a propulsive directional control: the throttle or power lever of the engine opposite of the inoperative engine. As was explained above, the vertical tail and rudder are normally sized – and the rudder on big airplanes is boosted – to be able to provide high enough control power to counteract the yawing generated by the maximum asymmetrical engine thrust after an outer engine fails down to certain minimum speed, the minimum control speed $V_{MCA}$. Ailerons have small control power under low-speed conditions as well, but are – on some airplanes – assisted by powerful spoilers. All pilots are aware though that the downward deflection of an aileron increases the local angle of attack of the wing section in front of that aileron, which – if the airspeed is low – might lead to a partial wing stall that results in an uncommanded roll, which only aggravates an already critical situation. Aileron deflection also generates adverse yaw and additional drag that both affect the sum of the yawing moments as well.

2.5.2. The moments needed for recovery after engine failure are a yawing moment, that adds to $N_\beta$, a rolling moment $L_{\delta a}$ opposite of the propulsive lift moment $L_T$ and the rolling moment due to sideslip $L_\beta$ (Figure 8). The rudder is the only aerodynamic control available to balance or counteract $N_T$. The side force due to rudder deflection $Y_{\delta r}$ can provide a yawing moment $N_{\delta r}$ that adds to the yawing moment $N_\beta$ due to the sideslip side force $Y_\beta$ (that normally provides the weathercock stability) to balance thrust yawing moments $N_T$. The ailerons (supported by spoilers) can be used to balance $L_T$ and $L_\beta$.

2.5.3. If the aerodynamic control power of rudder and/ or ailerons is insufficient to recover to a safe equilibrium under high asymmetrical thrust conditions, then the airspeed is below the *actual*[1] minimum control speed (*actual* $V_{MCA}$). Normally the elevator (pitch control) is used to adjust the vertical flight path and therewith to increase the airspeed as required. However, if the airplane is just after liftoff or during a go-around and is still close to the ground this might not be an option. If rudder and/ or ailerons are not effective enough to provide the control power needed for recovery, then the only option left is to decrease the problem-causing asymmetrical yawing moment $N_T$ and/ or rolling moment $L_T$. This can be achieved by partly (though temporarily) closing the throttle of the engine opposite of the failed or inoperative engine, therewith reducing the asymmetrical thrust moments $N_T$ and propulsive lift $L_T$ to a level that is equal to or lower than the aerodynamic moments that are being generated by rudder ($N_{\delta r}$), vertical tail ($N_\beta$) and ailerons ($N_{\delta a}$) at that very instant (and speed). The throttle of the opposite engine has very large control power because it decreases or even nulls the asymmetrical yawing moment on the airplane and decreases propulsive lift $L_T$. Of course, this *'propulsive control'* aggravates an already critical performance problem; the overall performance decreases for a while (until control is regained). Nevertheless, controllability is more vital to survival than performance, especially if the altitude is low during takeoff or go-around; a wingtip hitting the ground first results in more trouble than a controlled wings-level landing in the dirt. This thrust effect is shown in the FDR data of the accident analyzed in § 8.4.

2.5.4. The required control inputs in the roll and yaw axes to stop the dynamic or transient motions after engine failure and to return to stabilized flight might be larger than for maintaining equilibrium straight flight. Therefore, both a dynamic and a static $V_{MCA}$ are determined during experimental flight-tests. These flight-tests will be briefly described in § 5.2 below.

2.5.5. In the paragraphs to follow, the three most relevant options for straight flight while an engine is inoperative will be discussed.

## 2.6. Straight flight while an engine is inoperative

2.6.1. Following recovery, many combinations of rudder and aileron deflections are possible that will achieve balance of lateral and directional forces and moments for a safe straight (equilibrium) flight. The two combinations or options that are most relevant to takeoff and go-around will be discussed below. A third option, straight flight with no rudder input, is presented because this also caused many accidents, amongst which the accidents analyzed in § 8.4 and § 8.5 below. Although all options are good for maintaining control, only one option leaves maximum climb performance and a straight flight path (ground track) similar to all engines operative: straight flight with zero sideslip, i.e. with a small bank angle, § 2.8.

## 2.7. Straight flight with wings level (bank angle $\phi = 0°$)

2.7.1. As was mentioned before, not all forces and moments that act on an airplane are shown in accompanying figures, only the most important ones. Figure 8 shows this option after reaching straight flight equilibrium.

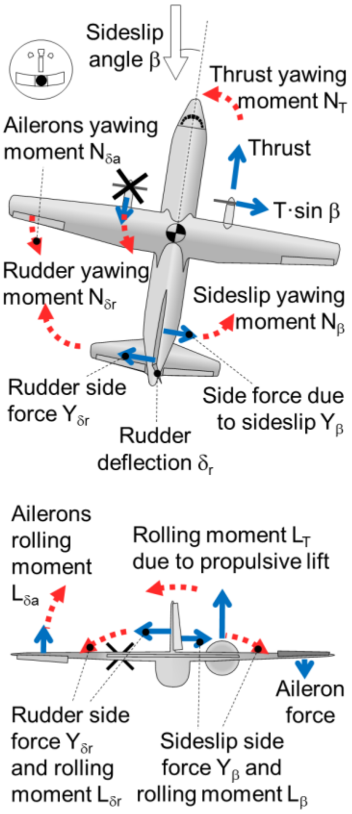

Figure 8. Straight flight with wings level ($\phi = 0°$).

2.7.2. After failure of the left engine (#1) on our sample multi-engine airplane, the asymmetrical thrust T of engine #2 generates a yawing moment $N_T$ about the center of gravity that can be balanced only by a yawing moment $N_{\delta r}$ generated by rudder side force $Y_{\delta r}$. However, $Y_{\delta r}$ also results in sideward acceleration and hence a sideslip built-up. This sideslip β results in a side force $Y_\beta$ opposite of $Y_{\delta r}$ and an 'air-bending' side force T·sin β generated by the thrust of operative propeller, that all decrease the sideward acceleration. The yawing moment $N_\beta$, generated by $Y_\beta$, adds to the asymmetrical thrust moment $N_T$. Therefore, the rudder deflection needs to be increased to counteract this yawing moment as well.

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[1] *'Actual $V_{MCA}$'* in this report means the real and instantaneous $V_{MCA}$ for the existing conditions, in the actual configuration with the actual values of all variable factors that have influence on $V_{MCA}$, unlike the worst case of the values used to determine the standardized $V_{MCA}$ that is published in AFMs. *Actual* $V_{MCA}$ can be higher or lower than the $V_{MCA}$ that is published in AFMs. Refer to § 4.

Aileron deflection $\delta_a$ not only generates a rolling moment $L_{\delta a}$ to counteract the propulsive lift moment $L_T$, but also an adverse yawing moment $N_{\delta a}$ for which also additional rudder deflection ($Y_{\delta r}$) is required to compensate for. On turbofan-equipped airplanes, the deflection of ailerons might be different from the deflection in the figures, because turbofans do not generate propulsive lift.

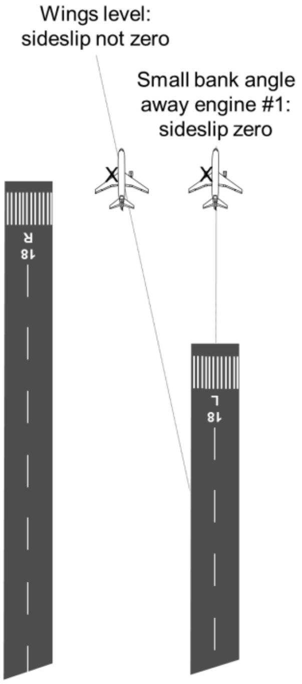

Figure 9. Takeoff flight paths after failure engine #1, parallel runways.

2.7.3. When the wings are kept level, the only side force that can balance side force $Y_{\delta r}$ is the side force due to sideslip $Y_\beta$. As the airspeed is decreased, $Y_\beta$ decreases (lift/ side force of the vertical fin with rudder deflected $\equiv V^2$) and an increased rudder deflection is needed to balance $N_T$, which increases the sideward speed and therewith $Y_\beta$ until a balance is achieved of side forces and yawing moments for straight flight with wings level. An equilibrium is possible (sum of forces = 0 <u>and</u> sum of moments = 0) if the airspeed is high enough, but at the cost of increased drag and hence, less (climb) performance.

2.7.4. The airspeed can be decreased until either one or more of the following limitations are met, both with the trims at normal setting:

- Rudder deflection is maximum (at mechanical limit) or pedal force is 150 lb (667 N – FAR/ CS 23 and 25, ref. 6) or 180 lb (Military Specification, ref. 14);
- Aileron control force is 25 lb (112 N) and deflection is maximum (civil FAR/ CS) or 75% (Military Specification; same references).

2.7.5. Below this airspeed, straight flight cannot be maintained; the rudder simply cannot provide a high enough yawing moment $N_{\delta r}$ anymore to balance the adverse yawing moments, like $N_T$, etc. Therefore, this airspeed is the *actual* air minimum control speed $V_{MCA}$ for flight with the *wings level*. '*Actual* $V_{MCA}$' is defined in a footnote on page 16.

2.7.6. *The ground track* or flight path after engine failure during takeoff or go-around is not the ground track that would be flown with all engines operative. As was explained above, keeping the wings level results in a sideslip that causes the airplane to deviate from the extended runway centerline while still maintaining the heading (Figure 9). In case of airport operations from parallel runways, or in mountainous terrain, a conflict might evolve when an engine fails on the side of the other runway or mountain. The Standard Instrument Departure might be affected as well.

2.7.7. ***Summary***. Although a good and easy to fly straight flight can be achieved while keeping the wings level, a sideslip cannot be avoided. Hence, the drag is not as low as possible to achieve maximum climb performance while an engine is inoperative. This is the reason that some Part 23 airplanes at high weight will not be able to achieve a positive rate of climb when the wings are kept level. Refer to § 7.8 for a note that often accompanies engine inoperative performance data in AFMs. Furthermore, due to the unavoidable sideslip angle $\beta$, the prop wash of operating engines might disturb the airflow around the vertical tail, affecting the local angle of attack and hence influencing the maximum obtainable rudder control power. The stall characteristics might be degraded as well. During flight-tests performed by the author, the sideslip angle required for straight flight during testing a small twin-engine airplane in a certain configuration with an inoperative engine and level wings was observed to be as large as 14 degrees.

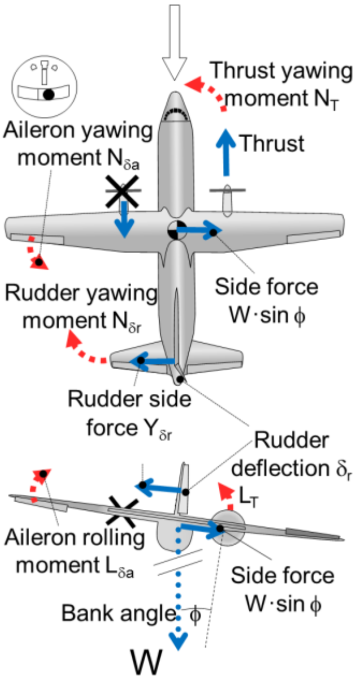

Figure 10. Straight flight with zero sideslip ($\beta = 0°$).

## 2.8. Straight flight with zero sideslip ($\beta = 0°$)

2.8.1. Zero sideslip means lowest drag possible and, hence, maximum possible climb performance, which should be the preferred case for flight while an engine is inoperative. If sideslip $\beta$ is zero, there obviously will be no side force due to sideslip ($Y_\beta$). As explained in the previous paragraph, besides rudder and aileron deflections to balance the asymmetrical thrust moments $N_T$ and $L_T$, a side force opposite of $Y_{\delta r}$ is required to balance this side force. Otherwise, the airplane will start side slipping into the dead engine side again and $\beta$ will not be zero. This balancing side force can easily be generated. The tail design engineer already used it at the drawing board for sizing the vertical tail (§ 2.4.4).

2.8.2. When an airplane is banking, a component of the weight vector acts as side force $W \cdot \sin \phi$ in the center of gravity. This side force can be used to replace $Y_\beta$ of the wings level case (§ 2.7) and achieve a balance of side forces and hence, straight flight after engine failure. Side force $W \cdot \sin \phi$ generates no rolling or yawing moments because this force acts in the center of gravity (the moment arm is zero). Side force $W \cdot \sin \phi$ varies obviously with the weight (W) of the airplane and the bank angle ($\phi$), acts in the direction of banking and is zero if the wings are level ($\sin 0° = 0$).

2.8.3. In Figure 10, bank angle $\phi$ is approximately 5º away from the inoperative engine, which generates a side force $W \cdot \sin \phi$ opposite of $Y_{\delta r}$, as is required for the balance of the side forces. As was explained in § 2.4.4, the engineer designing the vertical tail is allowed by FAR and CS to use a bank angle of maximum 5º for reducing the required size of the vertical tail.
Side force $W \cdot \sin \phi$ not only depends on bank angle $\phi$, but also on the weight W of the airplane. The required bank angle for zero sideslip will therefore also vary with the actual weight of the airplane. The effect of bank angle and weight on $V_{MCA}$ will be described in greater detail in § 4.3 below.

2.8.4. In this zero-sideslip case, the rudder side force $Y_{\delta r}$ only has to generate a moment for balancing $N_T$ and $N_{\delta a}$ (adverse yaw due to aileron deflection) and does not have to overcome $Y_\beta$ and the other side forces due to $\beta$, like air bending force $T \cdot \sin \beta$, so less rudder deflection $\delta_r$ is required for the same airspeed as for straight flight with wings level as discussed in § 2.7. Therefore, the airspeed can be further decreased until again the Regulatory rudder and/ or aileron limitations, that were listed in § 2.7.4, are reached.

2.8.5. The airspeed at which this occurs is an *actual* air minimum control speed $V_{MCA}$ for straight flight with *zero sideslip* in the given configuration. Flight-testing has shown that for the given tail size a small constant bank angle, usually between 3° and 5° away from the inoperative engine, generates a side force $W \cdot \sin \phi$ that is large enough to replace $Y_\beta$ and the other side forces due to sideslip angle $\beta$. This bank angle is called the *favorable bank angle*. $W \cdot \sin \phi$ generates no side effects since it acts in the center of gravity. The ball of the slip indicator is in this case about half a ball width to the right, or into the good engine(s).

2.8.6. Displaying sideslip $\beta$ would be best for maintaining this zero-sideslip option for all configurations and weights, but the sideslip angle cannot (yet) be easily measured accurately. A simple means would be a woolen tuft on the windscreen, but that does not look very professionally on an airliner. A bank angle however, even as small as 5°, can be read directly and quite accurately from the attitude display (ADI or FD). The flight path/ ground track following an engine failure during takeoff or go-around will be approximately the same as for all engines operating, which is favorable to parallel runway operations (Figure 9 above).

2.8.7. Another flight-tests based example: the actual $V_{MCA}$ of a small twin-engine airplane in a certain configuration during testing decreased from 58 kt with the wings level to approximately 53 kt with a favorable bank angle of 5° away from the inoperative engine. As will be shown below, the small bank angle decreases the actual $V_{MCA}$ up to 30 kt for bigger airplanes.

2.8.8. ***Summary***. The *actual* $V_{MCA}$ during straight – equilibrium – flight with zero sideslip, i.e. with a small bank angle away from the inoperative engine, is lower than *actual* $V_{MCA}$ with the wings level. The safety margin between the actual takeoff airspeed and the *actual* $V_{MCA}$ during takeoff increases if a small bank angle is used, which means that this small bank angle increases the safety considerably. For a continued takeoff or a go-around while an engine is inoperative, it is important that the remaining performance is maximal, requiring the drag to be minimal, which will be the case if the sideslip is zero. Sideslip is smallest when a small bank angle between 3° and 5°, depending on the airplane type, is attained and maintained. The engineer designing the vertical tail used this zero-sideslip case and, hence, a small bank angle for sizing the control surface. Zero sideslip is difficult to determine in-flight, but not a small bank angle.

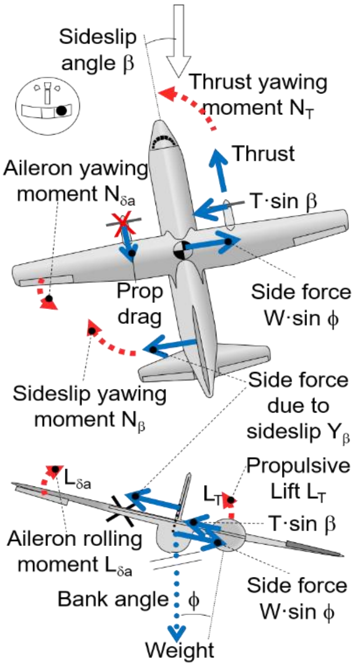

Figure 11. Straight flight with zero rudder.

### 2.9. Straight flight with zero ($\delta_r = 0$) or partial rudder

2.9.1. This option is included because pilots do not always use adequate rudder to counteract the yawing while an engine is inoperative; this happened too preceding the accidents analyzed in § 8.4 and § 8.5 below. Banking, rather than rudder is used to control the heading. Figure 11 shows the forces and moments that act on the airplane during straight equilibrium flight with zero rudder ($\delta_r = 0$), which is the case if the pilot would not deflect the rudder at all to counteract the thrust yawing moment $N_T$. Then $Y_\beta$ is the only side force that can provide the yawing moment $N_\beta$ required to counteract $N_T$. Therefore, the required sideslip angle for balancing $N_T$ will have to be quite considerable at low airspeed (and high thrust setting); the airspeed needs to be high enough for the vertical tail and fuselage to generate a large enough side force $Y_\beta$. To counteract $Y_\beta$, side force W·sin ϕ is required to balance $Y_\beta$ + T·sin β and prevent sideward acceleration to the dead engine side. Bank angle ϕ is again away from the inoperative engine and will usually be around 8 degrees at high weight and larger at lower weights (W·sin ϕ). This option for straight flight might look attractive because no rudder input is required. However, the sideslip angle β at low takeoff or go-around speeds can be quite considerable (greater than 20°) leading to high drag (which should be avoided during takeoff) and to a high local angle of attack of the vertical tail which might lead to fin stall and, consequently, to the sudden loss of directional control, which is potentially dangerous. To avoid this loss of control, the airspeed needs to increase, as is shown in Figure 7 for $V_{MCA}$ at bank angles greater that 7°. Also shown is that the rudder deflection should reverse to reduce the side forces on the fin.
The prop wash might also have adverse effect on airstream around the vertical tail. Hence, the *actual* $V_{MCA}$ is increased. The airspeed with zero rudder needs to be higher than when the rudder is deflected to balance the side forces. Because of the greater sideslip angle and hence, higher drag, there might not be any climb performance left. Therefore, zero rudder is not an option for maintaining straight flight during operations while an engine is inoperative; the rudder must be used to counteract the asymmetrical thrust, to reduce the *actual* $V_{MCA}$, reduce the drag and to maximize the climb performance.

2.9.2. If the *rudder* is deflected only *partial* and the side force $Y_{\delta r}$, generated by the rudder, is not large enough to counteract the asymmetrical thrust yawing moment, a sideslip will develop and increase until the sum of $Y_\beta$ and $Y_{\delta r}$ result in a yawing moment that is large enough to counteract the asymmetrical thrust yawing moment. The lower the airspeed, the larger the sideslip angle will be. If the sideslip angle increases too much, the vertical tail might also stall, leading to the loss of control. The *actual* $V_{MCA}$ is still higher than the AFM-published standardized $V_{MCA}$ (for $\beta = 0$) and the drag will reduce or even reverse the climb performance into a rate of descent. For a given airspeed, the rudder deflection must be large enough to maintain the heading (zero yaw rate) and to reduce the sideslip to near zero. Partial rudder is also discussed in § 4.8 below.

2.9.3. ***Summary***. The drag during straight – equilibrium – flight with zero rudder is much higher than with wings level and with a small bank angle away from the inoperative engine. *Actual* $V_{MCA}$ will be higher than the AFM-published standardized $V_{MCA}$. Zero or partial rudder might lead to stalling the vertical tail. This option is therefore definitely not recommended for recovery following an engine failure and during (straight) flight while an engine is inoperative.

2.9.4. ***Subconclusion***. After discussing three options for maintaining straight flight equilibrium after engine failure or while an engine is inoperative, the following conclusion can be drawn. In case the airspeed is low while the asymmetrical power setting is high, the only option for maintaining control of the airplane and for a maximum positive rate of climb is to deflect the rudder as much as required for maintaining the heading and to apply the small favorable bank angle away from the inoperative engine to reduce the drag to a minimum. Then also $V_{MCA}$ will be lowest. The manufacturer should present the magnitude of the favorable bank angle together with the $V_{MCA}$ data in the AFM, which is usually between 3° and 5° away from the inoperative engine – to the same side as rudder pressure. Any other bank angle or less rudder deflection than required for maintaining a zero-yaw rate will result in a less favorable balance of side forces and in yawing and/ or rolling moments, which all result in increased drag and in less or no climb performance at all, or in the complete loss of control. Some manufacturers limit the bank because roll-assisting spoilers kick-in when the control wheel is rotated 7° or more, and therewith accept a higher than minimum $V_{MCA}$ and higher drag.

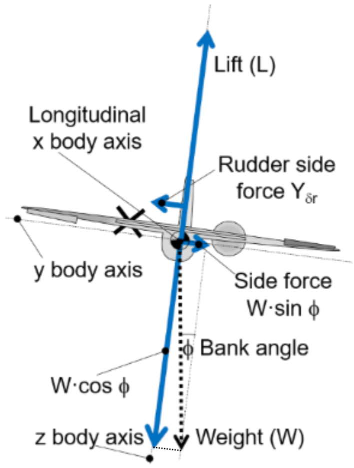

Figure 12. Forces in y and z body axes.

### 2.10. Control during turns when one engine is inoperative

2.10.1. In an all-engines operative steady level turn, the horizontal component of the lift ($L \cdot \sin \phi$) provides for the radial acceleration toward the center of the turn. All pilots know this, but don't get to learn that this is only valid for coordinated flight (symmetrical thrust) and not for large bank angles. A knife-edge maneuver (straight flight with 90° bank) cannot be explained with a horizontal component of the lift (in the flat Earth coordinate system). Therefore, when reviewing forces and moments while the thrust is asymmetrical, the body-fixed axis system is used, as airplane design engineers and experimental test pilots & flight test engineers also do while working with equations of motion, to calculate the required size of control surfaces or to prepare engine-out flight-tests. In this body-fixed system (see also § 2.1.2 and Figure 2 on page 9 above), there is no component of the lift that plays a role as side force in the direction of the y body axis, as shown in Figure 12, because lift acts perpendicular to the y body axis. The weight vector of the airplane however, always points to the center of the earth and indeed has, when banking, a side force component ($W \cdot \sin \phi$), a component ($W \cdot \cos \phi$) in the z body axis (equal to the Lift (L)) and, while climbing or descending, a component in the direction of the longitudinal x body axis (towards the front or aft; not shown in Figure 12). Weight does not generate rolling, pitching or yawing moments, because it acts in the center of gravity (moment arms are zero).

2.10.2. When an engine is inoperative, the asymmetrical thrust yawing moment ($N_T$) must be counteracted by one or more side forces that are generated by the vertical tail with rudder due to a sideslip and/or by deflecting the rudder, not only during straight flight as discussed before, but also during turns. An engine-out turn can therefore not be a coordinated turn (ball not centered), certainly not at low speed and high (asymmetrical) thrust setting. The rudder and/or a sideslip can provide for the required side force to balance the thrust yawing moments if the airspeed is high enough, as was explained above, but at the cost of drag (and climb performance). At high airspeed less rudder is required, but at low speed, such as during takeoff and approach, much rudder might be required when the asymmetrical thrust is high or is increased in order to maintain the descent path, or for a go-around.
It is assumed that the turns discussed below begin with the airplane in a zero-sideslip straight flight equilibrium as shown in Figure 12 and discussed in § 2.8 above. As also shown in Figure 10 on page 17 above, in this straight flight equilibrium the side force generated by the rudder ($Y_{\delta r}$) is equal to the side force component of the weight of the airplane ($W \cdot \sin \phi$). Then the sideslip is zero, hence the drag as low as possible.

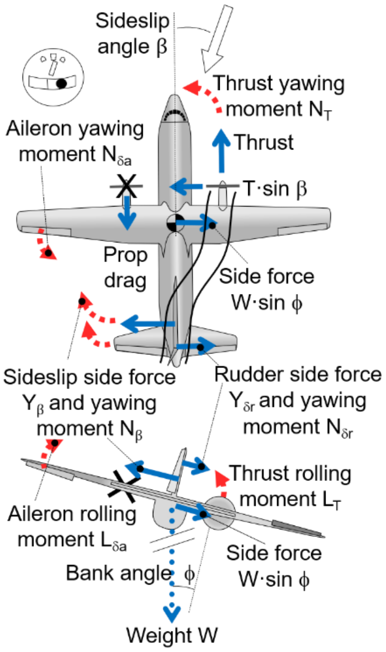

Figure 13. Turn into operative engine; mind the required rudder reversal.

2.10.3. Figure 13 shows the most influential forces and moments that act on the airplane when banking approximately 15° into the operative engine. During increasing the bank angle to 15°, side force $W \cdot \sin \phi$ increases after which the aircraft starts accelerating to that side causing the sideslip to that side to increase, resulting in an increasing opposite side force due to sideslip $Y_\beta$ on the fin and fuselage, which in turn generates yawing moment $N_\beta$. Other (destabilizing) yawing moments are caused by air bending by the propeller ($T \cdot \sin \beta$) and by the (windmilling) propeller drag. The increasing sideslip not only causes the increase of the horizontal angle of attack on the vertical tail (fin) with deflected rudder, which might result in a fin stall, but also unavoidable increased drag leading to the loss of altitude that needs to be compensated by elevator input, increasing the Lift as long as elevator power is adequate and either wing does not stall. These pitch forces and moments do not play a role in the lateral equilibrium of forces and moments though, as mentioned before.
At larger bank angles, the sum of the sideslip and rudder yawing moments ($N_\beta + N_{\delta r}$) might increase above the sum of asymmetrical thrust yawing moments ($N_T$ and others). To avoid the airplane to continue yawing the nose to the ground (about the cg), it might therefore be required to reduce the rudder deflection, or even reverse the rudder deflection as discussed in § 2.4.10 and shown in Figure 7, both on page 14. For the sample airplane used for calculating that figure, a bank angle larger than 5° into the operative engine requires the pilot to reverse the rudder to be able to maintain the equilibrium of lateral forces and moments and requires a higher airspeed to avoid the fin to stall because of the increasing sideslip. Also note the rudder side force difference

with Figure 10 on page 17. The reversed rudder decreases the horizontal angle of attack on the fin, increasing the stall margin, but the sideslip is still large. If the rudder is not reversed, then the rudder side force increases the sideslip side force causing an increased yawing moment and increased drag; an equilibrium might not be achieved. If the banking maneuver and the subsequent 'recovery' to straight flight result in a different heading, then a kind of flat turn was made. Maintaining control during banking is more demanding when an engine is inoperative, and not always possible, as many accidents prove. Many pilots lost control of their airplane during engine-out turns because the airspeed was too low.

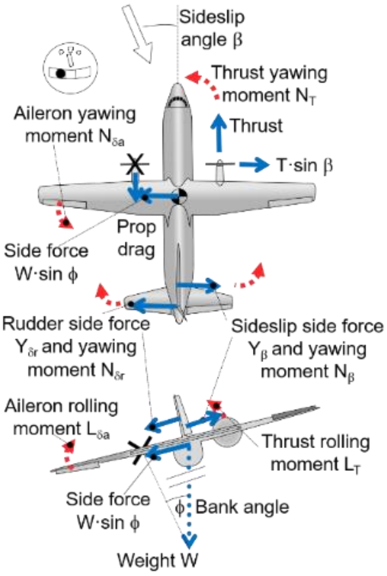

Figure 14. Turn into dead engine.

2.10.4. During a turn (banking) to the other side, into the inoperative or dead engine, as shown in Figure 14, side forces also act to the other side as in Figure 13, with the exception of the side force, or the sum of the side forces, that are required to counteract the asymmetrical thrust. In this case, and at low speed and a high asymmetrical thrust setting, the pilot will need up to maximum rudder into the good engine to maintain balance of forces and moments, or if the rudder power at the current airspeed falls short, a much higher airspeed (which might not be achievable at low altitude).
Safely turning while an engine is inoperative might be challenging during engine-out training; the loss of altitude when losing control might be considerable.
See also § 8 and § 9 below for the analyses of accidents that occurred after banking.

2.10.5. Turns at low airspeed and high asymmetrical thrust settings, including after takeoff, while in a *holding pattern* or in the traffic pattern for landing, result in an increased sideslip angle, which in turn results in increased drag and hence, reduced climb performance or an unavoidable rate of descent. Therefore, turning at too low a speed is definitely not recommended at low altitude when the thrust is high or if the (asymmetrical) thrust needs to be increased during the turn, but only at a safe altitude when the increased sideslip angle and resulting loss of altitude during the turn do not create a controllability or performance problem. If the airspeed is increased prior to, and/or the asymmetrical thrust (throttle) is decreased a bit during the turn (temporarily), the loss of control can be avoided, sometimes at the cost of some altitude. Consider a less than maximum flap setting for the approach, for which less asymmetrical thrust is required to maintain the glide path, and a higher approach speed which increases the safety margin above the actual minimum control speed $V_{MCL}$ / $V_{MCA}$. Use extreme care with power applications in asymmetrical thrust operation, especially at lower altitudes; be prepared to increase or decrease rudder with the thrust changes.

2.10.6. If during an engine-out approach an increase of (asymmetrical) engine thrust to (near) maximum might become necessary for maintaining the approach path or for a go-around, increased rudder and a small favorable bank angle are required to avoid the loss of control. This cannot be done safely during a final turn from a close base leg. Therefore, if an engine-out landing becomes necessary, it is much safer to conduct a long straight-in approach. Refer also to § 4.3.9. In § 4.3 below, the effect of weight and bank angle on $V_{MCA}$ will be illustrated in graphs. In § 5 below the flight tests to determine minimum control speeds will be further discussed.

2.10.7. ***Summary***. When turning while an engine is inoperative, a side force, i.e. rudder, remains required to counteract the asymmetrical thrust yawing moment. A turn while an engine is inoperative will therefore never be a coordinated turn. During a turn into the good engine, the rudder input might have to be reversed to avoid overyawing. Turning either side increases the sideslip considerably leading to the loss of altitude if the elevator power and/or the airspeed are inadequate to maintain altitude or approach path; a much higher airspeed will be required. When an engine already failed in-flight, consider a long straight-in approach with a less than maximum flap setting to avoid making turns during which the thrust might have to be increased.

## 2.11. Engine Inop Trainer

2.11.1. A very interesting and easily accessible reference for pilots and investigators who want to understand the principles of airplane control after engine failure is an *Engine-Out Trainer* presented on-line by the University of North Dakota. This trainer, simulating a small twin, allows several variables to be changed to learn about their effects on $V_{MCA}$, drag, rate of climb, etc. Open the trainer by clicking the full URL in ref. 15. More variable factors that influence the minimum control speed in the Air ($V_{MCA}$) will be discussed in detail in § 4 below.

## 3. PERFORMANCE WHILE AN ENGINE IS INOPERATIVE

### 3.1. General Performance Considerations

3.1.1. In paragraphs above was already mentioned and explained that failure of an engine not only has consequences for airplane control, but also for performance (through the loss of thrust and sideslip angle $\beta$). When the wings are kept level ($\phi = 0$), a sideslip cannot be avoided; if the bank angle is larger than the favorable bank angle (between 3° and 5°) away from the inoperative engine, or if banked into the inoperative engine, a sideslip cannot be avoided either for the forces and/or moments to be balanced. A sideslip results in increased drag, which in turn results in less or no, or even negative climb performance. In order to achieve the highest possible climb or range performance while an engine is inoperative, the drag must be as low as possible. This will be the case only when using the small favorable bank angle, as should be specified by the manufacturer. This bank angle is usually between 3° and 5° away from the inoperative engine and was also used to size the vertical tail. Then the sideslip is minimal and hence, the climb performance maximal. Regrettably, only a few manufacturers present the favorable bank angle. Below, the effect of bank angle and weight on sideslip $\beta$, hence on performance, is presented in figures.

3.1.2. The maximum climb performance for any given airplane configuration is available when maximum thrust is set, the airspeed is adjusted to the required value for either maximum angle/ range ($V_{XSE}$) or for maximum rate of climb ($V_{YSE}$) and the drag is as low as possible, i.e. sideslip $\beta = 0$ and the aircraft is configured for lowest drag, i.e. gear up, etc. When OEI, the sideslip, hence drag is only minimal by maintaining a small favorable bank angle, usually 3° – 5° away from the inoperative engine, as explained in § 2.4 and § 2.8 above and illustrated in Figure 7 on page 14. Then the side force due to bank angle ($W \cdot \sin \phi$) replaces the side force due to sideslip ($Y_\beta$) that results from the rudder side force ($Y_{\delta r}$) that is required to counteract the asymmetrical thrust yawing moment $N_T$, resulting in zero sideslip – hence lowest drag.

NOTE

2° TO 3° BANK TOWARD
OPERATING ENGINE

Figure 15. Note required in legend of OEI performance data tables in Flight or Performance Manuals.

3.1.3. The airspeeds for maximum single engine climb and/or range performance ($V_{YSE}$ and $V_{XSE}$) are higher than $V_{MCA}$. These higher airspeeds generate a larger rudder generated aerodynamic side force $Y_{\delta r}$. Therefore, the rudder deflection $\delta_r$ to counteract the still same asymmetrical thrust yawing moment $N_T$ can be smaller. In turn, the side force $W \cdot \sin \phi$ to balance $Y_{\delta r}$ for lowest drag can also be decreased by reducing the bank angle $\phi$ from 5° for the red-lined $V_{MCA}$ to 2° - 3° for blue-lined $V_{YSE}$. Therefore, in the legend of the OEI performance charts or tables, a **NOTE** should be included saying that the presented OEI performance data is valid only if a bank angle is maintained of 2 to 3 degrees toward the operative engine (Figure 15) while the thrust is maximum. In the OEI climb performance data of the PA-44-180 (page 5-24), the manufacturer indeed presents this note. In addition, a configuration change (a cleanup) might be recommended in the performance chart legend to decrease the drag, i.e. selecting gear and/ or flaps up.
Roll control on some large airplanes is enlarged by using roll assisting spoilers. These deploy asymmetrically to reduce the lift of the down going wing, as the roll control wheel rotation exceeds 7 degrees. Spoilers though, also increase the asymmetrical drag and decrease performance.

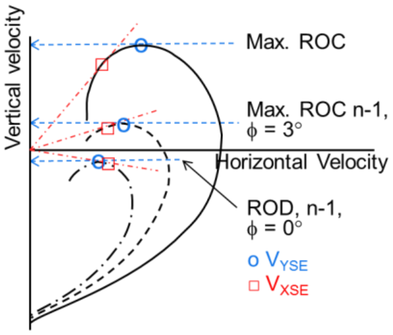

Figure 16. $V_{YSE}$ and $V_{XSE}$ before and after engine failure (n-1) for two bank angles.

3.1.4. Figure 16 shows the Rate of Climb/Descent (ROC/ROD) and $V_{YSE}$ and $V_{XSE}$ with and without a favorable bank angle. To achieve maximum ROC or range, the airspeed must be $V_{YSE}$ resp. $V_{XSE}$ (tangent to the curve) while maintaining a small bank angle. When the ROC is zero, $V_{YSE}$ and $V_{XSE}$ are equal. During drifting down with the wings level, $V_{XSE}$ (speed for maximum range) for this sample airplane is higher than $V_{YSE}$, the blue line speed.

3.1.5. The standardized $V_{MCA}$ that is published in the limitations section of AFMs was determined using the small bank angle for lowest drag ($\beta = 0$, refer to Figure 7 and flight-test § 5.2).

3.1.6. In § 2.11 above, an on-line Engine-out Trainer was introduced, that should be used to visualize the effects that have influence on both $V_{MCA}$ and climb performance, see ref. 15.

3.1.7. Small multi-engine airplanes with a stall speed lower than 61 knots at maximum takeoff weight are not required to demonstrate a minimum rate of climb while the critical engine is inoperative at an altitude of 5,000 ft. Refer to the climb performance data in the AFM to ensure a positive OEI climb performance for the expected takeoff weight in anticipation of an engine failure during takeoff. The application of a small bank angle immediately after engine failure while maintaining straight flight might just provide some climb performance.

3.1.8. Takeoff performance is usually well documented in the AFM of the airplane. A few performance-affecting issues will also be discussed in paragraphs on controllability in the remainder of this report.

### 3.2. Performance (Sideslip) during OEI climb, cruise

3.2.1. Figure 17 below illustrates the sideslip versus airspeed for four conditions (combinations of weight and bank angle) in which equilibrium of forces and moments is achieved (the airplane is in trim). The subject airplane is the same as used before; the source of the data and analyses are ref.'s 12 and 13.

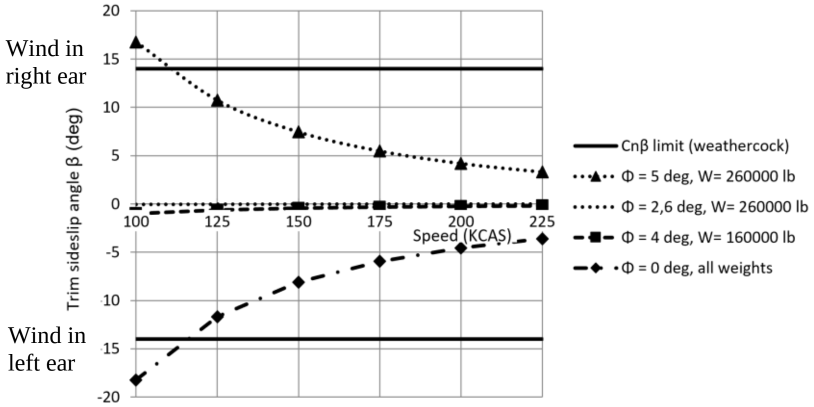

Figure 17. Sideslip versus airspeed at given bank angle and weight, SL, MCT, 4-engine turbojet, #1 inoperative.

3.2.2. When the wings are kept level (bank angle $\phi = 0$), side force $W \cdot \sin \phi$ is zero and only sideslip $\beta$ is providing the side force required to balance the rudder side force ($Y_{\delta r}$) that is counteracting the asymmetrical thrust yawing moment $N_T$ (refer to § 2.7 above). As shown in Figure 17, at a speed of 225 KCAS still a sideslip of a few degrees result depending on weight and bank angle. The lower the speed, the larger the sideslip angle will be (effect of $V^2$ in the aerodynamic force/lift equation).
The effect of bank angle is also shown. For a heavy airplane (at MTOW) a bank angle of 5° away from the failed engine results in a large opposite sideslip. In order to reduce the sideslip, a favorable bank angle of only 2.6° rather than 5° is required for sideslip $\beta$ to be near zero.

3.2.3. The sideslip $\beta$ – hence the drag – at climb and cruise speeds while maximum continuous thrust (MCT) is set is only minimal if a bank angle is maintained of 4° at low all-up weight or a bank angle of 2.6° at high weight, as the data shows. At other weight and bank angles, including wings level, the sideslip angle is larger, as is the drag; precious energy is wasted.

3.2.4. In Figure 18 below, rudder and aileron deflections are presented for the same datapoints as in Figure 17, also for trimmed (equilibrium) flight.
In the rudder deflection plot on the left side the curved line for $\phi = 0$ intersects with the maximum rudder angle of 30° (= right rudder pedal), which equals wings-level $V_{MCA}$ (120 kt), but due to the pedal pressure limit of 180 lb, the actual wings-level $V_{MCA}$ is a little higher, 125 kt. Below this speed, the wings-level equilibrium cannot be maintained, control will be lost.

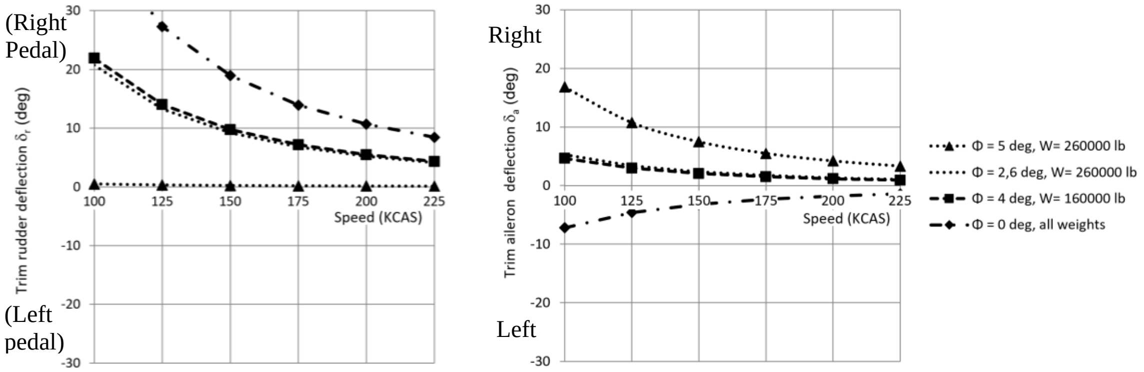

Figure 18. Rudder and aileron during trimmed OEI flight, SL, MCT, 4-engine turbojet, #1 inoperative.

3.2.5. In Figure 18 right, the aileron deflection is presented. Maximum available aileron on this airplane is 20°, while the maximum required aileron for the given weights and bank angles is ≤ 18°, hence the aileron deflection does not restrict airplane control at low speed.

3.2.6. Although the figures are made using data of a Boeing 707/DC-8 class airplane, because the author did not have lateral-directional stability derivatives of other types, similar figures apply to all multi-engine airplanes. Most critical is the performance of small multi-engine airplanes. If a pilot, after engine failure, does not maintain a small bank angle into the good engine and rudder to maintain straight flight, performance is lost. If a small bank angle is being maintained, it could be that just a small rate of climb remains, in which case it may take up to 30 min to reach a safe altitude, where the speed can be increased in level flight to make safe turns.
As explained in § 2.10 above, sideslip β increases during OEI turns and control might be lost if the airspeed is low. The EMB-120ER accident discussed in § 8.5 below happened because the pilots did not maintain straight flight at too low a speed. It will save lives to reduce the drag by banking a few degrees while maintaining straight flight and take time to climb and only then turn. The probability that the other engine will fail too is very small (unless onboard fuel is exhausted).
Many airplanes that suffered from an engine failure during climb or cruise didn't make it to the shore or to an airport. A small bank angle – less drag, smaller rate of descent – provides for increased OEI range and might save lives.

3.2.7. Dr. Jan Roskam (KU) wrote in one of his college books: "*Performance and control are tied together by bank angle*". In § 2.4.8 above the large effect of bank angle on airplane control was already mentioned, in this paragraph the favorable effect of bank angle on the performance was shown. The effect of bank angle and other variables on $V_{MCA}$ will be discussed further in § 4 below.

### 3.3. Drift down and descent OEI

3.3.1. When an engine fails enroute, during cruising, the remaining engine power might not be adequate to maintain the altitude; the airplane is drifting down to an altitude where the thrust required equals the remaining thrust available, or the OEI ceiling of the airplane. Flight manuals usually provide recommended OEI airspeeds during the drift down and subsequent flight. Refer to Figure 16 above for a sample polar diagram. Although there are manufacturers who recommend a small bank angle for maximum performance, most of them do not. In order to achieve maximum range while OEI, the airplane should be trimmed for maintaining a small bank angle to reduce the sideslip, hence drag and maximize the OEI range, if required, as is illustrated in Figure 17 above, at the proper speed for maximum range.

## 4. VARIABLE FACTORS THAT INFLUENCE $V_{MCA}$

4.1. $V_{MCA}$ is borne at the drawing board of the airplane design engineer and was already briefly discussed in § 2.4 above. As mentioned before, many variable factors have influence on the magnitude of the minimum control speed in the air, or airborne

($V_{MCA}$). Already discussed were the influences of thrust, bank angle (through side force $W \cdot \sin \phi$) and rudder deflection, all of which are under pilot control. Any other factor that influences the thrust or drag asymmetry about the yaw and/ or roll axes and that requires a change of rudder or aileron deflection to compensate for will have effect on the magnitude of the minimum control speed and will change the standardized, the AFM-published value of $V_{MCA}$ to some actual value, in this report also called the *actual* $V_{MCA}$. If, for instance, the asymmetrical thrust is not maximal, as during a reduced thrust takeoff, the *actual* $V_{MCA}$ is lower than the standardized $V_{MCA}$ that was determined using maximum asymmetrical thrust.

4.2. In the paragraphs below, most of the variable factors that have influence on $V_{MCA}$ and that might be of interest to pilots and accident investigators will be discussed. As was mentioned before, the worst-case values of these variable factors were used during designing the vertical tail and will also be used during experimental flight-testing to verify/ determine $V_{MCA}$ in-flight; these values will also be presented. Since $V_{MCA}$ is one of the factors to calculate the takeoff speed of Part 23 and $V_R$ and $V_2$ of Part 23 Commuter and Part 25 airplanes, this paragraph is applicable to all multi-engine airplanes.

### 4.3. Effect of bank angle and weight on $V_{MCA}$

4.3.1. Some effects of banking were discussed in § 2.10 above on turning performance while one engine is inoperative.
The pilot controls the bank angle, as long as roll control power is adequate. Therefore, it is very important for pilots and investigators to understand the effect of bank angle on $V_{MCA}$. As was already explained in § 2.8 above, a small bank angle away from the inoperative engine decreases the actual air minimum control speed $V_{MCA}$. In this paragraph, the effect of a change of bank angle into and away from the inoperative engine and of the weight on $V_{MCA}$ will be discussed in greater detail.

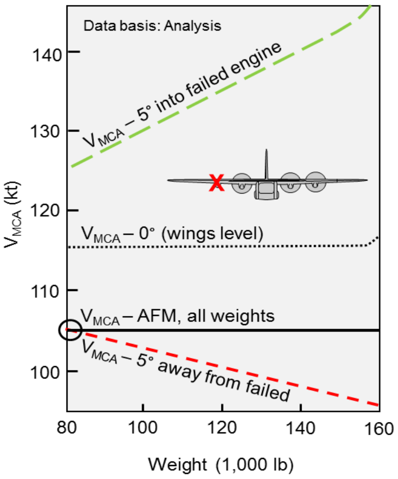

Figure 19. Effect of Bank Angle and Weight on $V_{MCA}$, *straight wing* airplane; max. takeoff thrust.

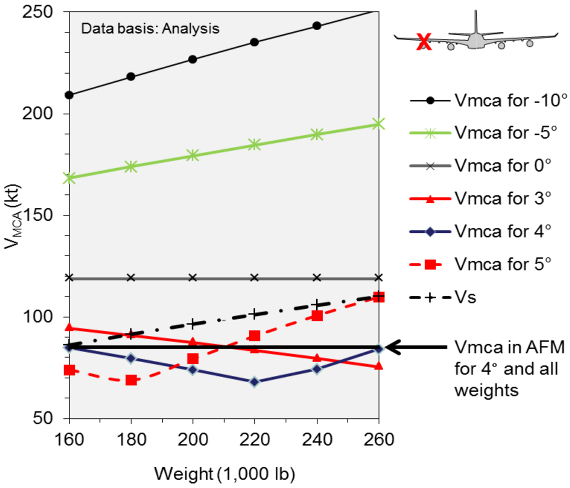

Figure 20. Effect of Bank Angle and Weight on $V_{MCA}$, *swept wing* airplane; max. takeoff thrust.

4.3.2. The effect of bank angle and weight on $V_{MCA}$ can be illustrated in different graphs than were presented above. Figure 19 and Figure 20 show these effects (through side force $W \cdot \sin \phi$) for a sample 4-engine straight wing propeller airplane and a swept wing turbojet airplane, both with one outboard engine (#1) inoperative during level, 1 g flight and with the remaining engines producing maximum available takeoff thrust. The data basis is the analysis of the stability derivatives of these sample airplanes while the thrust is asymmetrical. Actual airplane data could not be used, because manufacturers are very hesitant in allowing the use of their proprietary airplane data. Therefore, these graphs had to be calculated (ref. 13) as is normally performed prior to conducting $V_{MCA}$ flight-tests, see ref. 12. Lockheed published a similar graph as in Figure 19 in the Performance Manual (SMP 777 page 3-18) of the C-130 Hercules airplane. The linear decrease/ increase of $V_{MCA}$ with weight at constant bank angle is the effect of the vertical tail and rudder limit; the rudder cannot provide high enough side force to counteract side force W·sin ϕ while banking.

4.3.3. As shown in Figure 19, the *actual* $V_{MCA}$ for this sample straight wing turboprop airplane would decrease with increasing weight while maintaining the 5° bank angle away from the failed engine (effect of Weight (W) in side force W·sin ϕ). This bank angle was chosen because the sideslip angle then is smallest, the drag lowest as was discussed in § 2.8, see also Figure 7.

4.3.4. Low weight is used during sizing the vertical tail and to determine and measure $V_{MCA}$ during flight-testing because this results in the highest, the most unsafe or worst-case $V_{MCA}$ for the favorable bank angle (between 3° and 5°) away from the inoperative engine for all weights (Figure 19). If the highest gross weight would have been used to determine $V_{MCA}$, then $V_{MCA}$ would be lower for that weight, but the actual $V_{MCA}$ for any lower weight will be higher. Pilots would then have to use weight as entry variable in graphs or tables to determine the actual $V_{MCA}$ for takeoff or go-around; this would require too much data, be too complex and prone to failures. Low weight is the worst-case weight for determining $V_{MCA}$ and is therefore used during flight-testing and for publishing $V_{MCA}$ in AFMs. Remember that the design engineer used the lowest weight possible as well as a small bank angle away from the inoperative engine for sizing the vertical tail (§ 2.4).

4.3.5. Figure 20 shows analyzed $V_{MCA}$ data of a sample swept wing airplane. A positive bank angle is a bank angle away from the inoperative engine, in this case away from engine #1. As Figure 20 shows, the $V_{MCA}$ for bank angles of 4° and 5° away from the inoperative engine of this 4-engine swept wing airplane is not a straight line. $V_{MCA}$ for 4° bank increases when the weight is higher than 220,000 lb and $V_{MCA}$ for 5° increases and when higher than 180,000 lb, which is caused by the increase of sideslip angle β and hence, loss of control power of the downwind ailerons of the swept wings at lower speed, refer to Figure 7 on page 14. This effect is also visible at near maximum weight in Figure 19. The $V_{MCA}$'s on the left edge of Figure 20 (160,000 lb/ low weight) are the $V_{MCA}$'s that form the left side of the V-shape in Figure 7.

4.3.6. The manufacturer of this swept wing airplane could opt for a bank angle of 4° away from the inoperative engine for sizing the vertical tail (§ 2.4) and hence, for determining $V_{MCA}$ during flight-testing, because at that bank angle the sideslip angle β is near zero (as shown in Figure 7) and hence, the drag is minimal. The $V_{MCA}$ of this airplane that will be published in the AFM as standardized $V_{MCA}$ (after verification during flight-testing) would then be 85 knots calibrated airspeed, about the same as $V_S$ at low weight. The standardized $V_{MCA}$ will then be at or below $V_S$ for all weights, and be no factor for control; the airplane is said to be controllable down to the stall, but only as long as the bank angle is 4° to 5° away from the inoperative engine. Flight-testing will have to confirm this. As Figure 20 clearly shows, a bank angle smaller than 4° or a bank angle into the inoperative engine increases the actual $V_{MCA}$ above $V_S$ for all weights; then the airplane is definitely not controllable down to the stall anymore.

4.3.7. If the wings are kept level (ϕ = 0), the analysis (Figure 20) shows that *actual* $V_{MCA}$ for this sample airplane, in this configuration, at all gross weights (W·sin ϕ = 0) will have become 119 kt, 34 kt higher than $V_{MCA}$ with 4° bank away from the inoperative engine and also 11 kt higher than the stall speed $V_S$ at high weight. At or below an airspeed of 119 kt, straight flight cannot be maintained following the failure of an outboard engine when the wings are kept level and the opposite engine is at maximum available takeoff thrust setting, and also provided the other factors that have influence on $V_{MCA}$ are at their worst-case values. In addition, sideslip angle β increases (Figure 7) and therewith the drag.

4.3.8. If the bank angle is only 5 degrees into the failed or inoperative engine, the *actual* $V_{MCA}$ (for straight equilibrium flight) will be even higher: more than approximately 80 kt above the AFM-published standardized $V_{MCA}$ or above $V_S$ for this sample airplane at low weight. $V_{MCA}$ now increases with the weight (effect of opposite ϕ in W·sin ϕ). The graph for 10° of bank into the failed engine is presented in Figure 20 as well and speaks for itself. The increase of actual $V_{MCA}$ on straight wing airplanes will be smaller, but still a factor to consider (Figure 19). Straight wings obviously result in less adverse aileron effect than swept wing airplanes at higher sideslip angles.

Please remember that this is a pure theoretical analysis; however, any bank angle away from the favorable bank angle, which in this case is 4º away from the inoperative engine, will definitely increase the sideslip, and there with the drag, as well as *actual* $V_{MCA}$ (sideslip graph in Figure 7).

4.3.9. ***Turns***. Both Figure 19 and Figure 20 show the powerful adverse effect of side force W·sin ϕ if the bank angle ϕ is into the dead engine (ϕ = negative), during a turn at low speed and high thrust. Of course, $V_{MCA}$ is the minimum speed for maintaining straight flight only, which an intentional *turn* is not, but the control power of rudder and ailerons might be insufficient to be able to return to the favorable bank angle once the airplane is allowed to or cannot be prevented to bank away from the favorable bank angle (3° to 5° into the good engine). The maneuvering capability, while the airspeed is $V_{MCA}$ and when either $\delta_a$ or $\delta_r$ is (near) maximum, is not subject of flight-testing, and may therefore not be counted on. See also § 2.10 above on turns while an engine is inoperative. Handling qualities testing including during turns is conducted, but at an initial airspeed of $V_{MCA}$ + 30 kt for a small twin.
Figure 20 will be used again in § 6.5, while discussing the takeoff safety speed $V_2$.

4.3.10. Figure 21 below shows the effect of bank angle and weight for the sample airplane, at both low and high weight, on the actual $V_{MCA}$ and the resulting sideslip angle β and the required aileron and rudder control inputs. The low-weight data was also used in Figure 7. The effect of weight (W) in side force W·sin ϕ can be observed in this figure. At higher weights, the bank angle can be smaller for the same side force W·sin ϕ. $V_S$ for both high and low weight is added to illustrate the bank angles for which this sample airplane might be controllable down to the stall (to be confirmed by flight-testing).

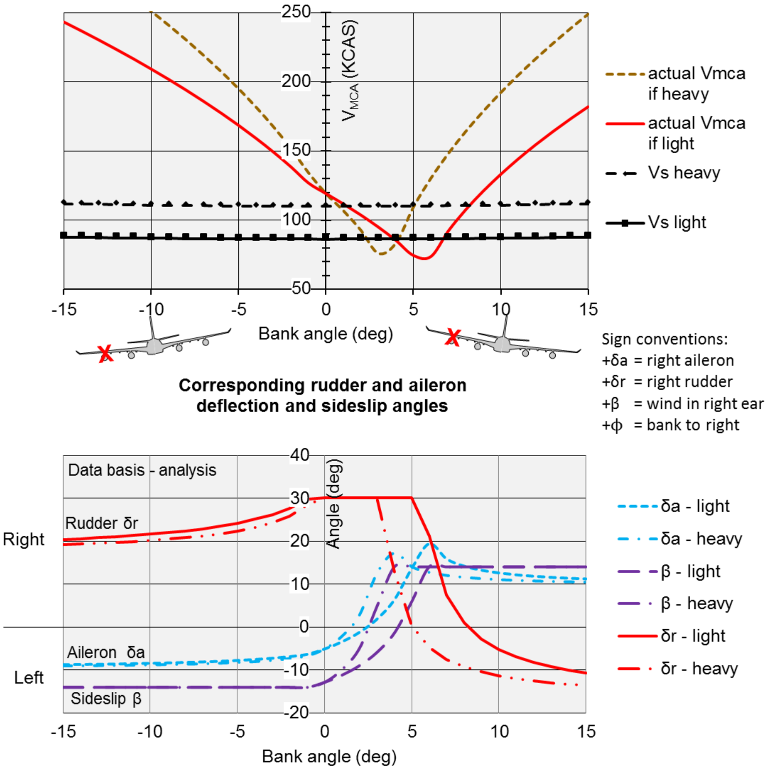

Figure 21. Effect of bank angle and low and high weight on $V_{MCA}$ on a 4-engine swept wing airplane.

4.3.11. ***Summary.*** The $V_{MCA}$ that is published in AFMs is a constant, standardized $V_{MCA}$ that is always determined using the lowest possible gross weight **and** a fixed (favorable) bank angle between 3° and 5° away from the inoperative engine (for which sideslip β is zero), that provides a safe $V_{MCA}$ whatever the airplane gross weight is. This bank angle results in minimum sideslip, hence minimum *drag* and maximum climb performance, and is used to size the vertical tail. This in fact means that the AFM-published, standardized $V_{MCA}$ is only *valid and safe* on the condition that the bank angle is exactly the favorable bank angle that was used by the manufacturer for

sizing the vertical tail and is away from the inoperative engine.
The *actual* $V_{MCA}$, the $V_{MCA}$ that the pilot experiences in-flight, varies considerably with bank angle; *actual* $V_{MCA}$ is definitely not a single fixed airspeed equal to the published, standardized $V_{MCA}$ in the limitations section of the AFM. The pilot can control *actual* $V_{MCA}$ with bank angle and asymmetrical thrust, as long as the lateral and/ or directional controls ($\delta_a$, $\delta_r$) are not maximal.

4.3.12. *Actual* $V_{MCA}$ increases many knots (while at high asymmetrical power settings) if the wings are kept level, instead of banking the favorable bank angle away from the inoperative engine. The increase will be smaller on straight wing airplanes (approximately 10 knots).

4.3.13. *Actual* $V_{MCA}$ increases even more while maneuvering into the inoperative engine' side. If the *actual* $V_{MCA}$ increases above the (calibrated) airspeed due to a change of bank angle, the heading cannot be maintained using full rudder; control will be lost right away.

4.3.14. The $V_{MCA}$ that is published in AFMs is a minimum speed for maintaining a straight flight equilibrium following the failure of an engine, and is definitely not a minimum speed for maneuvering the airplane.

4.3.15. Although the AFM of the sample airplane of Figure 20 might state that the airplane is controllable down to the stall, this will only be the case as long as the bank angle is the same as used to size the vertical tail and to determine $V_{MCA}$: between 3° and 5° away from the inoperative engine, as opted by the manufacturer. Maintaining the small favorable bank angle away from the inoperative engine(s) however, is a live-saving condition to ensure the lowest, safest possible *actual* $V_{MCA}$, whether the inoperative engine is the critical or a non-critical engine.

4.3.16. These facts about the effect of bank angle and weight on $V_{MCA}$ are neither elaborated in most Flight, Training and Operating Manuals, including engine emergency procedures, nor in textbooks on asymmetrical flight and in FAR's and CS's. This might very well be the real cause of many engine failure related accidents.

### 4.4. Two engines inoperative

4.4.1. On 4 or more engine airplanes, two engines might occasionally become inoperative simultaneously, for instance after bird ingestion in both engines on one side. Therefore, for 4 or more engine airplanes, both $V_{MCA1}$ and $V_{MCA2}$ ($V_{MCA}$ with one engine (n-1) and two engines (n-2) on the same wing inoperative, respectively) are determined and presented in the AFMs of these airplanes. FAR/ CS 25 do not require $V_{MCA2}$ to be determined anymore, but use $V_{MCL2}$ and $V_{MCL1}$ ($V_{MCA}$ for approach and landing configuration) only. Contrary to military requirements, civil FAR/ CS do obviously not anticipate a dual engine failure in takeoff, cruise, or approach configurations. Whether determined or not, a $V_{MCA2}$ will definitely take effect on any 4 or more-engine airplane after engine failure. Therefore, pilots and accident investigators should still know about it. The FAR/ CS requirements for $V_{MCL2}$ do not make any difference for the explanation in this paragraph.

4.4.2. $V_{MCA1}$, also published as $V_{MCA}$, is the minimum control speed in anticipation of the failure of any one engine of a 4- or more engine airplane. When an engine is indeed inoperative, the small favorable bank angle away from the inoperative engine is required for maintaining control at airspeeds as low as $V_{MCA1}$, i.e. during straight flight. For safety reasons however, $V_{MCA2}$ will have become the minimum control speed for maintaining airplane control after any one of the engines is inoperative, in anticipation of the failure of a second engine. When two engines on the same wing are indeed inoperative, the small favorable angle away from the inoperative engines is required for maintaining control at airspeeds as low as $V_{MCA2}$ while the power setting is maximal. $V_{MCA2}$ is much higher than $V_{MCA1}$ because it is determined after shutting down the critical engine and the engine next to it on the same wing. The value of $V_{MCA2}$ is determined like $V_{MCA(1)}$ using a worst-case airplane configuration for control.

4.4.3. In Figure 22 below, the effect of bank angle and weight of two inoperative engines on the same wing is presented for the same 4-engine turbojet airplane as used in Figure 20 on page 25 for the one-engine inoperative case. As shown in the figure, $V_{MCA2}$ from this analysis is expected to be 117 kt if determined with a 5° bank angle away from the inoperative engine, as well as using other standardized test conditions, including the lowest possible weight (160,000 lb in this example). If the gross weight is above 225,000 lb, the *actual* $V_{MCA2}$ is expected to be below the stall speed. Then the airplane is controllable down to the stall, but only if bank angle $\phi$ is 5º away from the failed engines. A bank angle $\phi$ of 3º, less than 3º or to the other side increases *actual* $V_{MCA2}$ above the stall speed $V_S$ for these weights.

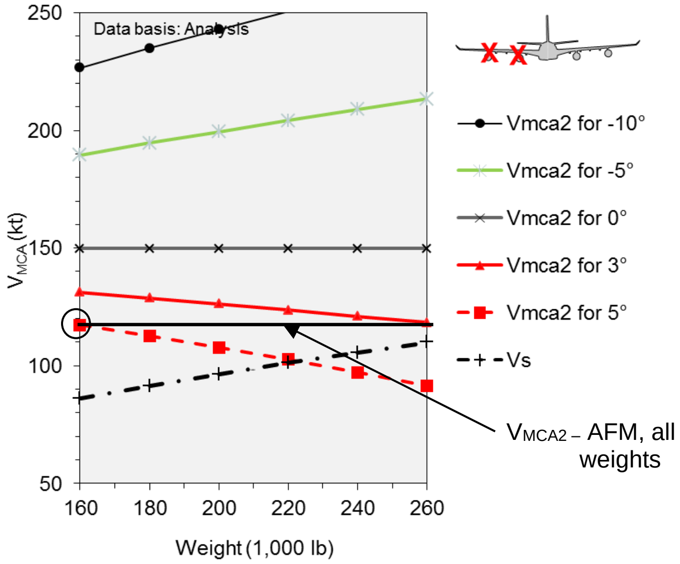

Figure 22. Effect of Bank Angle and Gross Weight on $V_{MCA2}$ – Two Engines Inoperative, max. takeoff thrust.

4.4.4. The $V_{MCA2}$ used in this example is obtained from analysis that is normally performed prior to conducting flight-testing to determine $V_{MCA2}$, in order to predict $V_{MCA2}$ as well as any control limitation that might be encountered during testing, see ref. 13 and § 5.3 below. Actual flight-testing is always required to determine the real $V_{MCA2}$ that is to be published in AFMs as operational limit.

4.4.5. Figure 23 below presents analyzed data for two inoperative engines, just like Figure 7 on page 14 for one inoperative engine. As can be observed in Figure 23, banking away from the favorable 5° bank angle to only 5º into the other side increases *actual* $V_{MCA2}$ in the analyzed configuration to a theoretical 190 knots at low gross weight and 213 knots at high gross weight, which is 73 kt respectively 96 kt above the standardized $V_{MCA2}$ that is published in the AFM. Compare this graph also to the one engine inoperative (n-1) graph in Figure 7.
These graphs show again that there definitely is a reason for maintaining a small bank angle away from the inoperative engine when the asymmetrical thrust is high.

4.4.6. Procedures for go-around if one engine is already inoperative require the airspeed to be increased first to at least $V_{MCA2}$ by accelerating down the glide slope to exchange available altitude for airspeed and by using symmetrical thrust only. Asymmetrical thrust may be added, provided directional control can be maintained. Any increase of asymmetrical thrust increases the requirement for rudder deflection, which increases the *actual* $V_{MCA}$, and should be accompanied by gradually increasing the bank angle to 5° (or less as opted by the manufacturer) away from the inoperative engine.

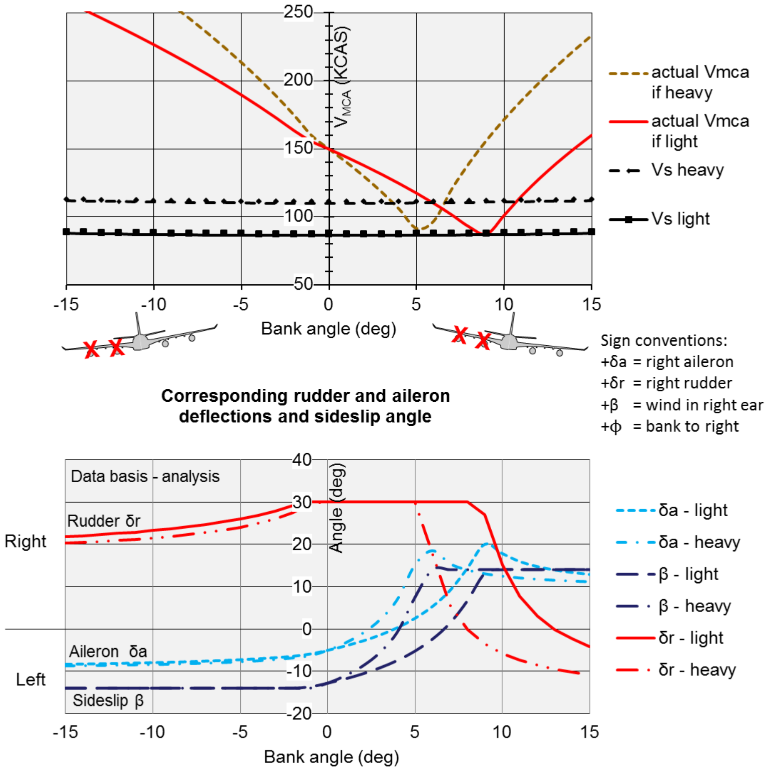

Figure 23. Effect of Bank Angle and Weight on $V_{MCA2}$, Two Engines Inoperative (n-2), max. takeoff thrust.

4.4.7. Pilots should be trained to use $V_{MCA2}$ for any *two inoperative engines*, inboard and/ or outboard, on the same wing or on both wings. Pilots and accident investigators will understand that the actual $V_{MCA1}$ after failure of an inboard engine (#2 or #3 on a 4-engine airplane) will most probably be no factor at all; the remaining yawing moment of the opposite inboard engine will be much smaller than after failure of an outboard engine, so is the rudder deflection to counteract this moment. The actual $V_{MCA(1)}$ in this case is anticipated to be below $V_S$. The same will be the case after failure of two opposite engines (#1 and #4, or #2 and #3) on a 4-engine airplane. Then there is no adverse thrust yawing moment for which a rudder deflection is required to counteract; the actual $V_{MCA2}$ will be very low.

If, for instance, engine #3 failed in-flight and a go-around becomes necessary during which engines #1 and #2 fail as well, the actual minimum control speed will be $V_{MCA1}$, because only engine #4 provides thrust and a yawing moment. The minimum control speed to be observed by the pilots for the go-around would however have to be $V_{MCA2}$, in anticipation of another engine failure. If the airspeed during the approach decreases below $V_{MCA2}$ and it will not be possible to increase the airspeed before going around, the airplane will in fact be committed to land. This order of engine failure actually happened during a *C-130 go-around accident* when #3 was shut down before or during the approach and #1 and #2 failed due to bird ingestion just after initiating a go-around at the threshold speed (108 kt). Because the airspeed (between 97 and 108 kt) was even below $V_{MCA1}$ (117 kt with wings level), control was lost; the airplane crashed 12 seconds later from threshold altitude on the terrain next to the runway. For a safe go-around, the airspeed should not have been lower than $V_{MCA2}$ (134 kt); this airplane was committed to land at the instant the airspeed decreased below $V_{MCA2}$ because one engine (#3) was already inoperative.

Engine #2 on a tri-jet has no influence on the thrust yawing moments; hence, its failure does not affect directional control, but only the pitching moments and performance.

## 4.5. Critical engine

4.5.1. At high-speed flight, the angle of attack α (AOA) of the wings of an airplane is small. The relative wind not only runs into the lift-producing wings, but also into the propeller blades. Figure 24 shows the up and down-going propeller blades of a two-bladed propeller on the same engine in a side view, both at the instant they are horizontal. The resultant blade velocity of each of the blades (dotted vector) is the resultant of the rotational blade velocity (Prop RPM) and the forward airspeed. In this case, the AOA's of both blades are nearly equal, so is the thrust developed by each of the blades.

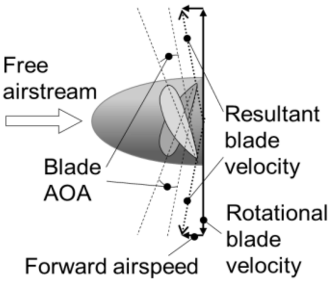

Figure 24. Propeller blades angles of attack, high speed level flight.

4.5.2. If the airspeed of the airplane decreases or is low (during takeoff or go-around), the AOA of the wings of the airplane has to increase to maintain the required lift for level flight or to climb. Not only the AOA of the wings increases, but also the AOA of the down-going propeller blade, increasing the thrust of this blade, as Figure 25 shows; the AOA of the opposite up-going blade decreases, decreasing the thrust generated by that blade. In addition, the resultant velocity of the down-going blade increases, increasing its thrust even more, because the forward airspeed vector is still in the direction of the free airstream; the resultant velocity of the up-going blade decreases (think of a helicopter rotor; the airspeeds of the forward and aft moving blades). Therefore, at low speed when the AOA is higher, the thrust or propulsion vector (P-vector – has a magnitude and a direction) of the whole propeller disc shifts in the direction of the down-going or descending propeller blade. This asymmetrical loading of the propeller disc is often also called *P-factor*, see Figure 26.

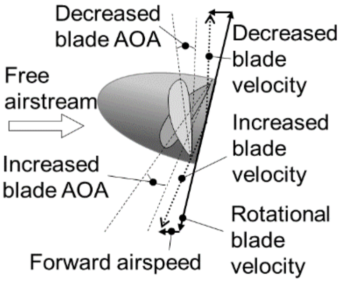

Figure 25. Propeller blades angles of attack, low speed level flight.

4.5.3. If both propellers of a twin-engine airplane rotate clockwise, an increasing AOA shifts the thrust vectors of both propellers to the right. The moment arm of the propeller thrust on the left wing (thrust #1) decreases and the moment arm of the propeller thrust on the right wing (thrust #2) increases. Then the yawing moment of engine #2 (thrust #2 × arm #2) is larger than the yawing moment of engine #1 (thrust #1 × arm #1). This effect is also noticeable during normal all-engines-operative operations at low speed (i.e. at high AOA), when a rudder input will be required to counteract the difference in thrust yawing moments for maintaining the heading.

4.5.4. If engine #1 fails, the total remaining thrust yawing moment (in this case generated by engine #2) is larger than the remaining thrust yawing moment if engine #2 would fail. A larger asymmetrical thrust moment requires larger rudder deflection to counteract or – if the rudder is at its limit as required for determining $V_{MCA}$ – a higher airspeed. Consequently, $V_{MCA}$ after failure of engine #1 will be higher than $V_{MCA}$ after failure of engine #2. The engine that, after failure, results in the highest $V_{MCA}$ is called the *critical engine*. This will be confirmed during flight-testing (§ 5.3.7). In this example the left engine (#1) is the critical engine, because both propellers rotate clockwise.

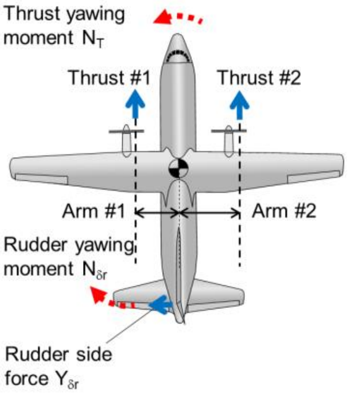

Figure 26. Asymmetrical propeller disc loading (P-vector); AOA increased; propellers rotate clockwise.

4.5.5. If the airplane is equipped with *counter-rotating propellers,* such as the PA-34 Seneca, or with *turbofans*, there is no difference between the thrust yawing moments with increasing AOA while an engine on the left or right wing is inoperative, provided the gyroscopic effects of rotating engines and propellers are negligible. The opposite engines are equally critical; the actual $V_{MCA}$ is the same after failure of #1 or #2. If a rudder boosting system is powered by only one of the engines, that engine might be the critical engine though. Rudder boosting is discussed in § 4.12 below. Slipstream effects might have influence as well, refer to § 4.9.

4.5.6. On *four or more engine airplanes*, the thrust yawing moments and hence the *actual* $V_{MCA}$'s differ for an inboard and an outboard engine. The outboard engines are most critical because of the longer moment arm. If equipped with four propellers that turn clockwise, engine #1 is the most critical engine. The minimum control speed $V_{MCA2}$ for two inoperative engines on the same wing (n-2) is discussed in § 4.4 above.

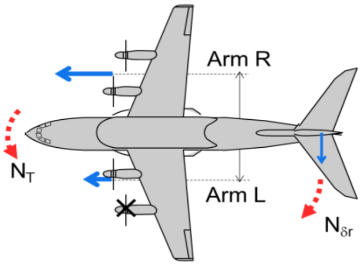

Figure 27. Airbus A400M with counter-rotating propellers, One Engine Inoperative.

4.5.7. Figure 27 shows a top view of the *Airbus A400M*. Unique to the propulsion system of this airplane are the counter-rotating propellers on both wings; both propellers on each wing rotate in opposite direction to each other, down in-between. If both engines on the same wing are operative, the shift of the thrust vector with increasing AOA is always towards the other engine on the same wing; the effect is that the resultant thrust/ propulsion vector of both engines on the same wing does not shift as the angle of attack of the airplane increases. There is no overall change of the P-vector; there will be no difference in magnitude of remaining thrust yawing moments $N_T$ after failure of either engine #1 or #4 with increasing AOA, only in direction left or right. This means that $V_{MCA}$ after failure of either one of the outboard engines will be the same, unless (boosting) systems, that may be required for controlling the airplane, are installed on only one of the outboard engines. This airplane does therefore not have a left- or right-hand critical engine; both outboard engines are equally critical.

4.5.8. If an outboard engine fails, for instance #1 as shown in Figure 27, the moment arm of the vector of the remaining thrust on that wing reduces from in between the engines to a bit outside of the remaining inboard engine. The vector itself is 50% of the opposite thrust vector. The resulting $N_T$ is much smaller than would be the case for conventional propeller rotation. The maximum $Y_{\delta r}$ and $N_{\delta r}$ to be generated by the vertical tail with rudder can be smaller and consequently, the size of vertical tail of this airplane can be smaller. There is however one very important condition: the feathering system of the big 8-bladed, 17.5 ft (5.33 m) diameter and therefore high drag propellers must be automatic, very rapid and failure free to ensure the lowest possible propeller drag following a propulsion system malfunction. If not, a failure of the feathering system of an outboard engine will increase propeller drag, which in turn enlarges $N_T$ considerably therewith increasing the *actual* $V_{MCA}$. The control power generated by the small vertical tail and rudder alone is low by the small design. Only rapid reduction of thrust of the opposite engine, or (increased) airspeed can restore the required control power to maintain straight flight following the failure of a feathering system. Designing and approving the feathering system for this airplane will be a real challenge to the design engineers and the certification authorities.
On airplanes with very powerful engines, an asymmetrical thrust problem is also being solved by applying automatic thrust asymmetry compensation, see also § 4.6 below, but this has consequences for takeoff performance.

4.5.9. AFMs present the $V_{MCA}$ that is determined after failure of the (or a) critical engine. This provides the highest, the worst case, $V_{MCA}$ after any engine failure that is valid as long as the bank angle is the same as used for sizing the vertical tail and during $V_{MCA}$ testing, and the thrust is maximal. The actual $V_{MCA}$ after failure of any other engine is lower – which is safer. The adjective 'critical' is only of use to airplane design engineers and test pilots to make sure they determine and use the highest $V_{MCA}$ after failure of any of the engines. Airline pilots should not have to worry whether a failing engine is critical or not; they should not even have to learn about the criticality of an engine. There is only one engine emergency procedure in the checklist or QRH and there is only one $V_{MCA}$ published in the limitations section of the AFM, which is a safe minimum control speed before and after failure of either engine. Pilots might only observe a small difference in yaw rate between failure of the critical and non-critical engine, if at all noticeable. See also § 7.3.4 below.

### 4.6. Engine thrust, altitude and temperature

4.6.1. The thrust setting used on the remaining engine(s) for determining $V_{MCA}$ is the maximum thrust that is guaranteed by the manufacturer in the specification of the engines. The lower the asymmetrical thrust setting while an engine is inoperative, the lower the rudder requirement will be and/ or the lower the airspeed can be to provide the required rudder control power ($\equiv V^2$) for straight flight; *actual* $V_{MCA}$ is lower. As discussed before, if the aerodynamic control power is insufficient to restore control or to maintain straight flight after engine failure, the throttle setting of the engine opposite of the failed or inoperative engine must be decreased a little but only temporarily, and also only as much as required to restore or maintain control. This happened prior to the accident analyzed in § 8.4.8.

4.6.2. If during the lifetime of the airframe, engines are replaced by more powerful versions, the vertical tail might have to be increased in size, or $V_{MCA}$ might have to be increased (or an increment applied). Derating new, more powerful engines is also an option for not having to modify the tail or change $V_{MCA}$, refer to § 4.7 below. The accident analyzed in § 8.5 might have happened because $V_{MCA}$ was not appropriately increased after installing more powerful engines, see § 8.5.8.

4.6.3. On airplanes that are retrofitted with more powerful engines without increasing the size of the vertical tail, a thrust asymmetry control system is required to decrease the thrust of the engine opposite of the failing engine automatically as required to maintain control. This keeps the *actual* minimum control speed to a safe lower level. The airplane manufacturer must have considered a system like this, if fitted, to be important if not indispensable for restoring and maintaining control after engine failure. A consequence is that this system will also decrease the acceleration during the takeoff run and, if used in flight, the remaining climb performance upon activation.

4.6.4. The thrust of most engines changes with air density (altitude) and temperature; increasing the altitude and/ or temperature will decrease the thrust. After engine failure at high altitude, the asymmetrical thrust yawing moment will be smaller. The *actual* $V_{MCA}$ will be lower (Figure 28). A large variation of engine thrust with density and temperature results in a large variation of *actual* $V_{MCA}$'s, which is the reason that (turboprop) airplane manufacturers provide several charts with (real) $V_{MCA}$ data for different altitudes and temperatures in the AFM to better facilitate hot and high operations. The $V_{MCA}$ and the therewith derived $V_R$ and $V_2$ that are used for takeoff planning will be more accurate for the actual circumstances. The $V_{MCA}$ obtained this way is the real $V_{MCA}$ for the given altitude and temperature. Any lower altitude or lower temperature will increase this $V_{MCA}$ to a higher actual value (Figure 28).

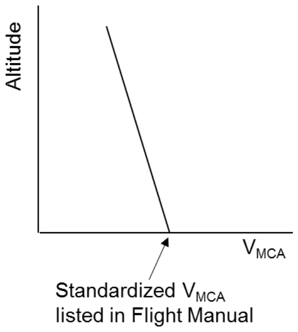

Figure 28. Change of (actual) $V_{MCA}$ with altitude.

4.6.5. During an approach with an inoperative engine, the thrust setting is low and hence the *actual* $V_{MCA}$ is low as well. If a go-around becomes necessary, adding asymmetrical thrust increases *actual* $V_{MCA}$ simultaneously with the thrust. To avoid controllability problems, the acceleration to the go-around speed should be performed while still flying down the glide path before initiating the climb, using symmetrical thrust, while adding as much asymmetrical thrust as possible to maintain straight flight. While adding asymmetrical thrust, simultaneous rudder deflection as well as gradual banking to the specified favorable bank angle (between 3° and 5°) both away from the inoperative engine is required to keep *actual* $V_{MCA}$ as low as possible and prevent the loss of control.

4.6.6. If during engine-out operations flight idle is set on the simulated failed engine, the spillage drag (turbofans) or propeller drag (the propeller will not feather while idling) increases the asymmetrical thrust yawing moment $N_T$. Either the rudder deflection must increase or, if already maximum, the airspeed must be increased. The actual $V_{MCA}$ might become higher than the AFM-published $V_{MCA}$, if the other variables that have influence on $V_{MCA}$ happen to be at their worst-case values.
For training purposes, airplane manufacturers provide a (number of) thrust setting(s) to be set on the simulated inoperative engine to match the drag of a feathered propeller or the spillage drag on a turbofan. These settings correspond to zero drag or zero thrust.

4.6.7. Asymmetrical engine thrust has the greatest effect on $V_{MCA}$. *Actual* $V_{MCA}$ is most critical (highest) when the thrust setting is high, but will be no factor for airplane control if the thrust is low. Then the asymmetrical thrust level is lower, as is the required rudder deflection to counteract $N_T$; actual $V_{MCA}$ is lower.

### 4.7. Thrust derating and flexible or reduced thrust

4.7.1. ***Derated thrust.*** In the case of thrust derating, the surplus thrust that is available in the engine design is not made available at hand by setting the thrust or power levers (throttles) in the cockpit fully forward. The thrust is limited by engineers by changing settings on the engine itself at the time of engine installation. This is common practice for installing similar engine types on different types and sizes of airplanes. Thrust derating might be required to limit the maximum asymmetrical thrust yawing moment for the available tail size and therewith keep the $V_{MCA}$ below 1.2 or 1.13 $V_S$ (§ 2.4.4). The $V_{MCA}$ published in the AFM must be based on the maximum thrust that the pilot can set by moving the throttles or power levers fully forward, and not on a thrust level that is lower than full throttle and that is sometimes inappropriately called 'derated', but in fact is 'reduced' thrust. The derived takeoff speeds $V_R$ and $V_2$ will also be based on the derated thrust level (§ 6.4, § 6.5).

4.7.2. On some modern types of airplanes though, thrust derating is settable to several levels during preflight from the cockpit for the next takeoff. In that case, the AFM must present a set of performance data for every possible derated maximum thrust setting, each including a specific $V_{MCA}$ as operating limitation, because $V_{MCA}$ is based on the maximum thrust that can be set with the thrust levers in the cockpit. The $V_{MCA}$ after this kind of thrust derating is lower because the maximum thrust yawing moment $N_T$ is lower following engine failure and after moving the throttles fully forward (to the derated maximum). If, however, the thrust is uprated, $V_{MCA}$ will increase.

4.7.3. ***Flexible or reduced thrust*** is a thrust level less than the maximum settable thrust with the throttles; it is being used to preserve engine life. An assumed higher outside air temperature and/ or reduced throttle setting are used to achieve the lowest possible thrust level for a takeoff on the available runway length. In this case, the same $V_{MCA}$ data apply as for the available highest takeoff thrust setting, because maximum takeoff thrust is still settable anytime by moving the throttles forward. As long as the thrust setting during flexible or reduced takeoff is lower, the *actual* $V_{MCA}$ is lower. If however, following the failure of an engine, the throttles of the operative engines are set from the flex setting to maximum available thrust to achieve maximum acceleration and climb performance, then the *actual* $V_{MCA}$ increases again to the value presented in the AFM, provided the bank angle is 5°, or the number of degrees specified by the manufacturer, away from the failed engine (§ 4.3). The text and caution in the AFM of the EMB-120 accident, as discussed in § 8.5.7 and § 8.5.8 below, suggest an illegal and inappropriately documented increase of thrust/ change of propellers or engines, after which $V_{MCA}$ in the AFM was not changed. Accident investigators should verify in the Type Certificate whether the propulsion system components are indeed approved.

### 4.8. Partial control deflection

4.8.1. $V_{MCA}$ of a multi-engine airplane is determined when the rudder and/ or ailerons are either fully deflected or when reaching a predetermined rudder or aileron control force limit, whichever occurs first during the test (explained in § 5). If the rudder is not fully deflected (while the asymmetrical thrust is maximum), then the *actual* airspeed for the vertical fin with rudder to generate a side force high enough to counteract the – still same – high asymmetrical thrust will have to be higher than the airspeed that was measured during the flight-test to determine the FAR and CS based $V_{MCA}$. The *actual* airspeed for maintaining control with partial rudder or aileron is therefore higher than the AFM published $V_{MCA}$ that was determined under FAR and CS 23.149 and 25.149, ref.'s 6, 7. See also to § 2.9.2. The accident discussed in § 8.4 was caused because of a too small rudder control deflection and hence, because *actual* $V_{MCA}$ increased above the indicated airspeed.

4.8.2. On military transport airplanes, only a maximum of ¾ (75%) of the available roll control deflection may be used to determine $V_{MCA}$, to leave some control margin for transient responses, and to cope with gusts; the rudder control force is allowed to be higher, though (§ 2.7.4). This in fact means that the $V_{MCA}$'s of airplane types that are used both as civilian and as military transports might differ from each other.

4.8.3. On some airplanes, one or more engine failures reduce the hydraulic power for operating the outboard and inboard ailerons and roll-assisting spoilers. This might increase the actual $V_{MCA}$ as well.

### 4.9. Slipstream effects

4.9.1. Asymmetrical and spiraling slipstream effects might influence the recovery after engine failure, as well as the magnitude of $V_{MCA}$. The accelerated slipstream over the wing of the failed engine is lost, reducing the lift. In addition, the slipstream of operating engines might influence the air stream around the horizontal and vertical tail (during side slipping immediately after engine failure). Some airplanes have vortex inducers on the vertical tail to prevent an early 'fin' stall when the sideslip angle increases during equilibrium flight with an inoperative engine, for instance with the wings level (§ 2.7) or while turning (§ 2.10). Slipstream effects might have influence on the magnitude of both static and dynamic $V_{MCA}$ (§ 5 below) and, if the effects are dominant, the slipstream might even determine which of the engines is critical or is the next critical engine. During flight-testing $V_{MCA}$, slipstream effects, if any, will have influence on $V_{MCA}$, for the bank angles and resulting sideslip tested. If a pilot maintains the small favorable bank angle to reduce the sideslip to near zero, the slipstream does neither affect the directional control with the rudder, nor actual $V_{MCA}$. However, if during airline operations following an engine failure a bank angle is allowed that results in an increased sideslip angle, the slipstream effects might increase *actual* $V_{MCA}$ to a value higher than the published $V_{MCA}$ or to an early fin stall. This is not flight-tested.

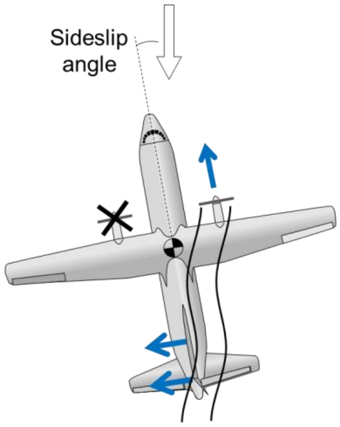

Figure 29. Slipstream effects due to sideslip.

### 4.10. Propellers

4.10.1. Following an engine failure, the airflow will start driving a not yet feathered propeller (windmilling) causing the drag of the propeller to increase significantly. Also, a propeller failure might prevent the propeller blades from feathering or decreasing the blade angle to zero (to min. drag). The yawing moment generated by this additional propeller drag increases the asymmetrical yawing moment of the opposite operative engine, which – during takeoff or go-around – might be at maximum available takeoff thrust setting to attain the maximum available climb performance. The lower the propeller drag, the smaller the asymmetrical yawing moment and the less rudder deflection is required to maintain straight flight at any given airspeed. Most propellers are equipped with an auto-feather system that automatically feathers the propeller blades after engine failure (unless disabled or not armed). The $V_{MCA}$ of these airplanes is determined with a feathered propeller. Small twin-engine airplanes might not have an automatic feathering system; the propeller might continue to windmill after engine failure, causing high propeller drag, until manually feathered. The $V_{MCA}$ of these airplanes is determined with a not-feathered propeller, hence with higher drag, and will therefore be high enough to be able to maintain control, provided again the bank angle is 5°, or the number of degrees specified by the manufacturer during certification, away from the failed engine. Not feathering a propeller contributed to the cause of the accident analyzed in § 8.4. The P-factor, i.e. the shift of the thrust vector in a propeller blade, was discussed in § 4.5 above.

4.10.2. Some airplanes do not have an automatic full feathering system, but a negative torque sensing system (NTS), the purpose of which is to reduce propeller drag and therewith an excessive yawing moment. When a negative torque is sensed, the propeller is driving the engine. The propeller will not be fully feathered but continues to rotate at high pitch, which makes a restart, if possible, easier. In case of engine failure or when the engine still generates some torque, the NTS might not operate. Therefore, on NTS equipped engines, the pilot should feather the propeller manually to reduce its drag (and *actual* $V_{MCA}$) to a minimum.

4.10.3. Propellers will only auto-feather after engine failure if the feathering system is enabled or armed and a few other conditions are met. Arming is normally set prior to both takeoff and landing (in anticipation of an engine failure during go-around). If feathering was used for determining $V_{MCA}$, the asymmetrical thrust yawing moment $N_T$ without feathering is (much) larger and hence a larger rudder deflection is required for straight flight: the *actual* $V_{MCA}$ is higher. This has a consequence for training too; a realistic $V_{MCA}$ cannot be demonstrated by just idling one of the engines, the thrust setting for zero drag has to be set; see also § 4.6.6.

4.10.4. For determining $V_{MCA}$, the propeller has to be in the pitch setting that it assumes by itself after engine failure without pilot intervention, which is either windmilling or feathered. $V_{MCA}$ data in AFMs are based on this condition although some manufacturers report two $V_{MCA}$'s, one with and one without auto-feathered propeller depending on the criticality of the auto-feather system of the airplane. The higher drag of an idling propeller enlarges the asymmetrical thrust yawing moment $N_T$. Larger rudder deflection is required for straight flight or a higher airspeed if the rudder is at maximum deflection; hence, $V_{MCA}$ is higher.

4.10.5. When a propeller is replaced by a propeller with a different part number, for instance a 3-blade is replaced by a 4-blade, the thrust that the propellers can provide changes as well. Increased thrust results in a higher $V_{MCA}$ which should be included in the AFM, for which $V_{MCA}$ needs to be re-established, or the vertical tail re-designed.

4.10.6. ***Torque and gyroscopic*** effects due to rotating engines and propellers are mostly neglected in the $V_{MCA}$ analysis. These effects, as well as the rapidness of the automatic feathering process, if any, play their role in determining the dynamic $V_{MCA}$ during transient effects flight-testing (§ 5.4). The effects will be included in the $V_{MCA}$ that is determined during flight-testing.

4.10.7. ***Summary***. In case the propeller of an inoperative engine is in a configuration other than used during flight-testing $V_{MCA}$, the *actual* $V_{MCA}$ might be much higher than the published, standardized $V_{MCA}$, which is very unsafe if the thrust of the operative engine(s) is high, or is increased during a go-around. A suspected failed propeller/engine should never be left idling as a 'standby source of thrust'; the engine should be shut down or set to provide zero thrust/ drag in order for the actual $V_{MCA}$ to be as low as or lower than the published $V_{MCA}$. If a propeller is not-feathered (because the engine is kept idling) or if the feathering system fails (or is not armed), the drag and, hence, *actual* $V_{MCA}$ is much higher than the published (and indicated) $V_{MCA}$. Loss of control will occur as soon as (asymmetrical) thrust is increased (during approach or go-around) or is high.

4.10.8. Flight training with an inoperative propeller/engine should be performed using some thrust on the simulated dead engine to simulate zero drag/ thrust to be able to demonstrate a more realistic $V_{MCA}$. Training the appropriate response to a sudden engine failure however, would require actually shutting down an engine in-flight, which is not recommended (by the owners) – use simulators instead.

## 4.11. Effect of center of gravity on $V_{MCA}$

4.11.1. ***Longitudinal center of gravity***. The yawing moment generated by the rudder ($N_{\delta r}$), is the product of the moment arm or distance from the center of gravity to the aerodynamic force $Y_{\delta r}$ developed by the rudder. If the center of gravity is at its approved aft limit, the moment arm is shortest and the yawing moment generated by the vertical tail and rudder deflection is smallest. If the center of gravity is more forward, the moment arm to the rudder side force $Y_{\delta r}$ is longer and rudder deflection can be smaller to counteract $N_T$ (Figure 30). Then the airspeed could be further decreased until rudder deflection is again maximum: *actual* $V_{MCA}$ with a forward center of gravity is lower – is safer because the margin between $V_{MCA}$ and the indicated airspeed is larger. Some airplanes allow longitudinal cg shift by transferring fuel from/ to a horizontal stabilizer tank.

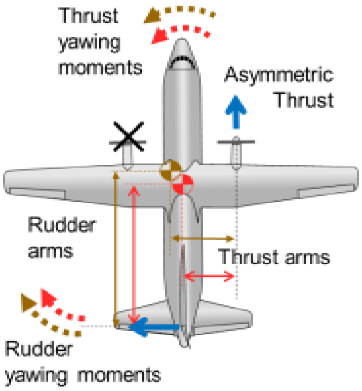

Figure 30. Center of gravity shift, longitudinal and lateral.

4.11.2. ***Lateral center of gravity***. A lateral shift of the center of gravity into the inoperative engine (Figure 30) increases the asymmetrical thrust yawing moment of the live engine(s) and requires a higher counteracting moment and force: increased rudder and aileron deflection are required or, if these are maximum already, the airspeed needs to be higher: *actual* $V_{MCA}$ increases. Therefore, AFMs present a maximum allowable wing-fuel imbalance or asymmetry (max. lateral center of gravity) to avoid controllability problems after engine failure due to excessive lateral shift of the center of gravity and to limit drag. Fuel could be transferred to the wing of the operative engine to shift the lateral center of gravity away from the inoperative engine and therewith reduce the thrust yawing moment and therewith the drag, and decrease the *actual* $V_{MCA}$.

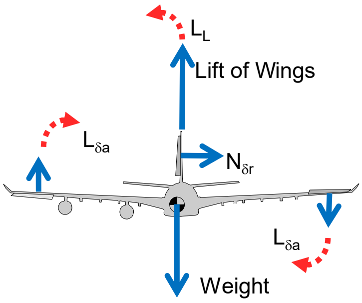

Figure 31. CG and lateral forces and moments after loss of two engines.

4.11.3. If an airplane loses one or more engines (for instance due to shear or fuse pin failure, Figure 31), the cg shifts laterally as well. The wing lift vector does not shift, unless damage to the affected wing reduces the lift of that wing (a bit). The wing lift vector now results in a rolling moment due to lift ($L_L$), that also must be counteracted by the ailerons ($L_{\delta a}$). For a Boeing 747, a (fuel) imbalance condition or quantity less than 900 kg (2,000 lb) is approved for the ailerons to provide adequate control power at takeoff and landing speeds, while each of its turbofan engines weighs approximately 4,000 kg (8,800 lb), a lot more than the approved fuel imbalance. In addition, fuel leaking from the affected wing shifts the cg even further into the good engine side. As the ailerons will not be sized large enough to counteract a larger than – in this case 900 kg (2,000 lb) – weight imbalance, the minimum speed to be able to maintain lateral control is and needs to be a lot higher. Roll assisting spoilers, if installed, might also play a role.
In addition, the asymmetrical thrust yawing moment of the two remaining engines is also increased, and is maximal if the thrust is increased to maximum.
To counteract the increased rolling and yawing moments, larger rudder and aileron deflections are required or, if any of these are already maximal deflected, a higher speed. The minimum speed at which control can be maintained, i.e. the *actual* $V_{MCA}$ of the airplane, is increased to a value much higher than the published $V_{MCA}$. If the airspeed is lower than, or is decreased below this increased *actual* $V_{MCA}$, and asymmetrical power is maximal or increased to maintain altitude or glide path during the approach, lateral control will be lost. The increased $V_{MCA}$ is not visible, but if either rudder or aileron deflection is near maximal to maintain straight flight, the airspeed is already very close to the *actual* $V_{MCA}$ and the airplane is on the brink of the loss of

control. Then do not decrease the speed any further, and do not increase the thrust of the operative engines.

4.11.4. ***Summary***. Considering all possible centers of gravity for determining the accompanying $V_{MCA}$ would be excessively complicated. $V_{MCA}$ is therefore determined with the center of gravity at the maximum approved lateral position into the critical engine and most aft, both representing the worst case, because this returns the highest $V_{MCA}$ due to center of gravity shift (at the proper bank angle). During normal operations, the *actual* $V_{MCA}$ will not increase above the published value due to any center of gravity shift within the approved envelope. Airline pilots therefore do not have to worry whether the center of gravity is forward or aft, left or right. The published $V_{MCA}$ is valid for any center of gravity within the approved envelope, as long as the small favorable bank angle is maintained away from the inoperative engine when the thrust is maximal. The location of the center of gravity is not a variable factor in the $V_{MCA}$ charts in AFMs; this would unnecessarily complicate looking-up the applicable $V_{MCA}$ during preflight or before landing.

4.11.5. As preparation for any landing, a go-around has to be anticipated. To increase the safety of a go-around, part of the preparation for a landing with an already inoperative engine on a 4 or more-engine airplane could be to move the center of gravity to a position that decreases actual $V_{MCA}$, i.e. as much forward and away from the inoperative engine as the center of gravity envelope allows. This could be done by transferring fuel away from the inoperative engine and forward, and/ or by moving passengers, if at all possible and feasible.

### 4.12. Yaw damper and rudder boosting

4.12.1. Yaw dampers are used in high-performance airplanes to reduce sideslip excursions due to outside influences such as turbulence, alleviate lateral-directional control problems, and to provide for automatic turn coordination (aileron to rudder interconnect). In addition, the rudder control forces might be too large and have to be reduced. For this purpose, airplanes might be equipped with an electric or hydraulic rudder boosting system to increase the rudder deflection per pound (or Newton) of pedal force, which might be crucial for maintaining control under asymmetrical thrust conditions. Some boost systems might only be available at low airspeeds to avoid damage to the vertical tail at higher airspeeds and might be automatically switched on as flaps are selected down in stages of one or more different boost pressure levels. As one of the engines fails, the boosting system kicks-in and deflects the rudder therewith assisting the pilot. The moving pedals might be surprising, but should not be resisted. Additional trimming via rudder pedals or manual trim knob might be required.

4.12.2. If a hydraulic pump that powers the boost system happens to be driven by the inoperative engine, the boost pressure might be lower than required, or not be available at all. If the airplane is equipped with only one hydraulic pump driven by one of the engines, that engine might have to be defined as the critical engine (§ 4.5). If boosting fails, the *actual* $V_{MCA}$ will be higher than the published $V_{MCA}$.

4.12.3. If the flap handle is not selected (above a certain setting), rudder boosting might not be switched on and *actual* $V_{MCA}$ will be much higher than anticipated. The boost system has a very powerful effect on the value of $V_{MCA}$. If not switched on, a $V_{MCA}$ increase of 30 knots is not exceptional. Refer to the AFM to determine whether the flap handle position affects $V_{MCA}$ on the airplane of interest, and whether other boost or damper switches might be disabling or interrupting.

4.12.4. A rudder ratio changer/system on some (larger) airplanes reduces the rudder deflection with increase in airspeed to avoid damage to the vertical tail. Figure 32 below shows the decrease of a Boeing 747-200. The decrease looks like a quadratic function, meaning that the aerodynamic side force generated by the rudder ($\equiv \rho V^2$) does not increase further at airspeeds above 160 KCAS. The influence of a rudder ratio system is not subject to flight-testing and is not included in the analysis of actual $V_{MCA}$ in § 2.4.8 above. Further analysis is required, if necessary.

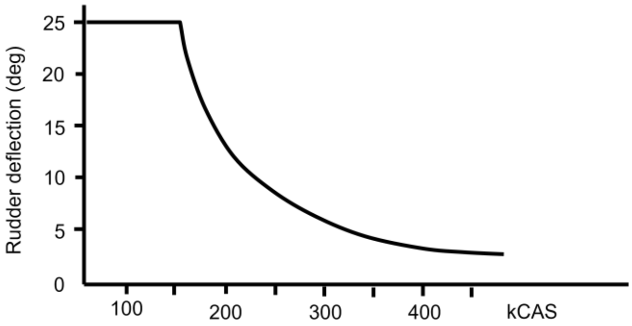

Figure 32. Effect Rudder Ratio System on rudder surface deflection of a sample airplane.

### 4.13. Landing gear, flaps, slats, and spoilers

4.13.1. The drag of the landing gear is symmetrical about the center of gravity, provided the pilot maintains straight flight with no sideslip. Then, the extended landing gear might have no influence on $V_{MCA}$. The total drag of course is higher, on some airplanes just a little, on other airplane types more. If, however, the sideslip angle $\beta$ is not zero, the extended landing gear has some influence on the equilibrium of lateral forces and moments. Because the moment arms of the main landing gears to the center of gravity are small, the yawing moments due to gear drag will not be large; furthermore, the drag induced forces act behind the center of gravity (for nose gear airplanes). It is dependent on the direction of the sideslip, whether these forces are in the same direction or opposite of the rudder generated side force. During side slipping, the side force of the nose gear on big airplanes has a much longer moment arm to the center of gravity. If the pilot allows a sideslip to build up by keeping the wings level after engine failure, the nose gear will generate a side force due to drag and hence an additional yawing moment that requires a change of rudder deflection: *actual* $V_{MCA}$ will either increase or decrease.

An extended landing gear has no asymmetrical effects if the sideslip is zero. Zero sideslip can be achieved with a small 3° to 5° bank angle, as was explained in § 2.8 and § 4.3. In addition, as long as the landing gear is down, its drag of course decreases the rate of climb, but retracting the gear might temporarily decrease the available rudder boost pressure (§ 4.12), therewith temporarily reducing the rudder deflection and increasing *actual* $V_{MCA}$. The opening of gear doors could also increase the drag temporarily. Retracting the gear might also affect the center of gravity, hence the rudder yawing moment a little. Check the AFM whether the gear should be left extended until reaching a safer speed and/ or altitude.

4.13.2. ***Flaps and slats***, after extension, might have an effect on the airflow striking the tail and therewith affect $V_{MCA}$ (if the sideslip is not maintained zero with the small favorable bank angle). Flaps might also affect the angle of attack of the airplane, and therewith, on propeller airplanes, the location of the P-factor in the propeller disc, and hence the thrust yawing moment, and $V_{MCA}$. In addition, flaps might result in a roll rate due to asymmetrical (propulsive) wing lift. The flap handle might also be mechanized to switch on or increase the rudder boost pressure system, so the position of the flap selector handle has influence on the rudder control force and on $V_{MCA}$ (§ 4.12). On some airplanes, $V_{MCA}$ with flaps up is more than 10 kt higher than with takeoff flaps. If boost would be off or low – as might be the case with the flap handle at zero – or during a flapless approach and landing, $V_{MCA}$ would be much higher. This increase of $V_{MCA}$ is indeed a factor to consider while returning to base while an engine is inoperative.

4.13.3. $V_{MCA}$ is to be determined with gear and flaps extended, but not with gear and flaps in transition. Refer to the AFM of the airplane to find out whether transitioning or retracted flaps affect $V_{MCA}$ on a particular airplane. This would be 'nice' to know for a safe return to base following the failure of an engine.

4.13.4. ***Spoilers*** affect the lift distribution (rolling moment) on and the drag of the wings (yawing moment). When flight spoilers kick-in asymmetrically (when the control wheel is rotated more than 7°) to assist roll control during the early phases of takeoff or during approach. By limiting roll control to 7°, the favorable bank angle might not be reached, hence, the actual $V_{MCA}$ is higher and sideslip is not zero, performance is not maximum (§ 4.3.7).

### 4.14. Ground effect

An airplane is in ground effect if the altitude is less than about half a wingspan above the ground. On some airplanes, $V_{MCA}$ might be influenced by the ground effect, because the aerodynamic control power might change while the airplane is close to the ground. On other airplanes, the pitot-static air data system might be influenced by the ground effect. Then, $V_{MCA}$ out of ground effect might differ a few knots from $V_{MCA}$ in ground effect. The AFM might present different graphs for $V_{MCA}$ in and out of ground effect. The highest $V_{MCA}$ of in and out of ground effect should be used for takeoff.

### 4.15. Stall speed

4.15.1. Some multi-engine airplanes with the engines mounted close to the fuselage (small thrust moment arm) or with counter-rotating propellers have a $V_{MCA}$ that is lower than the stall speed $V_S$, in which case the AFM either lists no $V_{MCA}$ at all, or states that 'the airplane is controllable down to the stall', which is of course the preferable and most safe situation. However, as was explained in § 4.3, this will only be the case if the pilot (after engine failure) actually maintains the bank angle that was used to design the vertical tail and to determine $V_{MCA}$, in most cases 5° away from the inoperative engine. If the bank angle differs from this favorable bank angle, actual $V_{MCA}$ might increase to a value higher than $V_S$ and a controllability problem might arise despite of the statement in the AFM. Refer to Figure 7 and to § 6.

### 4.16. Load factor

4.16.1. For airplanes that are controllable down to the stall while an engine is inoperative (§ 4.15 above), a pushover maneuver was sometimes used to decrease the load factor. This way, as was believed, $V_{MCA}$ could be determined or demonstrated. During this maneuver, a load factor less than 1 g decreases the apparent weight of the airplane and hence decreases the stall speed $V_S$ temporarily below $V_{MCA}$. In addition, the weight W in side force $W \cdot \sin \phi$ changes, changing the balance of forces and moments, unless the wings are kept level.
However, $V_{MCA}$ is defined for straight flight (equilibrium) while maintaining a small favorable bank angle. The transient effects of a sudden engine failure can only be determined from steady flight, a flight path similar to a normal takeoff flight path, i.e. unaccelerated flight with a load factor of 1 g, as well as many other standardized factors and conditions (discussed above), including maximum thrust on the (opposite) engine.

4.16.2. The dynamics involved, the different air stream and angle of attack from a normal takeoff flight path (P-vector) and the duration of these maneuvers make the use of load factor inappropriate for determining or demonstrating $V_{MCA}$.

### 4.17. Climbing flight

4.17.1. An airplane at low gross weight with the engines at takeoff power setting might develop a considerable rate of climb even with one engine inoperative. This results in the reduction of side force $W \cdot \sin \phi$ by a factor cosine of the pitch angle ($\cos \theta$). The consequence of a 30° climbing pitch angle is that the bank angle should be increased by approximately one degree to generate the same side force as for level flight. If a 5° bank angle was used to determine $V_{MCA}$, the climbing flight requires a bank angle of 6° to match the published $V_{MCA}$, which is however is against regulations for designing the vertical tail; so more rudder deflection is required, or a higher speed, for straight flight: *actual* $V_{MCA}$ increases.

4.17.2. On three and four-engine airplanes, a high rate of climb can be avoided by reducing the thrust of the centerline engine or of the symmetrical inboard engines. This does affect neither the thrust asymmetry nor $V_{MCA}$.

### 4.18. Configuration changes

4.18.1. Any configuration change, modification or alteration that changes the location of the lateral center of gravity or changes the asymmetrical thrust and/ or drag, and/ or affects the required rudder and aileron deflections after failure of an engine, will have influence on the published, standardized $V_{MCA}$. For instance, increasing the engine rating (setting on the engines, or replacing the engines with more powerful ones), the installation of new type propellers, external (camera) wing pods, antennas, or other external equipment on the wings, as well as changes inside the cabin that influence the location of the lateral center of gravity, etc. could change $V_{MCA}$ significantly.
Unscheduled events might have influence as well; the loss of engines, or the inadvertent operation of a thrust reverser, or of a side-cargo door or panel in-flight, or anything else that increases the asymmetrical drag, will affect the balance of yawing moments, even without engine failure. A de-icing boot that comes loose from the leading edge of a wing results in asymmetrical drag and might also become a factor that increases the actual $V_{MCA}$, even if all engines are operative.
Flight-tests (certification) are required to determine the effect of these configuration changes on $V_{MCA}$, if at all feasible and required. Manuals should be amended accordingly.

## 5. MINIMUM CONTROL SPEEDS $V_{MC}$ – DEFINITIONS AND TESTING

### 5.1. Seven defined minimum control speeds $V_{MC}$

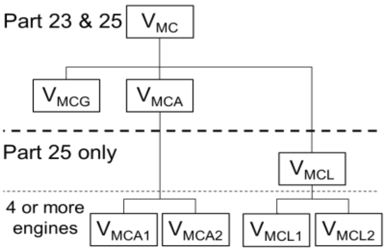

Figure 33. Schematic diagram with all Regulation-defined $V_{MC}$'s.

5.1.1. AFMs of two-engine Part 23 airplanes present two different minimum control speeds ($V_{MC}$); four or more engine airplanes have five defined $V_{MC}$'s. As illustrated in Figure 33, the defined $V_{MC}$'s for all Part 23 and 25 airplanes are: Minimum Control speed – Ground ($V_{MCG}$) and Minimum Control speed – Air, or Airborne ($V_{MCA}$). In addition, Part 25 airplanes have a Minimum Control speed – Approach and Landing ($V_{MCL}$). The Minimum Control speed – Air ($V_{MCA}$) is often inappropriately abbreviated as $V_{MC}$.

5.1.2. Four or more engine airplanes (Part 25) not only have a $V_{MCA}$ and a $V_{MCL}$, but also a $V_{MCA2}$ and a $V_{MCL2}$, both for two engines inoperative (n-2). $V_{MCA1}$ and $V_{MCL1}$ are the same as $V_{MCA}$ and $V_{MCL}$ respectively, both for one engine inoperative (n-1).
Civil Regulations (FAR/CS-25) do not require a $V_{MCA2}$ anymore, for unknown reasons, but military regulations do, because $V_{MCA2}$ not only applies if one engine is already inoperative, but also applies as the acting $V_{MC}$ in anticipation of a second engine to fail (on the same wing).

5.1.3. $V_{MCA}$ is the most important minimum control speed of all $V_{MC}$'s and was already discussed in greater detail in this report (§ 2.4 and § 4). Below, the definitions of all $V_{MC}$'s are presented, as well as the flight test techniques for determining the $V_{MC}$'s, which are included for a better understanding of these important minimum control speeds.

5.1.4. Figure 33 shows the Regulation-defined $V_{MC}$'s of which the standardized values are determined during flight-testing and published in the limitations section of AFMs. As was explained in § 2.7, § 2.8 and § 2.9, and shown in Figure 7 and Figure 20, there are many more *actual* $V_{MCA}$'s, that differ from the AFM-published standardized $V_{MC}$'s, because the configuration, thrust setting, weight, bank angle and control inputs are not the same as used during tail design and flight-testing. As was explained in § 4.5.9 above, the published $V_{MC}$'s represent the worst case $V_{MC}$'s.

### 5.2. $V_{MCA}$ flight-test preparation

**WARNING**
$V_{MC}$ testing is dangerous!
Experimental Test Pilots and Flight Test Engineers prepare these tests thoroughly using in-depth theoretical analysis and simulators.

5.2.1. To assist in understanding $V_{MCA}$ better, this paragraph is included. The flight-test techniques presented below are not the complete flight-test techniques for engine-out testing; they are provided to a certain extent and for information purposes only. Please do not start testing $V_{MCA}$ on your own. $V_{MCA}$ testing is not without danger. Experimental test pilots take many precautions; on some occasions, they even have parachutes in their seats and a prepared escape hatch!

5.2.2. As was explained in § 4, many variable factors have influence on the magnitude of $V_{MCA}$. It would be impossible to determine a separate $V_{MCA}$ for all values of all variable factors. Therefore, the worst cases of many of the variable factors that have influence on $V_{MCA}$ and produce the highest – most unsafe – $V_{MCA}$ are used to determine the standardized $V_{MCA}$ that will be published in the AFM. The advantage of standardizing these factors is that both the testing and looking up $V_{MCA}$ by the flight crew during preflight and before approach are very much simplified and less prone to failures. The consequence however is that the standardized $V_{MCA}$ that is presented in AFMs almost never corresponds to the actual $V_{MCA}$ that will be encountered during a particular flight, but is always on the safe side for any value of the variable factors, provided a few more conditions are adhered to, like maintaining a small favorable bank angle and adequate rudder deflection to stop the yawing, i.e. maintain the heading.

5.2.3. In most cases, only altitude, temperature and flap setting are the variable factors during the testing and in the $V_{MCA}$ data provided in the AFM. As was explained in § 4.3, bank angle influences $V_{MCA}$ considerably. During testing, a bank angle between 3° and 5° (as opted by the airplane manufacturer) away from the inoperative engine is used; this will reduce the sideslip to near zero, maximizing the remaining climb performance and also decrease $V_{MCA}$.

5.2.4. The worst-case values of the variable factors used during testing of $V_{MCA}$ were already mentioned in § 4, but are again presented below; the numbers between parentheses refer to the paragraphs where more details can be found:

- A constant bank angle of 5° away from the inoperative engine, or less than 5° at the option of the applicant of the certificate of airworthiness of the airplane (the airplane manufacturer, § 4.3);
- Lowest possible gross weight (no pax, no cargo, low on fuel, minimum crew, § 4.3);
- Critical engine inoperative (§ 4.5);
- Maximum available takeoff thrust on the operative engine(s) (§ 4.6, § 4.7);
- Propeller of the inoperative engine feathered if an automatic feathering system is installed, otherwise wind milling (§ 4.10);
- Center of gravity most aft and laterally into the inoperative engine, in the approved envelope (§ 4.11);
- A maximum of 150 lb (667 N, military: 180 lb) on the rudder pedal and a maximum of 25 lb (112 N) on the aileron control as per FAR/ CS § 23.149 and 25.149. Military Specifications limit roll control power to 75% to maintain a margin to cope with gusts, for transient effects after engine failure and to maneuver (ref.'s 6, 7);
- Flaps in takeoff setting or as opted by the manufacturer (§ 4.13);
- Landing gear down or as opted by the manufacturer (§ 4.13);
- Normal load factor 1 g (§ 4.16).

5.2.5. The *flight-test techniques* for performing $V_{MCA}$ flight-testing (ref.'s 11, 12) are taught and trained by formal Test Pilot Schools and can also be found in CS 23, ref. 6 and in FAA Flight Test Guides (AC 23-8C, ref. 3, and AC 25-7C, ref. 5).

5.2.6. $V_{MCA}$ is determined at a safe altitude of at least 5,000 ft AGL after which the data are reduced and extrapolated to sea level (SL) on a standard day or to different altitudes and temperatures as required for use in charts (more accurate $V_{MCA}$ data for hot & high operations).

5.2.7. To prepare for the safe conduct of $V_{MCA}$ flight-testing, the approximate value of $V_{MCA}$ is determined by using computer analysis of models or stability derivatives of the subject airplane. An abbreviated version of the technique of predicting $V_{MCA}$ is presented in the report *The Effect of Bank Angle and Weight on the Minimum Control Speed $V_{MCA}$ of an Engine-out Airplane*, ref. 13. This technique was also used to calculate and plot the graphs in this report.

5.2.8. Flight-testing begins with selecting the configuration to test, like takeoff or landing, followed by static and dynamic $V_{MCA}$ flight-testing and handling qualities testing. Handling qualities testing is required to determine the adverse effect of, for instance, the loss of systems driven by the failed engine on airplane control. The initial airspeed for these tests is 30 kt higher than $V_{MCA}$ for a small twin. Static and dynamic (or transient effects) $V_{MCA}$ flight-testing are both described in the paragraphs below.

5.2.9. Figure 7 on page 14 showed the effect of bank angle on actual $V_{MCA}$ (during equilibrium flight). Such plots can be calculated for sea level and for any altitude, including the test altitude (engine thrust changes with altitude, § 4.6 ). $V_{MCA}$ in the graphs was calculated using the maximum of either aileron deflection (20°), rudder deflection (30°) or sideslip $\beta$ (14°) versus bank angle. The pedal force limit (150 lb or 667 N) was not included. On this sample airplane, a sideslip angle $\beta$ in excess of 14° should be avoided to prevent the vertical tail from stalling. Therefore, as shown in the bottom graphs in Figure 7 on page 14, sideslip $\beta$ (14°) is the limiting factor for bank angles exceeding the range –1° to +10°. Rudder deflection (max. 30°) is the limiting factor between 0° and +6°. Furthermore, on this specific airplane type, $V_{MCA}$ is expected to be lower than the stall speed at bank angles between 4° and 7° (at the test weight, which is low weight). The airplane is said to be controllable down to the stall but, as is shown in Figure 7, this is true only for bank angles between 4° and 7° away from the inoperative engine (test weight). Actual flight-test data, or analysis of different types of airplanes, might show different graphs from the ones shown. Refer to § 2.8 for details on this equilibrium.

5.2.10. $V_{MCA2}$, the minimum control speed with two engines inoperative, is flight-tested on military 4 or more engine airplanes only (no civil requirement). The second engine to be shut down is the engine next to the outer (critical) engine on the same wing. This generates the largest yawing moments possible, hence the worst- case $V_{MCA2}$. Figure 23 on page 30 illustrates the results of the pre-test-flight analysis. At the test weight (low gross weight) and at a bank angle of 5° away from the inoperative engine (positive in this example), $V_{MCA2}$ is expected to be 117 kt and higher than the stall speed. The lowest theoretical $V_{MCA2}$ will be reached at about a 9°, the lowest drag at 7° bank angle. However, Regulations do not allow the use of a bank angle in excess of 5° away from the inoperative engine (at airspeeds as low as $V_{MCA}$) because of the flow separation on the vertical fin, which on this airplane is expected above 8° of bank when light, but above 6° when heavy, see the $\beta$ graph in Figure 23. Flight-testing will have to confirm this though. Figure 23 also shows the effect of both weight W and bank angle $\phi$ in side force $W \cdot \sin \phi$: a higher weight requires a smaller bank angle for the same side force (§ 4.3).

### 5.3. Static $V_{MCA}$ flight-testing

5.3.1. Static $V_{MCA}$ flight-testing is performed to determine the lowest airspeed at which the airplane can maintain straight flight with an inoperative engine in a predetermined configuration as described in § 5.2.4 above. The only two test points for measuring static $V_{MCA}$ in-flight are shown in Figure 34 below. The second test point at $\phi = 4°$ is expected to be at or very close to the stall speed (Figure 7). That is 'nice to know' prior to conducting the test-flight.

5.3.2. First, a trim shot at a safe altitude with symmetrical thrust in the required test configuration is established at an airspeed approximately 20 knots higher than the expected $V_{MCA}$ that was determined during the analysis. Then the engine that is expected to be the critical engine (§ 4.5) will be idled, then shut down, propeller feathered, if applicable and if automatic (§ 4.10.4), and the opposite engine selected at maximum available thrust while maintaining straight flight without changing the trim controls. The throttles of the symmetrical operative engines on 4 or more engine airplanes, or the centerline engine on 3-engine airplanes, may be set at a lower (reduced) thrust level as to be able to maintain the altitude and decrease the speed during the testing of the lightweight test airplane; this does not affect the yawing moments. For 2-engine airplanes, airspeed will be decreased by establishing a rate of climb, if required; data are taken while passing the test altitude.

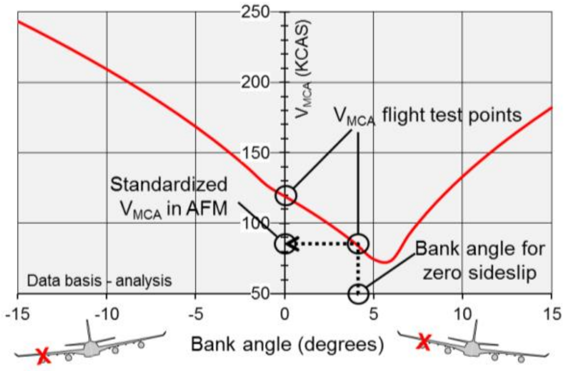

Figure 34. Test points during flight-testing for static $V_{MCA}$ this sample airplane.

5.3.3. While keeping the wings level, the airspeed is gradually decreased until the heading can no longer be maintained by rudder and/ or aileron inputs or until one of the control power or force limits (listed in § 2.7.4 and in § 5.2.4) is reached. The airspeed at which this occurs is the *actual* $V_{MCA}$ for wings level. Then, while slowing down and maintaining heading, the bank angle is slowly increased away from the inoperative engine until the bank angle is 4° for this sample airplane (or the number of degrees opted by the applicant, for instance 3° or maximum 5°) until again one of the control power or force limits is reached. The turn needle will be centered and the slip ball will be approximately half a ball width off-center (refer to § 2.8). The airspeed at which this occurs is the $V_{MCA}$ of the airplane for the test day and test altitude. On most airplanes, maximum rudder deflection or force is reached before an aileron limitation. If an aileron limit is reached first, for instance on an airplane with big propellers, i.e. large propulsive lift, or on airplanes with counter-rotating propellers, then $V_{MCA}$ is a laterally limited $V_{MCA}$. In some cases, a $V_{MCA}$ is also determined with zero rudder; then the bank angle will be little larger than 5° and the sideslip large (§ 2.9).

5.3.4. The test will also end if during the deceleration the stall speed $V_S$ is reached while the bank angle is zero or the opted degrees away from the inoperative engine. If this happens, the airplane obviously is controllable down to the stall (at this bank angle), which would be the preferable test result. The prediction for the sample airplane in Figure 7 on page 14 shows that the airplane is controllable down to the stall only if the bank angle is 4° – 7° away from the inoperative engine.

5.3.5. While decelerating, several false bank angle zero (false $\phi = 0$) points might be observed. At these unstable points, the slip ball will not be centered. The direction of sideslip $\beta$ should also be noted. Other data to be recorded are altitude, thrust level, bank angle, sideslip, rudder force and deflection and aileron force and deflection.

5.3.6. This procedure is normally repeated at lower, still safe altitudes. The acquired $V_{MCA}$ test data will, after reduction and extrapolation to sea level (§ 5.2.6), be published as (the standardized) $V_{MCA}$ of the tested configuration in AFMs.

5.3.7. To ensure that the engine that is made inoperative in the procedure described above is indeed the critical engine, the procedure is repeated after shutting down the opposite engine. The engine that after shutting down returns the highest $V_{MCA}$ is the critical engine (§ 4.5).

5.3.8. Then, on 4 or more engine airplanes, the same test procedure is repeated to determine the static minimum control speed with two engines inoperative (TEI, $V_{MCA2}$). The second engine to be shut down is the engine inboard of the first shutdown engine on the same wing. This generates the highest $V_{MCA2}$.

5.3.9. As already mentioned before, bank angle has great influence on $V_{MCA}$. $V_{MCA}$, as defined and tested, is definitely not a minimum speed for maneuvering, but for maintaining straight flight only, while maintaining the opted favorable bank angle.

Therefore, the bank angle ϕ that is used to determine $V_{MCA}$, which in most cases is between 3° and 5° away from the inoperative engine, should be specified in certification documentation as well as in the AFM with the $V_{MCA}$ data and in engine emergency procedures. Any deviation from this bank angle might result in a higher actual $V_{MCA}$ and in losing control if the CAS is lower than the actual $V_{MCA}$.

### 5.4. Dynamic $V_{MCA}$ or transient effects flight-testing

5.4.1. This test is conducted because an airline pilot must be able to avoid dangerous conditions that might result from a sudden engine failure in flight, especially during takeoff or go-around when the airspeed is low. The test method is to stabilize with symmetrical thrust (trim shot) and then cut-off the fuel supply to the critical engine at several airspeeds. After observing a realistic time delay for recognition, decision, and reaction (normally one second total), the test pilot arrests the airplane and achieves engine-out straight flight. Data to be recorded are the changes in yaw, bank angle, sideslip, rudder force and deflection, aileron force and deflection, the lost airspeed, and the new rate of climb.

5.4.2. Experimental test pilots start the engine cuts at a safe airspeed higher than static or predicted $V_{MCA}$ and gradually decrease the speed for the next test points. Tests on propeller airplanes are performed with auto-feather on and off, if applicable. Normally, only a small number of test points are required to check the validity of the measured static $V_{MCA}$'s for transient effects.

5.4.3. Requirements for these tests are that control should be maintained without exceeding a heading change of 20° (or excessive yaw or a rudder pedal force of 150 lb in accordance with FAR/ CS 23/ 25 Flight Test Guides, ref.'s 3, 5, 6. The bank angle should not exceed 45°; no dangerous attitudes may occur. The lowest airspeed at which these requirements are met is called dynamic $V_{MCA}$. Torque and gyroscopic effects of rotating engines or propellers might have influence on the dynamic $V_{MCA}$, as might propeller slipstream effects (§ 4.10.6 and § 4.9).

5.4.4. The AFM should present the higher of the dynamic $V_{MCA}$ and static $V_{MCA}$ as the $V_{MCA}$ of the airplane, to be able to survive an engine failure, but should present the static $V_{MCA}$ anyhow as well, for a safe continuation of the flight with an inoperative engine.

### 5.5. Definition of $V_{MCA}$

5.5.1. The definition of $V_{MCA}$ in an AFM is often: "Minimum control speed is the minimum flight speed at which the airplane is controllable with a bank angle of not more than 5 degrees when one engine suddenly becomes inoperative and the remaining engine is operating at takeoff power". This line is copied inappropriately out of an Aviation Regulation (ref.'s 6, 7) that is intended to be used by airplane design engineers for designing airplanes (including sizing the vertical tail) and for flight-testing and certification of the airplane. Once the airplane is in operational use, for which the AFM applies, pilots should definitely not keep the wings level to within 5 degrees of bank, left or right, as the definition suggests. On the contrary, in order to ensure that control of their airplane after engine failure can be maintained, whatever the configuration and center of gravity are, and that the remaining climb performance is positive, pilots need to maintain the same bank angle that was used to design the vertical tail and that was also used to determine the published $V_{MCA}$ during flight-testing, which is usually between 3 and 5 degrees away from the inoperative engine. Any other bank angle, including a bank angle to the other side, will disturb the balance of side forces and yawing moments and will result in lateral accelerations and rolling and yawing moments that cannot guaranteed be balanced by the aerodynamic controls, simply because the vertical tail with rudder (and the ailerons) were not sized large enough to do so. The word *suddenly* in the $V_{MCA}$ definition in an AFM does not make sense at all, it is misleading; $V_{MCA}$ applies always, even during the approach when an engine already failed during takeoff or en-route. The above quoted definition of $V_{MCA}$ is definitely deficient. A suggestion for an improved definition is presented below.

5.5.2. For Part 25 airplanes, $V_{MCA}$ might be defined and published, but not be displayed. Rotation speed $V_R$ and takeoff safety speed $V_2$ are used on these airplanes.

The $V_{MCA}$ of these airplanes is used to calculate $V_R$ and $V_{2MIN}$, ref.'s 6, 7. See also § 6.4 resp. § 6.5 below.

5.5.3. ***Definition of $V_{MCA}$ for pilots:*** $V_{MCA}$ is the minimum speed for maintaining straight flight when an engine fails or is inoperative and the opposite engine provides maximum thrust, provided a constant bank angle is being maintained of 3° – 5° (exact number to be provided by the manufacturer) away from the inoperative engine.
It is strongly recommended to include the following warning:

> ***Warning.*** *Do not initiate a turn away from this bank angle while the thrust is maximal and the airspeed is, or is close to $V_{MCA}$. Not only the loss of control is imminent, climb performance might become less than positive as well. $V_{MCA}$ is not a safe minimum airspeed for making turns, only for straight flight.*

### 5.6. Minimum control speed – ground ($V_{MCG}$)

5.6.1. When an engine fails during the takeoff run, the thrust yawing moment will force a displacement of the airplane on the runway. If the airspeed is not high enough and hence, the rudder generated side force is not powerful enough, the airplane deviates from the runway centerline and might even veer off the runway if the asymmetrical power setting is maintained. The airspeed at which the airplane, after engine failure, deviates no more than 9.1 m (30 ft) from the runway centerline, despite using maximum rudder, but without the use of nose wheel steering, is called the Minimum Control Speed on the Ground ($V_{MCG}$). The propeller, if applicable, is in the position is automatically achieves after engine failure.

5.6.2. The $V_{MCG}$ presented in AFMs is, like $V_{MCA}$, a standardized minimum control speed. The *actual* $V_{MCG}$ is lower, safer, whatever the configuration of the airplane is. If the nose wheel steering is operative, the nose wheel supports the vertical tail for keeping the airplane on the runway; the *actual* $V_{MCG}$ is lower, safer. At airspeeds below $V_{MCG}$, all throttles should be closed at once when one or more of the engines fail, in order to prevent the airplane from veering off the runway.

### 5.7. $V_{MCG}$ testing

5.7.1. The airplane will be in the test configuration, i.e. takeoff configuration, maximum available takeoff thrust on the operative engines, most unfavorable center of gravity (aft, for less pressure on the nose wheel), trimmed for takeoff and at the most unfavorable weight in the range of takeoff weights (civil: highest weight (!?), ref. 5; military: lowest weight, ref. 12, because of less tire friction). First, the airplane will be accelerated to an airspeed well above the predicted $V_{MCG}$, while kept on the ground. Then the critical engine is shut down after which the test pilot will try to keep the airplane on the runway centerline using the rudder while maintaining maximum takeoff thrust on the opposite engine for maintaining the maximum asymmetrical thrust forces and moments. During the test, a pilot reaction time of one second will be added. For the next test points, the airspeed for cutting the thrust is gradually decreased until the deviation from the runway centerline is (not exceeding) 9.1 m (30 ft) with maximum rudder deflection. That airspeed is $V_{MCG}$. In addition, at every test point, the transient response and handling qualities are subject to testing.

5.7.2. When one engine of a high-performance twin-engine airplane fails, the airplane might still accelerate because of the high thrust of the remaining engine. Therefore, it will not be possible to conduct the deceleration $V_{MCG}$ test technique on such twins, but an acceleration method has to be used. On three or more engine airplanes, the thrust of the centerline or symmetrical inboard engine(s) may be reduced to prevent acceleration after shutting down the critical engine, because these engines do not contribute to the yawing moments.

### 5.8. Definition of $V_{MCG}$

5.8.1. Besides the formal definition in FAR/ CS 25.149 (e), as copied in § 5.6.1 above, the following definitions are also used:

- "$V_{MCG}$ is the lowest speed at which the takeoff may be safely continued following an engine failure during the takeoff run", or

- "$V_{MCG}$ is the lowest speed at which directional control can be maintained on the runway following an engine failure while the thrust is maximal".

5.8.2. CS and FAR 25.107 (a) allow the manufacturer to add an 'increment' to $V_{MCG}$ (by defining a higher speed called Engine Failure speed $V_{EF}$) that could be used to include the effects of a wet or otherwise contaminated runway and of crosswind.

5.8.3. For Part 23 commuters and Part 25 airplanes, $V_{MCG}$ (like $V_{MCA}$) might be defined and published, but not displayed. $V_{MCG}$ of these airplanes is used to calculate decision speed $V_1$. $V_1$ is $V_{MCG}$ plus an increment to engine failure speed $V_{EF}$ plus the speed gained until the (test) pilot reacts to the engine failure, usually one second, ref.'s 6 and 7. $V_1$ is discussed in § 6.2 below.

5.8.4. ***Definition of $V_{MCG}$ for pilots:*** $V_{MCG}$ is the speed below which the takeoff has to be aborted at once when an engine fails to avoid runway excursion. The same definition applies for $V_1$ for airplanes that do not use or display $V_{MCG}$.

### 5.9. Effect of crosswind and runway condition on $V_{MCG}$

5.9.1. When a crosswind takeoff is made, some rudder deflection may be required to keep the airplane on the runway centerline. When the (or an) upwind engine fails, the rudder deflection needs to be increased to counteract the thrust yawing moment as well. Because the rudder is already deflected against the crosswind, the pilot may not have as much rudder power available as is required to keep the airplane on the runway. The *actual* $V_{MCG}$ will be higher. The critical engine for $V_{MCG}$ with crosswind might be the, or an, upwind engine and not the in-flight critical engine.

5.9.2. Runway condition is relevant to $V_{MCG}$ as well, because of the friction of the landing gear tires on the surface of the runway. A wet or slippery runway results in higher *actual* $V_{MCG}$'s.

5.9.3. There are no requirements for crosswind and runway conditions during $V_{MCG}$ testing. Check the AFM for conditions that might apply to $V_{MCG}$ or to the derived decision speed $V_1$ for the subject airplane for these conditions.

### 5.10. Minimum control speed – landing ($V_{MCL}$)

5.10.1. $V_{MCL}$ is the minimum control speed in the approach and landing configuration and is similar to $V_{MCA}$, but the airplane configuration is different. $V_{MCL}$ is defined for Part 25 airplanes only in FAR and CS 25, ref.'s 6, 7. There is no military requirement for $V_{MCL}$, its existence is questionable, as might become clear below.

5.10.2. During a normal stable approach, the required thrust of the engines, even if one of the engines is inoperative, will not have to be at maximum setting. $V_{MCL}$ will therefore not be a factor until the thrust has to be increased to maximum, for instance during severe turbulence or after initiating a go-around.

5.10.3. In addition to $V_{MCL}$, a $V_{MCL2}$ exists for airplanes with four or more engines. $V_{MCL}$ for these airplanes is sometimes published as $V_{MCL1}$ (n-1). $V_{MCL2}$ (n-2) is the minimum control speed during approach or landing when two engines on the same wing are inoperative, or after failure of a second engine. If one engine is already inoperative prior to, or fails during the approach, $V_{MCL2}$ applies from that moment on as the minimum control speed for landing, in anticipation of a second engine to fail. If the airspeed during the approach decreases below $V_{MCL2}$, increasing the asymmetrical thrust to maximum for a go-around will result in the loss of control (if both failed engines are on the same wing). Therefore, when two engines are inoperative, the airplane is committed to land, unless the altitude can be exchanged for airspeed down the glideslope, before the remaining (asymmetric) engines are throttled up to maximum thrust.

5.10.4. During a go-around, following cleaning-up the airplane (gear up, flaps takeoff), $V_{MCA(1)}$ applies, or $V_{MCA2}$ if one engine is inoperative, and not $V_{MCL}$ anymore. The AFM will most probably state that a go-around with an inoperative engine is not recommended because the approach and/ or threshold speeds are lower than $V_{MCA2}$. $V_{MCA2}$ is the applicable minimum control speed when the airplane is not in the landing configuration and while one engine is inoperative, in anticipation of another engine to fail. If a second engine on the same wing fails during going-around with maximum thrust on the operative engines while the airspeed is as low as or lower than $V_{MCA(1)}$, airplane control will be lost right away.

### 5.11. $V_{MCL}$ testing

5.11.1. The flight-test to determine $V_{MCL}$ is similar to static $V_{MCA}$ testing (§ 5.3), with the exception of airplane configuration. The airplane configuration for $V_{MCL}$ testing is: low weight, aft center of gravity, landing configuration (flaps and gear down), trimmed for the approach, critical engine out, go-around power on the operative engine(s) and the propeller of the inoperative engine, if applicable, in the position it achieves without pilot action.

5.11.2. In addition, the test must demonstrate that lateral control at $V_{MCL}$ (and $V_{MCL2}$, if applicable) is adequate to roll the airplane from straight flight through an angle of 20 degrees away from the inoperative engine in not more than 5 seconds, ref.'s 6, 7.

### 5.12. Definition of $V_{MCL}$

5.12.1. $V_{MCL}$ is the airspeed at which it is possible to maintain control of the airplane in the landing configuration and maintain straight flight provided a bank angle is being maintained between 3° and 5° (exact number to be provided by the manufacturer) away from the inoperative engine, when an engine fails or is inoperative and the other engine(s) are at go-around power. In addition, a $V_{MCL2}$ exists.

### 5.13. Other engine-out evaluations

5.13.1. Other engine-out evaluations may include, but are not limited to a go-around evaluation (performed at a safe altitude), an approach, a landing, and a takeoff. These tests are very dangerous, require extreme care and hence are not recommended to be performed without proper knowledge and training; the crew must be very cognizant and well prepared. Refer to § 4.3 above for a few advices. The incorrect application of rudder and ailerons might result in an attitude from which safe recovery is not possible (accidents analyzed in § 8.4 and § 8.5). In case another engine fails during the maneuver, immediate reduction of asymmetrical thrust might be required to save the airplane and the souls on-board.

5.13.2. The flight-testing of airplanes with fly-by-wire flight control systems might have to differ from the procedures described above. Some flight control systems of 'electric' jets schedule controls without the pilot noticing, following the failure of an engine. Control surfaces deflect without any stick input, and without the pilot realizing what is going on. It will be evident that the data acquired during $V_{MCA}$ testing need to include the actual control surface deflection data of aileron, rudder, and elevator, as well as actual thrust data measured at each engine.

5.13.3. Experimental flight-test crews conduct engine-out flight-testing well prepared and in accordance with approved flight-test techniques. They demonstrated that all multi-engine airplanes on the market today are controllable after engine failure, because they understand the limitations and conditions that apply after engine failure.

### 5.14. Many more minimum control speeds

5.14.1. Although three types of minimum control speeds ($V_{MC}$) are defined ($V_{MCG}$, $V_{MCA}$ and $V_{MCL}$), many more *actual* $V_{MC}$'s exist. Every factor that has influence on the asymmetrical forces and moments that act on an airplane while an engine is inoperative, results in an *actual* $V_{MC}$. The defined $V_{MC}$'s are determined using the worst case of these factors. These defined and AFM-published $V_{MC}$'s are always safe though, provided the pilot maintains the required rudder deflection for zero yaw rate (straight flight) and a small bank angle of 3 to 5 degrees, as specified by the manufacturer, away from the inoperative engine when the asymmetrical thrust is maximum. Refer to § 4.

## 6. TAKEOFF, APPROACH AND LANDING SPEEDS

6.1. *Takeoff speeds* are published as numbers or in tables or graphs in AFMs to provide safety during takeoff and go-around, even when an engine fails or is inoperative. Part 23 utility and aerobatic category airplanes only use rotation speed $V_R$ and a minimum speed requirement at 50 ft.

Part 23 commuter category (< 19 pax, MTOW < 19,000 lb) and Part 25 airplanes use takeoff decision speed $V_1$, rotation speed $V_R$ and takeoff safety speed $V_2$ that must be reached before 35 ft AGL. In the paragraphs below, these speeds will be explained; they are defined in FAR/ CS 23.51 or 25.107, ref.'s 6, 7.

### 6.2. Takeoff speed (Part 23)

6.2.1. The rotation speed $V_R$ of Part 23 utility and aerobatic category twin-engine airplanes must be greater than 1.05 $V_{MCA}$ or 1.1 $V_S$ (§ 23.51 in ref. 6 and ref. 7). The climb speed at 50 ft AGL must be the greater of 1.1 $V_{MCA}$ or 1.20 $V_{S1}$ (or a speed safe for continuing the flight). If the wings are kept level, the actual $V_{MCA}$ is higher than the published $V_{MCA}$ used to calculate $V_R$. It should be emphasized in procedures to attain the small favorable bank angle as soon as possible to avoid the loss of control. Refer to the first reviewed accident in the video (ref. 3).

### 6.3. Takeoff decision speed $V_1$

6.3.1. $V_1$ is the minimum speed in the takeoff at which the takeoff may be safely continued following the failure of an engine. A pilot may not count on being able to come to a full stop before reaching the end of the runway if the speed is higher than $V_1$. For Part 23 commuters, $V_1$ is not less than 1.05 $V_{MCA}$ or $V_{MCG}$ (option manufacturer). For Part 25 airplanes, $V_1$ is not less than $V_{MCG}$ or the little higher engine failure speed $V_{EF}$ as selected by the manufacturer, plus the speed increase gained in one second reaction time after engine failure. $V_{EF}$ might provide for a margin for runway condition and crosswind effect above $V_{MCG}$, that was determined on a dry runway and without crosswind component.

6.3.2. At speeds below $V_1$, it is not guaranteed that the airplane will stay on the runway using aerodynamic controls if the (asymmetrical) thrust setting is maintained maximum. Also refer to $V_{MCG}$ testing in § 5.7. Above $V_1$, the lateral deviation after engine failure will be less than 30 ft, but runway overrun might occur after aborting the takeoff.

6.3.3. The definition of $V_1$ for pilots is presented in § 5.8.4 above; the effects of crosswind and runway condition in § 5.9.

### 6.4. Rotation speed $V_R$

6.4.1. $V_R$ for both Part 23 commuter and Part 25 airplanes is not less than the greater of 1.05 $V_{MCA}$ or 1.10 $V_{S1}$, or the speed that allows attaining $V_2$ before reaching 35 ft AGL. The rotation speed $V_R$ is a critical speed for airplane control, because the rotation starts while the main gear is still on the runway and hence, the wings are still level. As was explained before (§ 4.3), the *actual* $V_{MCA}$ with the wings level is higher (8 – 30 kt) than the standardized $V_{MCA}$ that is published in AFM (small bank angle away from the inoperative engine) and hence, that was used to calculate $V_R$. The airspeed normally continues to increase after passing $V_R$ and might, at liftoff, be higher than $V_{MCA}$ with the wings level. Nevertheless, the favorable bank angle should be applied immediately after liftoff to keep the actual $V_{MCA}$ low and the sideslip (drag) as low as possible.

### 6.5. Takeoff safety speed $V_2$

6.5.1. $V_2$ is also one of the procedural speeds used for planning and performing a takeoff with FAR/ CS Part 25 airplanes.

As the name implies, $V_2$ is supposed to be a safe speed during takeoff, especially if an engine fails after passing decision speed $V_1$. In the analysis below, airspeed data of the sample 4-engine turbojet airplane presented before in this report will be used again to show that there is a very important condition to indeed make $V_2$ a safe takeoff speed. The accident analyzed in § 8.5 confirms this.

6.5.2. Takeoff safety speed $V_2$ as defined in FAR/ CS 23/ 25.107 (c) must provide at least a (certain) positive one engine inoperative gradient of climb and may not be less than:

- minimum $V_2$ ($V_{2MIN}$);
- $V_R$ plus the speed increment attained before reaching 35 ft above the runway level;
- a speed that provides the maneuvering capability i.a.w. FAR/CS 25.143(h).

6.5.3. $V_{2MIN}$ may not be less than $1.10 \times V_{MCA}$ for all airplanes. In addition, a requirement exists for $V_{2MIN}$ to be at least 1.08 or $1.13 \times V_{SR}$, dependent on the number of engines and provisions for power-on stall speed reduction. $V_{SR}$ is the reference stall speed. $V_{2MIN}$ might not be the lowest $V_2$ a pilot may use, especially if the wings are kept level (which results in an actual $V_{MCA}$ that is higher than published $V_{MCA}$).
Since the exact increment above rotation speed $V_R$, which is attained before reaching 35 ft above the runway level, is unknown for the sample airplane of this report, the $V_2$ data shown in the figures below is $V_{2MIN}$.

6.5.4. As was mentioned before in this report, it was not possible to use flight-test determined $V_{MCA}$, $V_S$ and $V_2$ data of a real airplane since these data are usually proprietary and not accessible. Therefore, data from analysis of stability derivatives of a sample 4-engine turbojet airplane, that are normally used to prepare for $V_{MCA}$ flight-testing, were used, ref. 13. As was explained before in § 5.2.4, other standardized variables for determining $V_{MCA}$ are the lowest possible gross weight and the most aft center of gravity in the approved envelope as well as the worst cases of other variables that have influence on $V_{MCA}$.

6.5.5. If the manufacturer had recommended a 4° bank angle away from the failed engine for lowest drag, the published standardized $V_{MCA}$ is 85 kt. Stall speed $V_S$ at low weight is also 85 kt. The standard $V_{2MIN}$ for low takeoff weights would have to be the higher of $1.10 \times V_{MCA} = 1.10 \times 85 = 94$ kt and $1.13 \times V_S = 1.13 \times 85 = 96$ kt, so the actual $V_{2MIN}$ would have to be 96 kt. However, if the pilot keeps the wings level, the actual $V_{MCA}$ is 119 kt, 23 kt higher than $V_{2MIN}$. $V_{2MIN}$ for a takeoff with the wings kept level, should have to be recalculated to $1.10 \times 119 = 131$ kt! This higher takeoff speed results in longer takeoff runs or less payload, which is what airlines do not like. Again, the real $V_2$ used for takeoff is higher than $V_{2MIN}$, but the question is whether the $V_2$ used for takeoff is high enough in case the favorable bank angle is not maintained after engine failure.

6.5.6. Normally, while using a small bank angle and at high gross weight, $V_{2MIN}$ is 10% above the standardized $V_{MCA}$ and – by definition – 8 or 13% above $V_S$. $V_{2MIN}$ is presented in Figure 35 below. This figure is similar to Figure 20, but with $V_{2MIN}$ data added. The $V_{2MIN}$ data in this figure are calculated using $V_{MCA}$ for a 4° bank angle.

6.5.7. Figure 35 below shows that if the pilot keeps the wings level following the failure of an engine, as is being advertised in many engine emergency procedures, the actual $V_{MCA}$ will be 119 kt for all weights and higher than $V_{2MIN}$, except for weights higher than 240,000 lb. At these higher weights, the margin to $V_{MCA}$ is less than 10%. This implies that with the wings level, $V_{2MIN}$ does not provide an adequate safety margin at all. The safety margin is now limited to an additional increase above $V_{2MIN}$. Therefore, the consequence of keeping the wings level following the failure of an engine is that the actual value of $V_{2MIN}$ should be increased to 1.1 × *actual* $V_{MCA}$ $= 1.1 \times 119 = 131$ kt to maintain the regulatory intended safety margin that $V_{2MIN}$ should provide. Again, $V_2$, rather than $V_{2MIN}$, might still be just above actual $V_{MCA}$, but the safety margin is definitely smaller. Actual flight-test data should be used to determine the real safety margins of $V_{2MIN}$ and $V_2$.

6.5.8. Since the calibrated airspeed during takeoff or go-around will be $V_{2MIN}$ or a little higher before and after engine failure at or below 400 ft, the consequences of banking away from the favorable bank angle (between 3° and 5° away from the inoperative engine) might be that the airplane will start drifting away from the runway centerline and that control will be lost already as soon as the wings roll through wings level. The airplane might continue to roll into the dead-engine-side until the flight

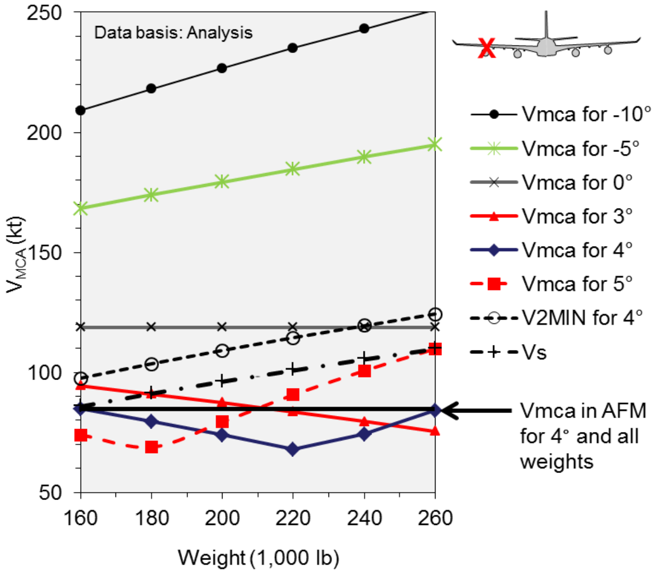

Figure 35. Effect of Bank Angle and Weight on $V_{MCA}$ – OEI, swept wing, maximum takeoff thrust.

ends in calamity. If controls seem ineffective, these uncommanded yawing and rolling, can only be counteracted by immediately decreasing *actual* $V_{MCA}$, which – at that altitude – can only be achieved by temporarily reducing the asymmetrical thrust a little, which instantaneously decreases *actual* $V_{MCA}$ to a safer value. If altitude is available to be exchanged for speed (for a go-around), that is an option too, but this might take too much time.

6.5.9. Instrument flying procedures and departure procedures are easier to fly at zero bank angle, so may be because of the 8 or 13% margin of $V_{2MIN}$ above $V_S$, it is often said that the wings can be kept level while maintaining $V_2$. However, if the wings are indeed kept level, the *actual* $V_{MCA}$ is usually 10 – 30 kt higher than the AFM-published $V_{MCA}$ (depending on airplane type); a sideslip (increased drag) cannot be avoided. Therefore, if a (procedural) bank angle is to be used that differs from the bank angle used to determine $V_{MCA}$, it is evident that *(actual)* $V_2$ needs to be revised (increased) as well, to allow for the procedural wings-level attitude to be safe.

6.5.10. $V_{MCA}$ is the minimum speed for maintaining straight (equilibrium) flight only, if an engine is inoperative; maneuvering requires a higher airspeed. If, however, one or more of the variable factors that influence $V_{MCA}$ (refer to § 4) are not at their worst-case value, actual $V_{MCA}$ might be lower than the published $V_{MCA}$ and not increase excessively after banking away from the favorable bank angle as illustrated in this paragraph. This might be the reason that following many engine failures, control could be maintained "easily" while the wings were kept level following the failure of an engine or during a training session with an inoperative engine. Nevertheless, quite a few accidents have also learned that after initiating a turn (while the thrust was high), it was impossible to end the turn and return to the original bank angle because of insufficient control power, because the *actual* $V_{MCA}$ increased above the calibrated airspeed. $V_{MCA}$ is definitely determined for a reason and the bank angle condition exists anyhow, which is of relevance to pilots 'who only use $V_2$' as well.

6.5.11. $V_{2MIN}$ is supposed to add at least a 10% safety margin on top of the minimum control speed $V_{MCA}$, but that is obviously not the case if the bank angle is less than or away from the bank angle used to determine $V_{MCA}$. If the manufacturer or operator applies an airspeed increment above $V_R$ to obtain takeoff safety speed $V_2$ (§ 6.5.2), takeoff safety is still not guaranteed. The pilot assumes to be safe while maintaining $V_2$ on the airspeed indicator after engine failure, but the actual $V_2$ that should be maintained after banking away from the favorable bank angle is many knots higher. During the takeoff accident analyzed in § 8.3, control was lost while the airspeed was 24 kt (!) higher than $V_2$, and the accident analyzed in § 8.5 happened even while the airspeed was only 2 – 4 kt below $V_{2(MIN)}$. Not maintaining the favorable bank angle reduces the safety margin required by FAR/ CS 25.107 considerably or even nulls it. In addition, sideslip is not zero, which might adversely affect the takeoff performance.

6.5.12. As illustrated in Figure 35 above, $V_S$ increases with weight. $V_S$ is the leading factor for calculating $V_{2MIN}$ at higher weights and for airplanes that are said to be controllable down to the stall, while $V_{MCA}$ is normally the leading factor for calculating $V_2$ at low airplane weights. Although $V_S$ also increases when the bank angle is away from wings level, this increase is negligible up to the approved maximum favorable bank angle of 5 degrees ($1/\sqrt{\cos 5°} = 1.002$). Referring to the analysis above, it will be evident that $V_{MCA}$ is not only the leading factor for $V_{2MIN}$ at low weights, but also for higher weights, and for airplanes that are controllable down to the stall, once the bank angle is deviating from the bank angle used to determine $V_{MCA}$ (and to size the vertical tail), even if this is just a few degrees (effect of $W \cdot \sin \phi$). This regrettably, is never mentioned with the calculation and display of takeoff safety speed $V_2$.

6.5.13. As was discussed before, roll assisting spoilers affect the lift distribution on the wings when the aileron control wheel deflection exceeds 7 degrees on some airplanes (§ 4.13.4). This adverse effect was not included in the $V_{2MIN}$ analysis above.

6.5.14. ***Summary***. For $V_2$ to be a safe takeoff safety speed it is certainly required for this sample airplane – and most probably for all multi-engine airplanes – to maintain the favorable bank angle that was used to determine $V_{MCA}$ and $V_{MCA2}$ (normally between 3° and 5° away from the inoperative engine(s)) and to maintain straight flight until reaching a safe altitude, as long as the asymmetrical thrust is high and the airspeed low. The small bank angle will keep the *actual* $V_{MCA}$ below $V_2$.

6.5.15. Takeoff safety speed $V_2$, which is not less than $V_{2MIN}$ or $V_R$ plus a speed increment at 35 ft AGL is only a safe takeoff speed as long as all engines are providing equal (symmetrical) thrust and, following the failure of an engine, only as long as a bank angle between 3° and 5°, as opted by the manufacturer (used to size the vertical tail and to determine $V_{MCA}$), is maintained away from the inoperative engine. This banking requirement is regrettably published neither with $V_2$ nor with $V_{MCA}$ in most AFMs. On the contrary, some AFMs even allow – and some Standard Instrument Departure (SID) procedures require – a turn with 15 degrees of bank to either side while the airspeed is as low as $V_2$, which will become dangerous if other factors that have influence on $V_{MCA}$ happen to be at their worst-case values (for $V_{MCA}$).

6.5.16. Appropriate crew response to propulsion system malfunction remains of utmost importance for takeoff and go-around accident prevention. Maintaining takeoff safety speed $V_2$ alone warrants no safety if an engine fails during initial climb.

### 6.6. Approach and Go-around speeds

6.6.1. The approach speeds of normal, utility, and aerobatic part 23 airplanes (< 2722 kg / 6000 lb) must not be less than the greater of $V_{MCA}$ with the wing flaps in the most extended take-off setting and 1.3 $V_S$. For higher weight airplanes of this category, this speed is called $V_{REF}$ (§ 23.73 in ref. 6 and ref. 7). For commuter category airplanes $V_{REF}$ must not be less than the greater of 1.05 $V_{MC}$ with flaps in landing position and 1.3 $V_S$. 1.3 $V_S$ is also called the threshold speed, the speed on which the calculation of landing distance is based.
Most manufacturers recommend additives up to 20 kt to $V_{REF}$ for high, steady state winds and gusts, and for windshear.

6.6.2. In § 2.10.5 some guidance was already presented for the increase of the safety margin above $V_{MCL}$ / $V_{MCA}$. A $V_{REF}$ of 1.05 $V_{MCA}$ is definitely not a safe approach speed when the wings are kept level. Then, as explained above, the *actual* $V_{MCA}$ for small airplanes can already be 8 kt higher than the published standardized $V_{MCA}$ used to calculate $V_{REF}$ and can easily increase above $V_{REF}$ during straight flight and turns. When the pilot maintains $V_{REF}$ during the approach at less than maximum thrust level, but has to increase the thrust to maximum for whatever reason such as the occurrence of windshear or go-around, a loss of control can occur at once. Some Operating Manuals do not take the increase of $V_{MCA}$ with bank angles away from the favorable bank angle into account.

## 7. REVIEW OF AIRPLANE FLIGHT AND TRAINING MANUALS

### 7.1. The use of CAS and IAS in AFM and Training Manuals

7.1.1. The airspeed indicator (ASI) in a cockpit indicates the Indicated Airspeed (IAS). An ASI is designed and calibrated to display the difference between total pressure $P_T$ and static ambient pressure $P_a$. But the instrument is and cannot be perfect. The indicated airspeed values have three categories of errors: instrument errors in the ASI, and lag and position errors of the pitot-static system. The IAS displayed on one ASI is not by definition equal to the IAS displayed on a second ASI in the cockpit or on a maintenance-replaced ASI, when connected to the same pitot-static system.
CS / FAR 23.1323 (b) defines the pitot-static system error, excluding the ASI calibration error, to not exceed the maximum of 3% of CAS or 5 kt, whichever is greater throughout speed ranges 1.3 $V_{S1}$ to $V_{NE}$ with flaps up, and 1.3 $V_{S1}$ to $V_{FE}$ with flaps extended.
In Technical Standard Order (TSO-C46a) the approved tolerance of an ASI from 60 – 120 kt = ±2.0 kt, at 150 kt = ±2.5 kt and at $V_{NE}$ = ± 3.0 kt. Hence, the difference in airspeed indications between the ASI of pilot and copilot may be up to 6 kt, if connected to the same pitot-static system.

7.1.2. The stall, takeoff, minimum control, cruise and landing speeds, and the handling qualities of the airplane were determined with a calibrated test system and were reported as Calibrated Air Speed (CAS) for a given gross weight (mass). These, for flight operations important speeds are usually published as numbers or in graphs as KCAS in the AFM of a type of airplane. Temperature and air density do not affect CAS; CAS has the same significance on all days: CAS today, even if hot or high, is CAS during a standard day. CAS is therefore the most important airspeed for pilots. The CAS in one airplane is the same as CAS in another airplane of the same type, with identical pitot-static systems; the limiting and operational speeds in CAS are the same and are published in their common, generic AFM.

7.1.3. The AFM-writer cannot know the instrument errors of each individual ASI installed in each production airplane, which is the reason that CAS is normally used in generic AFM's. In the cockpit of each airplane, correction tables show the relationship between the IAS and CAS of each individual installed ASI, except for a few categories of airplanes, or if the instrument errors are included in adjustable electronic display systems. Even then, the label with the speed tape or dial should read CAS.

7.1.4. Hence, if an IAS is used in an AFM, the inspectors assigned to review the manual before approval, and the investigators of an accident should disapprove the use of IAS in an AFM, unless the AFM is for a particular airplane tail number, and provisions are in place to amend IAS data following the remove- and replacement of an ASI.

7.1.5. An FDR records CAS data, not IAS data; only a pilot can read IAS data from the ASI. In some cases, the header of the airspeed column in FDR factual reports is inappropriately called Computed airspeed, probably by computer whizz kids who just believe that the letter C always means Computed. If an investigator notices IAS or the term Computed Air Speed in FDR data reports, questions should be asked what instrument errors were used to obtain IAS or Computed Air Speed from the CAS.

### 7.2. $V_{MCA}$ in AFM and training manuals

7.2.1. Multi-engine airplanes are designed, built, and subsequently flight-tested to continue to fly safely after failure of one of more of the engines. Nevertheless, many accidents after engine failure, or better after propulsion system malfunction, continue to happen. Following the investigation of the accident, often the loss of control, an aerodynamic stall or inappropriate crew response to propulsion system malfunction is concluded as the cause of such an accident. However, the crew is not always to be blamed, as will be explained in this paragraph. Most AFMs and training manuals as of today do not present the real and true value of $V_{MCA}$ and do not present the conditions for which $V_{MCA}$ and the derived takeoff speeds thereof are valid. In addition, the engine emergency procedures do not take into account the design criteria for sizing the vertical tail and the flight test techniques to measure the $V_{MCA}$ of the airplane. Therefore, besides investigating the wreckage of an airplane following an accident, the manuals and books used by pilots should also be reviewed to disclose the possibly real cause of an inappropriate crew response, being short falling manuals and textbooks.

7.2.2. As was explained in § 2.4, the design engineer at the drawing board for designing the vertical tail and rudder not only uses $V_{MCA}$, but also includes banking a few degrees away from the inoperative engine, because this small bank angle reduces both the drag and the required size of the vertical tail, and therefore saves manufacturing cost and weight. The design engineer determines the magnitude of the bank angle to be used for the tail design but is constrained by aviation regulations that allow a maximum of 5º (FAR/ CS 23.149 and 25.149, ref.'s 6, 7). Any other bank angle changes the forces and moments that act on the airplane and results in a different mostly higher *actual* $V_{MCA}$ (§ 4.3). In other words, for bank angles other than the bank angle used by the design engineer, the vertical tail might not be large enough to generate a side force and hence a yawing moment powerful enough to counteract the asymmetrical thrust moments for maintaining airplane control after engine failure if the opposite operative engine is set to provide maximum thrust. Therefore, this bank angle should be included in an appropriate way in or with the definition of $V_{MCA}$ and be published as a condition with the $V_{MCA}$ data in AFMs for which the published $V_{MCA}$ is valid, but the aviation requirements do not (yet) require manufacturers to do this.

7.2.3. Most airplane manufacturers present $V_{MCA}$ in their AFMs as a single speed or in a table of minimum control speeds for different ambient temperatures, flap settings and pressure altitudes to facilitate operations form hot and high airports. But they regrettably do not explain that $V_{MCA}$ changes considerably with changing bank angles or with less than maximum rudder deflection to some higher actual value, as was explained in § 2.4.2 above. Furthermore, they do not issue a warning for the potential hazardous consequences of maneuvering at airspeeds near or below $V_{MCA}$ while an engine is inoperative and the thrust setting on the operative engine(s) is high. The same applies to many multi-engine flight crew training programs, including simulator training.

7.2.4. In addition, $V_{MCA}$ is one of the factors in the calculation of both $V_R$ and $V_2$ of Part 23 Commuter and Part 25 airplanes. Therefore, the conditions that apply to $V_{MCA}$, apply to $V_R$ and $V_2$ as well (§ 6.5.9).

7.2.5. Not stating the requirement for straight flight while maintaining a small bank angle for the published $V_{MCA}$ (and $V_R$ and $V_2$) to be valid is definitely **a very dangerous omission** that has led and will lead again to misunderstanding of $V_{MCA}$ and consequently to accidents due to loss of control immediately following a propulsion system malfunction or during the remainder of the flight while an engine is inoperative and the (asymmetrical) thrust is high (§ 4.3).

7.2.6. Engine emergency procedures should list the requirement to attain the favorable bank angle immediately after engine failure at the current airspeed, or before or while the thrust setting is increased to maximum and the airspeed is low, to stop the yawing with adequate rudder deflection and to maintain straight flight only, until reaching a safe altitude.
Accident and air safety investigators should review the manuals to this effect. If the investigator concludes that the small bank angle is neither included with $V_{MCA}$, nor with $V_R$ and $V_2$ data, and is not presented in the engine emergency procedures either, a conclusion on this omission should be reported. The airplane manufacturer should be strongly recommended to include the requirement for straight flight while maintaining the small bank angle until reaching a safe altitude in order to prevent accidents after engine failure in the future.
A few imperfections on $V_{MCA}$ in some AFMs and textbooks will be given and explained below.

### 7.3. Definition of $V_{MC}$, $V_{MCA}$ in an AFM and in textbooks

7.3.1. Multi-engine rated pilots know $V_{MCA}$ from AFMs and textbooks in which either one of the following definitions of $V_{MC}$ / $V_{MCA}$ might be given. The first was also used in § 5.5.1:

1. *'Air minimum control speed is the minimum flight speed at which the airplane is controllable with a bank angle of not more than 5 degrees when one engine*

*suddenly becomes inoperative and the remaining engine is operating at take-off power'; or*

2. *'$V_{MCA}$ is the airspeed at which, with the airplane airborne and maximum takeoff power on the engines, when the critical engine is suddenly made inoperative, it is possible to recover control of the airplane and maintain straight flight with an angle of bank of not more than 5 degrees.'; or*
3. *'$V_{MC}$ is the minimum airspeed at which control can be maintained with the critical engine inoperative and the remaining engine operating at full power.'*

7.3.2. As already mentioned in § 5.5.1 above, these definitions are copied straight from the regulatory paragraphs (§ 23.149 or § 25.149 (ref.'s 6, 7) or are an interpretation thereof by the textbook or manual writer, but these paragraphs are intended for designing (sizing) the vertical tail of the airplane by the design engineer, not for use by the (airline) pilot. Once the airplane is in operational use, for which the AFM applies, pilots should definitely not keep the wings level to within 5 degrees of bank, left or right, as the first two definitions suggests. On the contrary, in order to ensure that control of their airplane after engine failure can be maintained, whatever the configuration is, and that the remaining climb performance is positive, pilots need to maintain the same bank angle that was used to design the vertical tail and that was also used to determine the AFM-published $V_{MCA}$ during flight testing, which is usually between 3 and 5 degrees away from the inoperative engine. Any other bank angle, or a bank angle to the other side, will disturb the balance of side forces and yawing moments and will result in lateral accelerations and yawing and rolling moments that cannot guaranteed be balanced by the aerodynamic controls, simply because the vertical tail with rudder (and/or the ailerons) were not sized large enough to do so (§ 2.4). The word ***suddenly*** does not make sense at all; $V_{MCA}$ applies always, even during the approach when an engine already failed during takeoff or en-route, see also § 5.5.1. The above quoted AFM definitions of $V_{MCA}$ are definitely deficient and must be improved. A warning should be included as well, refer to § 5.5.3.

7.3.3. If pilots would interpret $V_{MCA}$ from only these definitions, they might – after engine failure and with the thrust setting of the remaining engine(s) high – believe the airplane to be unlimited controllable at $V_{MCA}$. However, as was explained in § 4.3 above, a bank angle change of 10º (+ to – 5°) at an airspeed as low as the published $V_{MCA}$ can be catastrophic. On some airplanes, the actual $V_{MCA}$ increases 30 knots by doing so; returning to the original heading using aerodynamic controls alone might not be possible anymore, asymmetrical thrust needs to be reduced temporarily as well. $V_{MCA}$ is for maintaining straight flight after engine failure only while a small bank angle (as opted by the manufacturer) is maintained away from the inoperative engine (and the thrust setting is maximum). The unexpected increase of the *actual* $V_{MCA}$, while banking away from the small favorable bank angle during maneuvering and while the thrust is (increased to) maximum, and the subsequent inability to maintain control, i.e. to return to the original heading, is the real cause of many airplane crashes during takeoff after engine failure or during subsequent flight while an engine is inoperative.

7.3.4. ***Critical engine***. The second and third definitions above might also suggest that it is not a problem when a non-critical engine fails. During flight-testing, the critical engine is made inoperative because this results in the highest, the worst case and most unsafe $V_{MCA}$. The worst cases of most variable factors that have influence on $V_{MCA}$ are used during flight-testing but are not listed in the AFM definition. A forward center of gravity might have a greater effect on the actual $V_{MCA}$ than the difference between the yawing moments caused by the critical and the opposite less critical engine(s). We will never know, because it is not a subject of flight-testing. The AFM-published – worst case – $V_{MCA}$ applies after failure of anyone of the engines and for all values of the other variables that have influence on $V_{MCA}$. So, the adjective 'critical' with engine should not be used in AFMs either. AFMs present only one engine emergency procedure that applies after failure of any of the engines, critical or not critical, inboard or outboard. The single published $V_{MCA}$ applies in anticipation of, and following either engine failure. Therefore, the highest $V_{MCA}$ has been determined and is published as standardized $V_{MCA}$ in AFMs. Pilots do not need to know about the criticality of an engine, only test pilots and design engineers do.

## 7.4. $V_{MCA}$ in engine emergency procedures

7.4.1. Although engine emergency procedures of some airplane's present guidance on the use of the small favorable bank angle, this often comes too late in the procedure, when the loss of control is already irreversible.

7.4.2. In § 9.4, an accident with a DHC-6 Twin Otter is discussed. The engine emergency procedure of the airplane that crashed following an engine failure at liftoff is presented in that paragraph, including comments. Attaining the favorable bank angle as soon as possible after liftoff to reduce the drag and to keep the actual $V_{MCA}$ low was not included in the procedure.

## 7.5. $V_{MCA}$ in the cockpit

7.5.1. FAR and CS § 23.1545(b)(6), ref.'s 6, 7, require "*the airspeed indicator of reciprocating twin-engine powered airplanes of 2,722 kg (6,000 lb) or less maximum weight to be marked with a red radial line showing the maximum value of the one engine inoperative minimum control speed determined under § 23.149 (b)*". A sample airspeed indicator is shown in Figure 36. The blue radial line indicates the single engine best rate of climb speed $V_{YSE}$ while maintaining a 2 to 3° bank angle.

Figure 36. Air speed indicator Part 23 airplane with red $V_{MCA}$ and blue $V_{YSE}$ radial lines.

7.5.2. The airspeed numbers on the instrument dial are IAS, while the red, blue, and other radial lines are the same as published as text in tables in the AFM, hence in CAS. Something to be aware of, see also § 7.1.1.

7.5.3. FAR and CS § 23.1563 require "*an airspeed placard in clear view of the pilot and as close as practicable to the airspeed indicator. This placard must list for reciprocating multiengine-powered airplanes of more than 6,000 pounds maximum weight, and turbine engine-powered airplanes, the maximum value of the minimum control speed, $V_{MC}$ (one engine inoperative) determined under §23.149(b)*". A sample placard is shown in Figure 37.

ONE ENGINE INOPERATIVE
AIR MINIMUM CONTROL
SPEED 80 KIAS

Figure 37. $V_{MCA}$ placard in clear view of the pilot.

7.5.4. FAR and CS 23 do (regrettably) neither require the bank angle for which the indicated and/ or placarded $V_{MCA}$ is valid to be included on this placard, nor on a separate placard near the airspeed indicator. This could very well also be a recommendation by investigators for a change of Regulations to the FAA or equivalent authorities. As was mentioned before in § 3.1.3, some manufacturers do include the favorable bank angle in EOI performance data for $V_{YSE}$, which is smaller than for $V_{MCA}$, because the airspeed is higher, i.e. the rudder side force is larger. The manual writer obviously did not know about the effect of bank angle on $V_{MCA}$.

7.5.5. Part 25 airplanes do not display or placard $V_{MCA}$; takeoff safety speed $V_2$ is used instead, although $V_{MCA}$ is used to calculate minimum $V_2$ ($V_{2MIN}$). Please refer to § 6 for more facts on this subject, including the effect of bank angle on $V_{2MIN}$. For Part 25 airplanes, $V_{2MIN}$ gets very close to $V_{MCA}$ if the weight is low and the thrust is maximum (Figure 35 on page 50) as long as the small favorable bank angle is maintained. Actual $V_{MCA}$ increases above $V_{2MIN}$ if the small bank angle is not maintained. It should be recommended to list or display the favorable bank angle that was used to design the tail and for which $V_{MCA}$ and the derived $V_{2MIN}$ are safe minimum speeds.

7.5.6. The safe favorable bank angle (range) could be indicated on a PFD, using advisory eyebrows as illustrated in Figure 38 below. As the thrust is reduced, the airspeed increased or if any of the other variables that affect $V_{MCA}$ is not at its worst-case value, the eyebrows open up increasing the safe bank angle range. This feature could also be of use during turns at low speed during takeoff, go-around, SIDs, in holding patterns and during approaches while an engine is inoperative. All data required to calculate the safe bank angle range are available in the computers of modern airplanes.

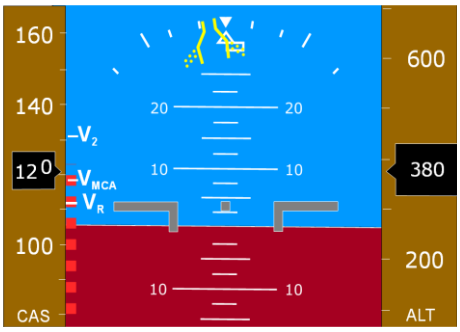

Figure 38. Suggested bank angle advisory eyebrows for safe bank angle range for lowest actual $V_{MCA}$ while OEI.

## 7.6. Inappropriate $V_{MCA}$ texts in training manuals and textbooks

7.6.1. Much guidance material is available to conduct engine-out training, but very few, if any, address the real value of $V_{MCA}$, the effect of bank angle and rudder deflection on $V_{MCA}$ and on the remaining performance as Test Pilot Schools do. Not only are most AFMs deficient on $V_{MCA}$ and the limitations that come with it, most student pilot text- and training books are incomplete as well, and flight schools do not warn pilots for the conditions that apply to $V_{MCA}$ either. The flight techniques that are taught to student pilots are not in agreement with the way that the airplanes were designed and flight-tested. Therefore, a review of training manuals and textbooks should be conducted as well during accident investigations.

7.6.2. Below, a number of imperfect and deficient $V_{MCA}$ definitions are quoted from a few textbooks and training manuals. It is irrelevant for the purpose of this report to list the sources; it merely supports the conclusion that many authors regrettably have an understanding of $V_{MCA}$ that differs from airplane design engineers, test pilots and flight test engineers. Investigators can use the examples for evaluating manuals and textbooks.

7.6.3. Seen in a training manual of a 4-engine turbofan airplane:

*'At low weights, lift off/ take-off speed is close to $V_{MCA}$. Limit bank to ±15° max.'*

- It is indeed correct that at low weight the lift off/ takeoff speed is close to $V_{MCA}$ (within 10%, § 6.4, § 6.5.3 ), but banking 15° into an inoperative engine at this low speed (and at high power setting) increases the actual $V_{MCA}$ considerably, up to 60 knots! Banking >10° into the operative engine at too low a speed might result in a fin stall. In both cases, control of the airplane will be lost and the flight will end in calamity if the other variables that have influence on $V_{MCA}$ happen to be at their worst-case value (§ 4.3) and the thrust is maximal.

*'At higher weight, smaller control wheel deflections are required and very small bank angles are required to maintain heading.'*

- Why is this *'higher'* weight mentioned? Is this a reference to the effect of bank angle and weight on $V_{MCA}$ ($W \cdot \sin \phi$, § 4.3)? The writer obviously is aware of the effect of weight on $V_{MCA}$, but does not mention it. Why does the writer say *'angles'* (plural) and not 'a small favorable bank angle away from the failed engine'?

*'With one engine out: use full rudder and wings level.'*

- *Full rudder* will only be required when the thrust is maximal and the airspeed is as low as $V_{MCA}$, provided the other factors that have influence on $V_{MCA}$ are at their worst values as well. Rudder is required to stop the yawing, i.e. to maintain the heading, no more. By recommending *wings level*, the writer accepts a drag penalty as well as a 10 – 30 kt higher actual $V_{MCA}$ (§ 2.7, § 4.3).

*'With two engines out: 3° bank required to maintain heading.'*

- Seems good point, but the *bank* is not only *required to maintain heading*, but for keeping the *actual* $V_{MCA}$ and the drag as low as possible. It is not specified into which direction the *bank* should be; away from the inoperative outboard engine, of course.

*'During IFR conditions & engine out: apply aileron to level wings, then smoothly rudder in same direction.'*

- What to do if not IFR/ IMC?
- The rudder is the only aerodynamic control available to counteract the thrust yawing moment and should be applied first (this will also roll the airplane). Then ailerons are required to attain the manufacturer-opted bank angle (between 3º and 5º) away from the inoperative engine. Applying ailerons first might delay reducing the sideslip angle and deploy roll assisting spoilers, increasing drag and reducing climb performance. To recognize an engine failure early, a turn needle (yaw rate indicator) might be of great help, but people who might have forgotten about $V_{MCA}$ took this indicator off the electronic displays on many airplanes.

*'$V_{MCA}$ is the minimum airspeed at which the airplane may be controlled in roll along the longitudinal axis with the critical engine failed, full thrust on the operating engines, and a maximum 5 degree bank toward the operating engine.'*

- The writer got confused about the effect of an inoperative engine. $V_{MCA}$ is for directional/ heading control except for airplanes on which propellers provide very high propulsive lift. Then $V_{MCA}$ might refer to a lateral or aileron limited minimum control speed (§ 5.3.3). The remaining roll authority at $V_{MCA}$ on civil airplanes is neither tested, nor documented and may therefore not be counted on; military airplanes still have 25% roll control power available at $V_{MCA}$ (§ 2.7.4). If roll control inputs are made at $V_{MCA}$, control might very well be lost right away. $V_{MCA}$ is the lower speed limit for maintaining straight flight, not for any controlling, neither in roll, nor in yaw. This definition is dangerously wrong! Refer to § 4.3.

*'At $V_{2MIN}$, the stall warning (after engine failure) occurs at about 35° bank angle whatever the configuration.'*

- $V_{2MIN}$ is normally the greater of $1.1 \times V_{MCA}$ and 1.08 or $1.13 \times V_S$ (FAR/ CS 25.107, see § 6.5 above). Can this airplane then safely use bank angles up to 35° without any increment to $V_{MCA}$ and therewith to $V_{2MIN}$ while one engine is inoperative? No, definitely not. This simply cannot be true by physics and aerodynamics laws. A truly dangerous statement made by somebody who does not understand asymmetrical powered flight (§ 6). ($V_S$ at $\phi = 35°$ is $1.1 \times V_S$ at $\phi = 0°$).
- At $V_{2MIN}$ ($1.10 \times V_{MCA}$ when the gross weight is low) the airplane might already become uncontrollable if the wings are about level (§ 4.3, § 6.5).

*'The speed increment values against $V_{2MIN}$ required by the JAR-OPS for bank angles at takeoff exceeding 15° are very conservative for [this airplane] and could be penalizing. The manufacturer recommends minor speed increments against $V_{2MIN}$: no speed increment whatever the bank angle up to 30°, and a 5 kt increment at 30° bank angle.'*

- As was explained many times before in this report, the actual $V_{MCA}$ increases considerably while banking away from the favorable 3° - 5° bank angle away from the failed engine. $V_{2MIN}$ is normally 10% higher than $V_{MCA}$ (at low weight), but after banking, actual $V_{MCA}$ will be much higher than $V_{2MIN}$ which definitely results in controllability problems at bank angles up to 30° (§ 6.5). A 5 kt increment at 30° bank angle will never have to be applied; the control of the airplane will already be lost by then (if the thrust is maximum and other factors that influence $V_{MCA}$ happen to be at their worst-case values as well, § 4). The accident analysis in § 8.5 shows that control was lost when the bank angle was only 13° into the dead engine.

- Authorities should require data on the effect of bank angle on $V_{MCA}$ before approving speed increments. Investigators should comment on this.

### 7.7. Training and demonstration of $V_{MCA}$

7.7.1. Accidents immediately following an engine failure or during flight with an inoperative engine continue to happen, so adequate training for recognizing the nearby loss of control and for controlling an engine-out airplane is of utmost importance. Pilots should also understand the real value of (actual) $V_{MCA}$, being the airspeed at which rudder and/ or aileron do not have any control authority left, despite maximum control deflections. Much engine failure related training can be done in simulators, provided these are modeled to simulate the real thing as closely as possible, because some engine-out airplane software models are not quite correct (by experience, next paragraph). The ultimate engine-out training can only be performed in the air in a multi-engine airplane.

7.7.2. After the first version of a paper on this subject was finished back in 2000, the author got the opportunity to attend a 3-hour detail in the simulator of a big 4-engine propeller airplane. After the planned training session was finished, a few engine failure test points were flown at the request of the author of this report to be able to confirm some of the statements in the report. The unexpected result of this little test was that the aileron deflection required for straight flight after failure of engine #4 was the same as for failure of engine #1, which of course should be opposite! This simulator was definitely not modeled correctly for engine-out training after failure of engine #4, only for training with engine #1 inoperative. This occasional test result came by surprise; the simulator instructors had never noticed this. They adduced that the simulator was FAA approved. It is unknown whether there was a requirement for this simulator to be used for engine-out training after failure of engine #4. It could very well be that in this simulator never a failure of any other engine than the critical engine (#1) was or had to be simulated during training sessions. A few years later, the same results were concluded in a simulator of a two-engine turboprop. It seems that the certification / approval of simulators is conducted by people who should read this report as well.

7.7.3. The result of this small test also adds to the point that the training program itself, the syllabus, the simulator, and any changes to either the simulator hardware or software should be properly verified and approved by (experimental) flight-test experts in order to avoid training for which the simulator is not (correctly) modeled. For this simulator, somewhere should have been stated not to simulate engine failures on the right wing! Following an accident, investigators should also look into training and demonstration to verify these are appropriate.

7.7.4. *Demonstration of $V_{MCA}$ in flight* should be conducted at low gross weight, for instance as the last exercise during a training flight. A low weight as well as an aft center of gravity (within the approved envelope) will cause the actual $V_{MCA}$ to be as close to the published standardized $V_{MCA}$ as possible (§ 4.3.4, § 4.11). The procedure for demonstrating or training $V_{MCA}$ could be the same as used for determining $V_{MCA}$; refer to § 5 for the procedure to conduct flight-tests to determine both dynamic and static $V_{MCA}$, the latter with both wings level and with a small 5° bank angle into the operative engine. It should not be attempted to duplicate the AFM-listed $V_{MCA}$, refer to footnote 1 on page 16.

7.7.5. FAR CS 23.149 (d) requires a minimum speed to intentionally render the critical engine inoperative must be established and designated as the safe, intentional, one-engine-inoperative speed ($V_{SSE}$), but not all manufacturers publish this speed in their AFM. $V_{SSE}$ provides a margin above $V_{MCA}$ when one engine is suddenly made inoperative during $V_{MCA}$ demonstration or training flights. It is not sure that this speed provides for a large enough margin above $V_{MCA}$ to enable safe turning (§ 2.10).

7.7.6. It is strongly recommended to demonstrate the influence of bank angle as well as the effect of only partial rudder deflection and the effect of reducing asymmetrical thrust on $V_{MCA}$ to achieve an improved appreciation of the minimum control speed. Training should include straight flight at less than maximum asymmetrical thrust and then increasing the thrust to maximum and decreasing it while maintaining the heading, to get a good feeling of the required rudder and aileron changes. Also to

practice is a shallow simulated final turn for landing during which the thrust has to be increased as well, all maneuvers at a safe altitude (>5,000 ft AGL).
These standard maneuvers resulted in accidents (§ 9.2 and § 9.3) because of inappropriate rudder handling (with thrust changes). In addition, demonstrate that control can be maintained by reducing the thrust a little before turning, at the cost of some altitude because of the increased drag and the loss of thrust (§ 2.10). See the cautions below!

7.7.7. Keep in mind that thrust decreases with increasing altitude and that the actual $V_{MCA}$ will decrease as well. If (the *actual*) $V_{MCA}$ decreases below $V_S$, the airplane during training (at altitude) might be controllable down to the stall which might not be the case at sea level. Then $V_{MCA}$ cannot be demonstrated; consider a demo with wings level, with a bank angle into the inoperative engine (at a safe altitude), the rudder boost system switched off or by limiting the rudder deflection to less than maximum, that all will increase *actual* $V_{MCA}$. On 4 or more engine airplanes, reduce the thrust of the other engine on the same wing to be able to demonstrate (an *actual*) $V_{MCA}$.

7.7.8. A real sudden engine shutdown should be part of the training as well. As a reaction to engine failure, all throttles normally have to be moved forward and not only the throttles of the operative engine(s) (FAR/ CS § 23.149 & 25.149 (b)). Only after a 'real' engine failure, the student pilot will get a feeling of the dynamics involved and will have to perform the standard emergency procedure and recover to and maintain straight flight. Left and right engine failures should both be trained.

7.7.9. ***Cautions for training and demo.*** If the airspeed is close to $V_{MCA}$, the sudden reduction of thrust on one wing generates both a yaw (heading change), and on propeller airplanes also a rapid roll due to the imbalance of the propulsive lift on both wings. The pilot must react fast with rudder and roll inputs to prevent excessive yawing and adverse bank angle from building-up. Any improper control input can result in an immediate loss of control of the airplane. Allowing a sideslip to build-up will increase drag, loss of airspeed and altitude, and to big trouble if conducted at low altitude.

7.7.10. Keep in mind that it is very dangerous to fly an airplane at low altitude and low airspeed while one engine is, or more engines are, inoperative. A catastrophic accident is to be expected while maneuvering at an airspeed that is close to the actual $V_{MCA}$ or to the actual stall speed, and also in case another engine fails. High risks are also taken if the fuel supply is suddenly cut while in takeoff; it is a very dangerous practice.

7.7.11. The accident analyzed in § 8.5 shows that reducing one throttle to idle to simulate an engine failure just after rotation is not without danger either. Zero drag should be set on the simulated failed engine, i.e. zero thrust, not zero torque or flight idle (propeller drag/ spillage drag, § 4.6.6).
One engine inoperative go-around training should initially be conducted at an altitude of at least 5,000 ft AGL. Following a demo and hands-on experience while the airspeed is at or very close to the actual $V_{MCA}$, a simulated engine-out go-around could be practiced while maintaining a bank angle of a few degrees into the good engine as the thrust or power is increased. Consider also rendering another engine inoperative than the critical engine, for training purposes. Every inoperative wing engine results in its own asymmetrical thrust yawing moment and has its own actual $V_{MCA}$ that is equal to or lower – safer – than the published standardized $V_{MCA}$. Also, keep in mind that the go-around speed of a 4-engine airplane with one engine inoperative is $V_{MCA2}$, which is much higher than $V_{MCA1}$ (§ 4.4.7, § 5.10.3).

7.7.12. If rudder and/or aileron deflections are (near) maximum for maintaining equilibrium flight, the airspeed is very close to the actual $V_{MCA}$. Then maintain, and do not bank away from, the favorable bank angle, between 3° and 5° into the good engine, as the manufacturer should have published with the $V_{MCA}$ data in the AFM.

7.7.13. Contrary to a sudden engine failure, the yaw rate/ heading change at (actual) $V_{MCA}$, when the airspeed was slowly decreased or when the thrust of a failing engine decays slowly, is usually not very large as is shown in the FDR data graphs of the analyzed accidents in § 8.3, § 8.4 and § 8.5. Nevertheless, during training or demonstrations, the instructor should be prepared to immediately reduce the asymmetrical thrust or power by closing the opposite throttle(s) if the attitude of the airplane changes unexpectedly. Do not release the rudder if initial buffet is encountered. This will cause the sideslip to increase rapidly with a resulting roll into the idling/ inoperative engine. A combination of high angle of attack and sideslip may cause a stall that could progress into a spin or a spiral dive. Also, be prepared for the case that another engine fails as well.

7.7.14. It is strongly recommended to thoroughly review § 4 in which most variable factors that have influence on $V_{MCA}$ are discussed, prior to training or demonstrating $V_{MCA}$.

### 7.8. Performance data OEI (n-1)

7.8.1. AFMs provide performance data in charts for all engines operative, and for one (or more) engines inoperative. Performance while OEI was already discussed in § 3 above.

7.8.2. During reviewing manuals, investigators should review the used takeoff performance data and determine whether the engine inoperative performance data in the AFM, such as $V_{YSE}$ and $V_{XSE}$, are accompanied by a power setting, an advisory and/ or limitation for the bank angle during maintaining straight flight and for configuration changes (§ 3.1.3 above). If the investigator, while analyzing engine failure related accidents, concludes that the AFM or other flight operations manuals do not include the proper conditions for maintaining n-1 climb performance and control, appropriate conclusions and recommendations for improvement should be included in the accident investigation report.

### 7.9. Role of AFM, FCOM, FCTM, Checklists and/or QRH

7.9.1. During the certification of airworthiness of an airplane, the AFM and Weight and Balance Manual are defined with title and number in the Type Certificate Data Sheet (TCDS) and hence are an integral part of the Certificate of Airworthiness. An AFM usually has an approved and a non-approved part. All procedures and performance data need approval of the aviation authorities, including modifications and alterations that affect procedures and performance. For instance, a new type propeller or an uprated engine both require change of the approved data in the AFM, because $V_{MCA}$, performance and weight and balance data change.
Operators often use AOM, FCOM or FCTM, and a QRH, rather than an AFM (with approved checklists). These manuals might be provided by the airplane manufacturer to allow a quick start of operations with the newly acquired airplanes, but larger airline companies write their own AOM, FCOM, FCTM, and/ or QRH, which do not require approval of the authorities. All of these manuals are so-called company manuals that are also maintained by the company, unless this is contracted out to the airplane manufacturer or to some other company. The procedures and performance data in these manuals must be in accordance with the procedures and data in the AFM and Weight and Balance Manuals that are defined in the TCDS, otherwise the certificate of airworthiness of the airplane is not valid, the airplane not airworthy. Accident or air safety investigators should also verify the used AFM and other manuals and checklists/ QRH following an accident.

## 8. ANALYZING FDR-EQUIPPED AIRPLANE ACCIDENT DATA

8.1. In this chapter, accidents that actually happened following an engine failure will be discussed using experimental flight test knowledge and experience. These accidents were chosen because the air minimum control speed ($V_{MCA}$) was not appropriately mentioned in the analysis section of the investigation reports, while just prior to the accidents the asymmetrical thrust was high, the propeller of the affected engine was not-feathered and the airspeed was low. These are all ingredients for the loss of control that can result in a catastrophe. The analysis in this report will be limited to controllability and performance after engine failure and will guide the reader through the presented graphs that originate from actual Flight Data Recorder data.
A circled number (e.g.①) refers to the same symbol in the figures; (sec.) refers to the elapsed time in seconds used in the figures.

### 8.2. Required data for analyzing control & performance after engine failure

8.2.1. Many factors have influence on the controllability of a multi-engine airplane after engine failure. Most of these factors were discussed in § 4 above. The worst-case of these factors were used to design (to size) the vertical tail for being able to counteract the asymmetrical thrust and to determine the minimum control speed $V_{MCA}$ that is published in the AFM of the airplane during experimental flight-testing. Most of the factors do not change at the instant an engine fails, like weight, location of the lateral and longitudinal center of gravity, etc. However, bank angle, rudder deflection and thrust have great influence on the controllability and performance after engine failure. These variables are under direct control of the pilot and are therefore indispensable for analyzing engine failure related accidents. All factors that have effect on the magnitude of $V_{MCA}$ might eventually become important for analyzing the accidents.

8.2.2. $V_{MCA}$ is to be observed by pilots as a lower speed limit prior to and following an engine failure. As was explained in this report, there are a few conditions for the published $V_{MCA}$ to be valid. The bank angle during measuring $V_{MCA}$ was, as used during tail design, between 3º and 5º away from the inoperative engine; 5° is often used. Any other bank angle results in a much higher *actual* $V_{MCA}$ (§ 4.3). In some cases, a little larger bank angle into the good engine lowers *actual* $V_{MCA}$, but increases the sideslip angle, therewith increasing the drag and the horizontal angle of attack of the vertical tail. Fin stall and hence, the loss of directional control, are imminent. Any lower thrust setting than maximum takeoff thrust results in a smaller thrust yawing moment, less required rudder deflection to counteract that yawing moment and hence, to a lower *actual* $V_{MCA}$ instantaneously (§ 4.6). With a lower than maximum thrust setting, airplane control can be maintained down to an airspeed lower than the redlined, placarded and/ or AFM-published $V_{MCA}$.

8.2.3. During analyzing engine failure related accidents, it is important for investigators to realize that the AFM-published $V_{MCA}$ is valid only when applying rudder for zero yaw rate, i.e. for maintaining the heading, and while banking the small favorable bank angle (5°) away from the inoperative engine (§ 4.3). Otherwise, the *actual* $V_{MCA}$ that was experienced and effective in-flight was higher than the AFM-published $V_{MCA}$.

8.2.4. The required manuals and data for analyzing engine failure related accidents include, but are not limited to the manuals and data listed below. Systems operation data might also be required, such as autofeather, autothrottle and rudder boost operation. Please refer to § 4 for a full description of the factors that have effect on both $V_{MCA}$ and the performance after engine failure.

- approved Flight and Weight and Balance Manuals that are listed in the Type Certificate Data Sheet.
  During accident and incident analyses, these formal manuals should be used. Owner-written or manufacturer provided manuals such as FCOM, FCTM, POH and checklists/ QRH might not be approved by certification authorities, but should be in agreement with the approved AFM, if used during operations. The use of data out of non-approved manuals during operations renders the Certificate of Airworthiness of the airplane invalid;

- AFM-published $V_{MC}$'s;
- takeoff speed, $V_1$, $V_R$, $V_{2MIN}$ and/ or $V_2$, if applicable;
- indicated/calibrated airspeed;
- heading;
- barometric and radar altitude;
- temperature;
- pitch, yaw and bank angle;
- angle of attack;
- control deflections (rudder, aileron and elevator), incl. max. deflections;
- Rudder ratio system data, if applicable;
- position of trim controls;
- seat/pedal adjustment (was full rudder/ 150 lbf foot pressure possible);
- flaps, flap handle position, landing gear;
- roll control spoilers;
- engines thrust/ torque levels;
- thrust derating or flexible/ reduced thrust setting, if applicable;
- propulsion systems (engines, its derating settings and propellers), in general airplane configuration, in accordance with the Type Certificate Data Sheet;
- which engine(s) failed, and when;
- the criticality of the failed engine(s);
- propellers, rpm and rotating directions, if applicable;
- propeller blade pitch, feathering, if applicable;
- rudder boosting, level and source, if any;
- actual airplane weight at the time of the accident;
- the location of the center of gravity (longitudinal and lateral);
- fuel imbalance, lateral and longitudinal (aft or stabilizer tank), if any, and fuel crossfeed selector(s) setting; and
- localizer deviation, if applicable.

8.2.5. Characteristic for the loss of control, unlike a stall, is the inability of counteracting uncommanded yawing and rolling motions with rudder and/ or ailerons. In some cases, the pilot does not apply adequate (up to full) rudder and/ or aileron and does not maintain straight flight. In other cases, a pilot forgets trim settings that were large as required while at high asymmetrical thrust, but should be neutralized when thrust is (going to be) reduced. This is also what to look for in FDR graphs and in witness reports while analyzing propulsion system malfunction related accidents. The accidents presented below are analyzed using the experimental flight-test knowledge and experience that was used to write this report. The analyses are limited to controllability prior to and following a propulsion system malfunction but include a review of data out of the Flight Manuals if the manuals or part thereof were included in the accident investigation reports.

## 8.3. Accident Jetstream 4100

8.3.1. Shortly after liftoff, a Jetstream 4100 crashed. Relevant Flight Data Recorder (FDR) data that were extracted from the Interim Report, ref. 17, and that are presented in Figure 39 below will be used. The analysis is limited to airplane control, because not all of the airplane and accident data that would be required for a thorough analysis were presented in the Interim Report. Circled numbers (like ①) refer to events in the figure.

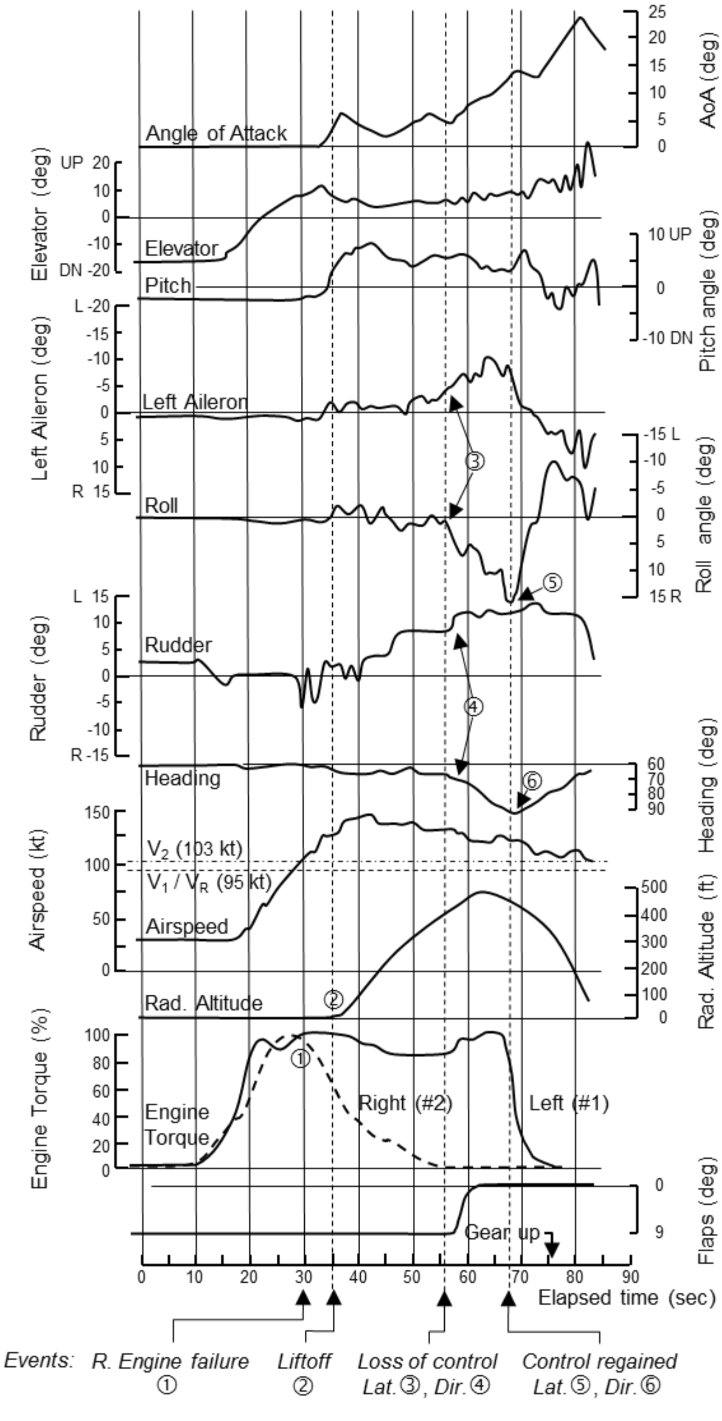

Figure 39. Relevant FDR data accident Jetstream 4100.

8.3.2. ***Analysis***. During takeoff, at about the instant of rotation, 5 sec. before liftoff (②), the right (#2) engine failed (①) and the thrust slowly decayed to zero in about 25 seconds. The takeoff was continued. As shown by the FDR data of pitch, roll and heading, the dynamic effects caused by the failing engine were minimal, although the pilot entered two small rudder pulses to the right, immediately following the engine failure. The airplane started to climb and the pilot initially maintained approximately runway heading with a small, but increasing rudder input to the left. The bank angle (roll) varied a little around wings-level. Roll control power by the ailerons was adequately available; the airplane responded adequately to the aileron inputs. Despite of the reduction of the thrust of the right engine, the airspeed continued to increase for about 12 seconds to approximately 135 kt, which was much higher than the required $V_2$ (103 kt) for this flight phase. The pilot increased the rudder deflection for maintaining the heading, but allowed a small bank angle to develop to the right, into the inoperative engine, rather than away from it. Consequently, a sideslip developed, increasing the drag after which, as a result, the airspeed started to decrease. The bank angle could still be controlled using the ailerons, but was not 5 degrees (or less as opted by the manufacturer) away from the inoperative engine as is required for minimum drag and a low actual minimum control speed $V_{MCA}$ while the thrust was asymmetrical.

8.3.3. Since the propellers of this type of airplane both rotate inward down, the $V_{MCA}$'s after failure of either engine are (approximately) equal; neither engine can be designated critical, both engines are equally critical (§ 4.5.5). Hence, the $V_{MCA}$ published in the AFM applies after failure of any of the two engines, but was not presented in the preliminary report, ref. 17. $V_R$ is usually 1.05 $V_{MCA}$. $V_R$ was 95 kt, so $V_{MCA}$ might have been published as 90 kt.

8.3.4. When the decreasing airspeed reached approximately 127 kt, the airplane started banking to the right (③), which could not be prevented by an increasing aileron input to the left, up to 10 degrees of maximum available 21 degrees control power. This only partial 10-degree aileron deflection was not large enough for the ailerons to generate a high enough rolling moment, at the decreasing actual airspeed, to counteract the propulsive thrust rolling moment generated by the blown wing section behind propeller #1 and other rolling moments. The pilot allowed the airplane to bank to the right, because the opposite aileron deflection was not large enough to prevent this. Lateral (roll) control was lost at this point because of only partial aileron deflection (③, § 5.3.3). The indicated airspeed had decreased below the *actual* lateral minimum control speed (≈ 127 kt) for the given partial aileron deflection, for the actual bank angle and the actual thrust setting. Uncommanded rolling (and/ or yawing) that is, or cannot be counteracted by the pilot is, during flight-testing, an indication that the current airspeed is the actual minimum control speed. In other words, not being able to counteract or not increasing available control power for counteracting (uncommanded) rolling and/ or yawing is an indication of the loss of control at the current airspeed (§ 5.3.3). In this case, the pilot did not counteract the rolling while adequate aileron control power was still available; hence, the current airspeed was the actual $V_{MCA}$. Refer to § 2.5.3 for a definition of *actual* $V_{MCA}$.

8.3.5. The torque of the left engine, which was reduced a little to approximately 85% for unknown reasons, was then slowly increased to over 100% in 10 seconds time. This increasing engine torque increased the thrust yawing moment (and the rolling moment due to thrust) even more. An increase of opposite rudder deflection can be observed, but could not prevent the yawing to continue to increase to the right. The rudder deflection was not larger than 12 degrees of an available 24 degrees; the control power provided by the partial, half rudder deflection was not high enough to stop the yawing and to maintain the heading at and below an airspeed of ≈ 125 kt. Directional control was lost as well at this point (④).
The *actual* directional $V_{MCA}$ for the 14 degrees of available 24 degrees of rudder deflection, the actual engine thrust and the actual bank angle, was ≈ 125 kt. The *actual* directional $V_{MCA}$ was obviously a little lower than the *actual* lateral $V_{MCA}$ (≈ 127 kt), most probably because of the counter rotating propellers. The airspeed at which control was lost was 24 kt higher than takeoff safety speed $V_2$! $V_2$ did obviously not provide the safety that is expected from it, because the controls were not adequately used to maintain both the heading and the favorable bank angle (§ 6.5.11).

8.3.6. Just after the torque increase started, the flaps were selected up, also at the instant of event ④. The flaps on the left wing were blown by the still running propeller #1 at higher airspeed than the flaps on the right wing with the failed engine. This might have contributed to the rolling moment. Flaps might also have had influence on $V_{MCA}$

because the effect of the airflow striking the vertical tail. Nevertheless, the aileron deflection was not maximal.
The flap handle might also be mechanized to switch on or increase the rudder boosting; this will have an effect on the value of $V_{MCA}$ and therewith on the controllability of the aircraft. Review of the AFM is required to confirm this.

8.3.7. The $V_{MCA}$ published in the AFM and that is used to calculate both $V_R$ and $V_2$ is measured while slowly decreasing the airspeed, at the instant that either the rudder or the aileron reaches maximum deflection (§ 5.3.3) or the control forces reach the maximum allowed value (§ 2.7.4). During the test, the airplane is in a test configuration, which includes, but is not limited to, the maximum takeoff thrust setting on the operative engine, the propeller of the failed engine feathered, if automatic, an aft center of gravity, lowest possible weight, and a bank angle of 5 degrees away from the inoperative engine. The manufacturer determines the bank angle though, during tail design, which is usually between 3 and 5 degrees. A not (fully) feathered propeller, a not fully deflected lateral and/ or directional control surface or any other bank angle than 5 degrees away from the inoperative engine will increase the standardized AFM-published $V_{MCA}$ to a higher, *actual* value. The standardized AFM-published $V_{MCA}$ is valid only while maintaining this bank angle during straight flight.

8.3.8. The consequence of not maintaining the bank angle after engine failure is not only that *actual* $V_{MCA}$ increases, but also that a sideslip develops, causing drag that reduced the airspeed as well as the rate of climb (to a negative value).

8.3.9. From the moment of event ④, the airplane kept rolling (③) and yawing (④) to the right, despite of the opposite control inputs. The aerodynamic forces generated by these partial, less than maximum control deflections and the actual airspeed, were obviously not large enough to counteract the propulsive thrust rolling moments and the yawing moments. Since lateral control was lost at an indicated airspeed of about 127 kt and directional control at 125 kt, 127 kt was obviously the *actual* $V_{MCA}$ of this airplane at that instant, with the actual values of power setting, control deflections, bank angle, center of gravity, weight, etc. This *actual* $V_{MCA}$ was higher than the $V_{MCA}$ published in the AFM because the actual bank angle and the actual control deflections were not the same as were used to determine the $V_{MCA}$ that is published in the AFM (§ 5.3.6) and that was used to calculate takeoff speeds $V_R$ and $V_2$ (§ 6.4 and § 6.5). In addition, $V_{MCA}$ might have been increased by flap retraction as well (at the same moment as event ④) or by gear retraction, therewith also deteriorating the controllability of the airplane.

8.3.10. Then, suddenly, the torque of the other engine also decreased to zero within 10 seconds. The crew must have mis-identified the failed engine and shut down the operative engine. Following this total power loss, there was no asymmetrical thrust anymore, and hence no adverse thrust yawing and rolling moments. The graphs in Figure 39 show that control was restored as soon as the torque of the left engine decreased below approximately 80%. The deflections of rudder and aileron at that moment were sufficient to counteract the reduced engine yawing moment from there on; both directional and lateral control were regained (⑤,⑥). The altitude was about 450 ft AGL. Because the ailerons and rudder were still deflected to the left, the airplane started rolling and yawing to the left. The rolling was allowed to continue past wings level to the left while the rudder deflection was maintained, without reason, because the thrust yawing moment was already zero. The resulting sideslip must have increased the rate of descent. The thrust reduction instantly decreased *actual* $V_{MCA}$ to a much lower level, in any case below the actual indicated airspeed, because the airplane responded to the still deflected ailerons and rudder to the left by rolling and yawing to the left. An emergency gear-up landing followed 10 seconds later.

8.3.11. The pilot did not apply lateral and directional controls as would be required for maintaining control after engine failure. This might be caused by inappropriate engine-out training and incomplete engine emergency procedures that might not have been in agreement with the way that airplanes are designed, and flight-tested by experimental test pilots and flight test engineers to determine the minimum control speeds.

8.3.12. During the takeoff roll, the elevator data in Figure 39 shows that the pilot slowly increased the elevator deflection while the airspeed increased. At airspeed $V_R$, the elevator was 8 degrees up, but the aircraft stayed on the ground. Then the elevator was lowered a little while pitch increased. The aircraft was not positively rotated from the runway using the elevator; a rather unusual takeoff technique that also increased the drag during the takeoff run. Despite the increased elevator deflection, the aircraft only took off when the airspeed was 125 knots, 22 knots higher than the presented takeoff safety speed $V_2$ of 103 knots. It should be analyzed why this difference existed. The landing gear was retracted 30 sec. after liftoff when the altitude was almost 500 ft; way too late and bad for climb performance, unless the AFM told otherwise.

8.3.13. It was not clear whether the autofeather system was armed and operating. From the engine torque graph in Figure 39, it appears that the automatic power reserve (APR) system was not armed or overridden either. Additional analysis is required.

8.3.14. ***Conclusions***. This analysis and the conclusions are limited to controllability issues following the failure of the engine.

8.3.15. The right engine #2 failed on rotation for liftoff. The torque of the operative left engine #1 was then allowed to decrease to 80%. When the torque of engine #1 was again increased to 100%, both lateral and directional control were lost because of too small aileron and rudder deflections against the acting rolling and yawing moments even while the airspeed was 24 kt higher than $V_2$. $V_2$ offered no takeoff safety, because rudder deflection and bank angle were less than required for $V_2$ and $V_{MCA}$ to be valid. Control was regained following the inadvertent shutdown of engine #1, the left engine.

8.3.16. If the left engine no.1 had not been shut down inadvertently, the aircraft would certainly not have survived the failure of engine #2 either. Control, both directional and lateral, was already lost at that time. Recovery at such a low altitude would not have been possible.

8.3.17. Another conclusion should be that the pilots obviously were not aware of how to control a multi-engine airplane after engine failure; they were not familiar with the real value of $V_{MCA}$ and $V_2$ either. During the training in a simulator or in-flight, the effects of an inoperative engine and the correct recovery techniques were obviously never taught correctly, i.e. in accordance with the way that airplanes are designed and flight-tested.

8.3.18. ***Cause of the accident.*** The probable cause of the accident was the inappropriate crew response to the failure of engine #2 after takeoff, leading to the loss of both lateral and directional control, loss of climb performance, the mis-identification of the failed engine and subsequent shutdown of the operative engine #1.

8.3.19. Based on the investigation data presented above, the conclusion of this limited analysis on the controllability of the airplane after engine failure would have to be that the pilot failed to counteract the rolling and yawing using adequate rudder and aileron deflections. In addition, the pilot did neither attain and maintain a 5-degree bank angle to the left (into the good engine) immediately following the failure of the right engine for keeping *actual* $V_{MCA}$ low, nor when applying again maximum thrust on the left engine for the *actual* $V_{MCA}$ to stay as low as possible and for the remaining climb performance to be as high as possible.

8.3.20. If the other engine would not have been shut down inadvertently, the airplane would certainly not have survived this engine failure either; control, both directional and lateral, was already lost, because the pilot allowed the bank angle to increase into the dead engine side way too much. Recovery at such a low altitude would not have been possible.

8.3.21. Although the AFM was not available for review, the $V_{MCA}$ definition and engine emergency procedures were most probably not in accordance with the way that airplanes are designed and with the flight-test techniques used by experimental test pilots during flights-tests for determining the minimum control speeds while an engine is inoperative.

8.3.22. *Contributing factors* were the inappropriate execution of the takeoff procedures as prescribed in the AFM (late rotation, not maintaining $V_2$, late gear retraction, too early (mis-)identification of the failed engine) and an obviously incomplete understanding of, or unfamiliarity with, the engine emergency procedure in the AFM (no requirement to bank away from the failed engine).

8.3.23. ***Recommendations***. The recommendations are limited to improving airplane control after engine failure.

8.3.24. Review the definitions of $V_{MCA}$ and other takeoff speeds in AFM and other operations manuals, and in the engine inoperative training manuals. Review in-flight as well as in-classroom training for engine-out, and improve as necessary to be in agreement with the way that airplanes are designed and flight-tested (as is the subject of this report).

*8.3.25.* The engine emergency procedures should be reviewed and improved as necessary by the type certificate holder.

### 8.4. Accident Saab SF-340B

8.4.1. Ten minutes after takeoff from runway 24, an oil pressure warning of the right engine (#2) made the captain decide to return to the airport. He left the affected engine #2 idling; its propeller was not-feathered. The wind was 270/ 11 kt when the captain accepted landing runway 06. On short final, with an actual wind of 280/ 8 kt, the airplane was displaced to the right. At 45 ft Radar Altitude, the captain therefore decided to go-around using the thrust of the left engine only; the right engine was kept idling. The airplane crashed 13 seconds later, far to the right of the runway.

8.4.2. In this report, the factual information that is presented in the formal Aircraft Accident Report (ref. 18) was used, limited to the data that were required to analyze the controllability of the airplane during the final phase of the flight. Refer to the formal report for the other details.

8.4.3. ***Analysis***. Two of the Flight Data Recorder readout graphs that are included in the formal Aircraft Accident Report contain the data that were used to perform this Analysis. These plots were combined into Figure 40 below. In the text, event markers (like ①) are again used to link the text to the events in the figure. The interesting flight phase for this analysis begins at 12:45:41, defined as event ①.

8.4.4. Engine #2 was kept idling throughout the entire final phase of the flight; the torque was approximately 10%. The propeller of this engine was not-feathered, causing additional drag that resulted in a yawing moment that enlarged the thrust yawing moment of the operative left engine #1 (§ 7.7.11). For maintaining straight flight in this condition at maximum thrust of engine #1, the side force generated by the vertical tail (and rudder) would have to be larger by either increasing the rudder deflection or, if the rudder deflection is already maximum, by increasing the airspeed. If the heading cannot be maintained while the rudder deflection is less than maximum, the *actual* $V_{MCA}$ is obviously higher than the current airspeed for that partial rudder deflection. *Actual* $V_{MCA}$ is defined in § 2.5.3. This *actual* $V_{MCA}$ will be higher than the standardized AFM-published $V_{MCA}$ (103 kt). The standardized $V_{MCA}$ was measured while the propeller was feathered, provided the feathering system was automatic, and with maximum rudder deflection (§ 5.2.4).

8.4.5. During final approach, at 12:45:41 (①), at a radar altitude of 110 ft and an airspeed of 115 kt, 4 kt below the threshold speed for 20 degrees flaps ($V_{TH20}$), the torque of engine #1 was increased from 40% to 65%. The increased propulsive lift of the blown wing section (plus flaps) of the left wing behind the propeller caused the airplane to bank from approximately wings level to 3 – 4 degrees to the right. As the bank angle started to increase to the right, the pilot increased the aileron deflection to the left, to approximately 20 degrees of maximum 24 degrees available, to counteract the bank angle.
Since the aileron deflection was not maximum, the pilot obviously did not attempt to attain a safe small favorable bank angle (3° to 5°) away from the inoperative engine to keep the drag and *actual* $V_{MCA}$ as low as possible (§ 4.3). The exact required favorable bank angle was not presented in the Aircraft Accident Report, most probably because the manufacturer did not provide this number in the AFM. Rather than attaining a safe bank angle away from the inoperative engine, a bank angle of 3 degrees was maintained to the wrong, right side, into the dead engine for a few seconds, which

must definitely have adversely affected (i.e. increased) the *actual* V$_{MCA}$. At this time, the airplane was still controllable about the longitudinal (roll) axis though, as shown by the response to the aileron deflection in the bank angle plots.

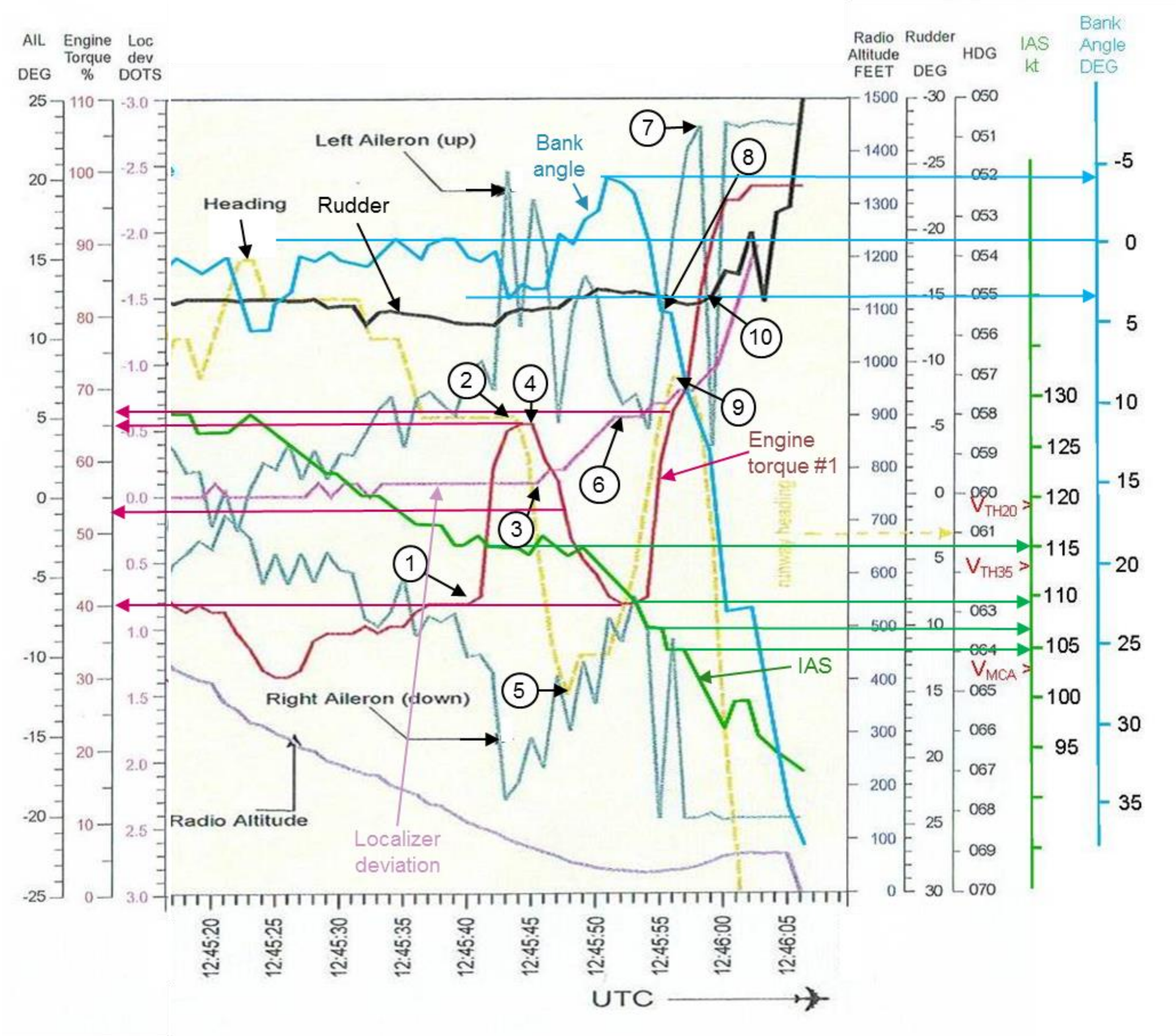

Figure 40. FDR data go-around accident Saab SF-340B while engine #2 idling.

8.4.6. The increased thrust of engine #1 also increased the yawing moment to the right. The drag of the not-feathered propeller of the idling engine #2 continued to add to this thrust yawing moment. The rudder deflection was increased by only 2 degrees to 14 degrees of the available 30$^{+}$ degrees to the left, which was obviously not large enough to counteract the yawing at the current airspeed, because the nose of the airplane started to yaw to the right while the torque reached (only) 65% (at 12:45:43, ②).

The partial rudder deflection was not large enough to counteract the current asymmetrical thrust yawing moments. The airspeed was too low for the vertical tail with only partial rudder to generate a high enough side force to counteract the yawing; the heading could not be maintained, i.e. controlled anymore. This in fact means that the *actual* V$_{MCA}$ for the partial rudder, the current bank angle, thrust setting, propeller drag, etc. at that time must have been higher than 115 KIAS. The airplane was already out of (directional) control at 12:45:43 (②), two seconds after increasing the thrust, while the IAS was 115 kt, still 12 kt above the AFM-published standardized V$_{MCA}$.

The increase of the *actual* V$_{MCA}$ to a value higher than the AFM-published V$_{MCA}$ was caused by the incorrect bank angle (into the idling engine, rather than into the operative engine), by the additional yawing moment caused by the drag of the not-feathered propeller #2 and by the limited, partial rudder deflection as well.

8.4.7. In addition, this yawing must have resulted in an increase of the sideslip (into the left ear), causing a side force to the right that started displacing the airplane to the right, away from the runway centerline. The tail wind (8 kt from 7 o'clock) will also have contributed to this displacement. The localizer deviation graph shows the total displacement (③). The sideslip increased the total drag of the airplane even more, therewith reducing the remaining one-engine-inoperative climb performance.

8.4.8. Then, at 12:45:45 (④), the pilot slowly reduced the torque of the engine #1 to 40% (in 6 seconds). The propulsive lift of the left wing decreased instantaneously, causing the bank angle to return towards wings level with the existing aileron deflection. The aileron deflection to the left was reduced, but then again increased to the left, most probably because the pilot wanted to return to the runway centerline.
As the torque decreased below 53% (12:45:48) and the airspeed was still approximately 115 KIAS, the yawing (heading change) reversed (⑤), indicating that the yawing moment generated by the still small 15° rudder deflection to the left was then large enough to counteract the decreasing yawing moments due to the asymmetrical thrust and the drag of idling engine/ propeller #2. Since directional (yaw) control was reestablished at this time (⑤), the *actual* $V_{MCA}$ had obviously decreased below the IAS. This decrease was caused by both the bank angle change (from 3 degrees into the wrong side to wings level) and the thrust reduction (initiated at ④).
The airspeed reduction, as shown in the graph, was caused by the increased drag due to sideslip, by increasing the pitch angle and by the thrust reduction, and not because of lateral or directional control.

8.4.9. At 12:45:53, the airplane had, as shown by the localizer deviation graph (⑥), apparently drifted so much to the right of the runway centerline that the pilot decided to go-around. The airspeed at that time was 109 kt, 10 kt below $V_{TH20}$ but still 6 kt above the AFM-published $V_{MCA}$. The torque of engine #1 was increased from 40% to 98% in 7 seconds. The rudder deflection remained unchanged, approximately halfway, 15 degrees, to the left. Due to the increase of the propulsive lift of the blown wing section (plus flaps) behind propeller #1, the aircraft started to bank to the right to which the pilot responded with full aileron deflection to the left (⑦). The bank angle however, continuously increased slowly (3 degrees per second) to the right for the remainder of the flight while the aileron deflection remained full left, apart from a pulse to the right. This pulse is not visible in the right aileron graph and might be a data glitch. Due to the low airspeed, the ailerons were no longer effective enough to control the banking under the given thrust and drag asymmetry conditions, resulting in the loss of lateral/ directional control (⑧) The *actual* $V_{MCA}$ must have increased to a value higher than the indicated airspeed 107 kt.

8.4.10. After the engine torque increased above 67% (⑨), the half rudder deflection to the left could not prevent the yawing from reversing to the right. The yaw rate increased to approximately 4 degrees per second to the right, also for the remainder of the flight. Directional control was then also lost while the airspeed was 105 kt and while bank angle $\phi$ had increased to 8° to the right, into the dead engine, the wrong side, and while the torque had only increased to 67%. At event ⑩, about 7 seconds prior to the impact with the ground, the rudder deflection finally was increased, with some hesitation, to be fully deflected to the left at the instant of impact. However, neither lateral nor directional control could be reestablished because of the sustained asymmetrical thrust. The two-second discontinuity in the bank angle and airspeed data as shown in the graph at 12:46:00 may have been caused by the increased rudder deflection or by the aileron pulse to the right (from ⑦). In any case, the full rudder deflection came way too late.

8.4.11. Control was again lost at an airspeed higher than the AFM-published standardized $V_{MCA}$, because the rudder deflection was not large enough to generate a large enough yawing moment for counteracting the yawing moments caused by the engine thrust and the drag of the not-feathered propeller. In addition, the banking to the right resulted in an additional side force ($W \cdot \sin \phi$) to the wrong, right side that added to the rudder generated side force that both 'pulled' the airplane away from the runway. Equilibrium of lateral forces and moments could not be achieved anymore. The bank angle to the wrong side, the only partial rudder deflection and the not-feathered propeller caused the *actual* $V_{MCA}$ to increase way above the IAS, resulting in the loss of control, and a catastrophe (§ 4.8).

8.4.12. ***Conclusions***. The propeller of the idling right engine #2 was not-feathered and consequently caused high additional drag and a yawing moment that enlarged the yawing moment generated by the operative left engine #1. Because of this increased yawing moment, a higher airspeed than the AFM-published $V_{MCA}$ was required for the vertical fin and rudder to be able to generate a high enough side force to counteract the increased yawing moments and maintain control of the airplane during the final phase of the flight. The rudder however, was not fully deflected. Therefore, the airspeed required for generating a high enough rudder yawing moment was also higher.

8.4.13. The standardized $V_{MCA}$ that is published in the AFM was 103 KIAS and was determined while the rudder deflection was maximal (travel or pedal force, § 5.2.4). Other factors used to determine the AFM-published $V_{MCA}$ were a feathered propeller (if automatic and armed) for lowest drag and a small constant bank angle (as opted by the manufacturer, but max. 5 degrees) away from the inoperative engine. The *actual* $V_{MCA}$ is almost always lower, safer, when the small bank angle is maintained. However, the *actual* $V_{MCA}$, the $V_{MCA}$ that the pilot experiences in-flight, varies considerably with bank angle and rudder deflection. Therefore, the AFM-published $V_{MCA}$ is valid only if the bank angle is the same as the bank angle that was used during flight-tests to determine $V_{MCA}$, usually a small bank angle between 3° and 5° away from the inoperative engine, as opted by the manufacturer, and with maximum rudder deflection (for zero yaw). The small bank angle is most probably not prescribed in the SF-340B AFM as a requirement for maintaining control while an engine is inoperative, the thrust setting of the operative engine is high and the airspeed low. This is regrettably not required by Aviation Regulations (yet). The higher required airspeed for the rudder to develop a higher side force to overcome the drag of the not-feathered propeller for maintaining control of the airplane was in fact a higher *actual* $V_{MCA}$ than the standardized $V_{MCA}$ that was published in the AFM.

8.4.14. During the final phase of the flight, control was lost twice, both times at the instant that the thrust of the left engine was increased, despite the fact that in both cases the airspeed was higher than the AFM-published $V_{MCA}$. Therefore, the pilots might not have expected control problems and must have assumed the airspeed to be safe, but in fact, it was not.
The first loss of directional control was at 12:45:43 (②), during the approach, but was restored because the pilot (happened to) reduce(d) the thrust while maintaining the existing control deflections.

8.4.15. The third loss of control, now directional, during the approach occurred following event ⑨ at 12:45:56 and resulted in a catastrophe. Control of the airplane was lost because the *actual* $V_{MCA}$ increased above the airspeed of 105 KIAS at that time. The increase of *actual* $V_{MCA}$ was caused by:

- not attaining a small bank angle of 3 – 5 degrees away from the inoperative engine, (just) before advancing the throttle. This small bank angle is required to keep the *actual* $V_{MCA}$ to the lowest possible value for the given conditions and configuration and to minimize the sideslip, therewith minimizing the drag and maximizing the remaining single-engine climb performance. Due to not maintaining the small bank angle away from the inoperative engine, the *actual* $V_{MCA}$ was higher than the AFM-published standardized $V_{MCA}$ and in this case also higher than the indicated airspeed, causing the loss of control. The AFM-published $V_{MCA}$ (103 KIAS in this case) is valid only if the bank angle is the same as was used to determine $V_{MCA}$, in most cases 5 degrees away from the inoperative engine;
- not increasing the rudder deflection while increasing the thrust in order to maintain the heading. The rudder yawing moment generated by only half (50%) of the available rudder deflection, at the given airspeed, was not high enough to prevent the airplane from yawing into the dead engine following the thrust increase.
  Although the indicated airspeed was still higher than the AFM-published $V_{MCA}$, the *actual* $V_{MCA}$ for the given 50% rudder deflection and the thrust setting must have increased to a value higher than the indicated airspeed, leading to the loss of control. The AFM-published standardized $V_{MCA}$ is valid only if the rudder deflection is the same as used to determine $V_{MCA}$,

which usually is full rudder, or a deflection for which the pedal force is 150 lb (180 lb for military airplanes).

8.4.16. The *actual* $V_{MCA}$ could increase to a value higher than the AFM-published standardized $V_{MCA}$ because the use of the controls by the pilots following the engine failure was neither in agreement with the way that controls are used by experimental flight-test crews during the flight-tests to determine $V_{MCA}$ (§ 5.3), nor with the assumptions that the design engineer used to calculate the required size of the vertical tail and rudder (§ 2.4). However, the pilots are not to be blamed because the limitations and conditions for the AFM-published $V_{MCA}$ to be valid are most often not presented in AFMs because there is no regulatory requirement for the manufacturer to do so. Nevertheless, manufacturers have their own responsibility, and usually have adequately trained flight-test personnel to provide for the correct guidance and data that are essential to maintaining control after engine failure with their airplanes.

8.4.17. The accident happened because the pilots were obviously not familiar with the effects of an idling engine on the controllability of the airplane, not with the real meaning of $V_{MCA}$ and not with the conditions under which the AFM-published standardized $V_{MCA}$ is valid either. The only aerodynamic control for counteracting a thrust yawing moment is the rudder; this control was not appropriately used. As a result of the inappropriate crew response to the propulsion system malfunction, the *actual* $V_{MCA}$ was higher than the AFM-published $V_{MCA}$ and also higher than the indicated airspeed, resulting in the loss of control. A contributing factor, if not the main cause of the accident, is that US Federal Aviation Regulations and EU Certification Specifications 23 and 25, or equivalent, do not require the manufacturer to present the conditions under which the published $V_{MCA}$ is valid in the AFMs of their airplanes. Flight schools do not teach these anymore, either. Writers of course books for the multi-engine rating seem to have never heard of these. However, airplane design engineers use them, as do experimental test pilots.

8.4.18. ***Recommendations***. In addition to the recommendations that were already presented in the Aircraft Accident Report (ref. 18), it is recommended to add a review of the Airplane Flight and Performance Manuals to the investigations of all future engine failure related accidents to ensure that engine-out procedures comply with the applied design and flight-test procedures, in any case to verify that the bank angle, thrust setting and control deflections are included for which the published $V_{MCA}$ is valid.

8.4.19. Improve the definitions of $V_{MCA}$ in AFMs, by adding that the published $V_{MCA}$ is valid only if the same bank angle is applied away from the inoperative engine that was used to both design the vertical tail and determine $V_{MCA}$ (and that no turns should be made as long as the airspeed is low and the thrust setting is high), and that the rudder deflection is adequate to stop yawing. The other conditions that were used to determine $V_{MCA}$ should also be included. $V_{MCA}$ is a *minimum* control speed for straight flight only; the *actual* minimum control speed can be a lot higher if the other conditions are not met.

8.4.20. Improve Aviation Regulations (FAR and CS 23.149 and 25.149) by adding the requirement to list the bank angle that was used to design the vertical tail and determine $V_{MCA}$ with the $V_{MCA}$ data in the AFM. Additional recommendations for improvement of Regulations are presented in ref. 18.

8.4.21. Improve engine inoperative training to include flight while an engine is inoperative at an airspeed for which full rudder and/ or aileron deflection is required, of course only at a safe altitude (> 5,000 ft AGL).

### 8.5. Accident EMB-120ER

8.5.1. During the takeoff of an EMB-120ER twin-turboprop airplane for a revalidating command instrument rating, the training and checking captain retarded the left power lever to zero torque just after liftoff. The propeller of the engine was not feathered. The limited analysis below is again limited to airplane control, but also includes remarks on the quotes out of the AFM that were included in the safety report, ref. 19. Refer also to the YouTube video with this accident, ref. 3.

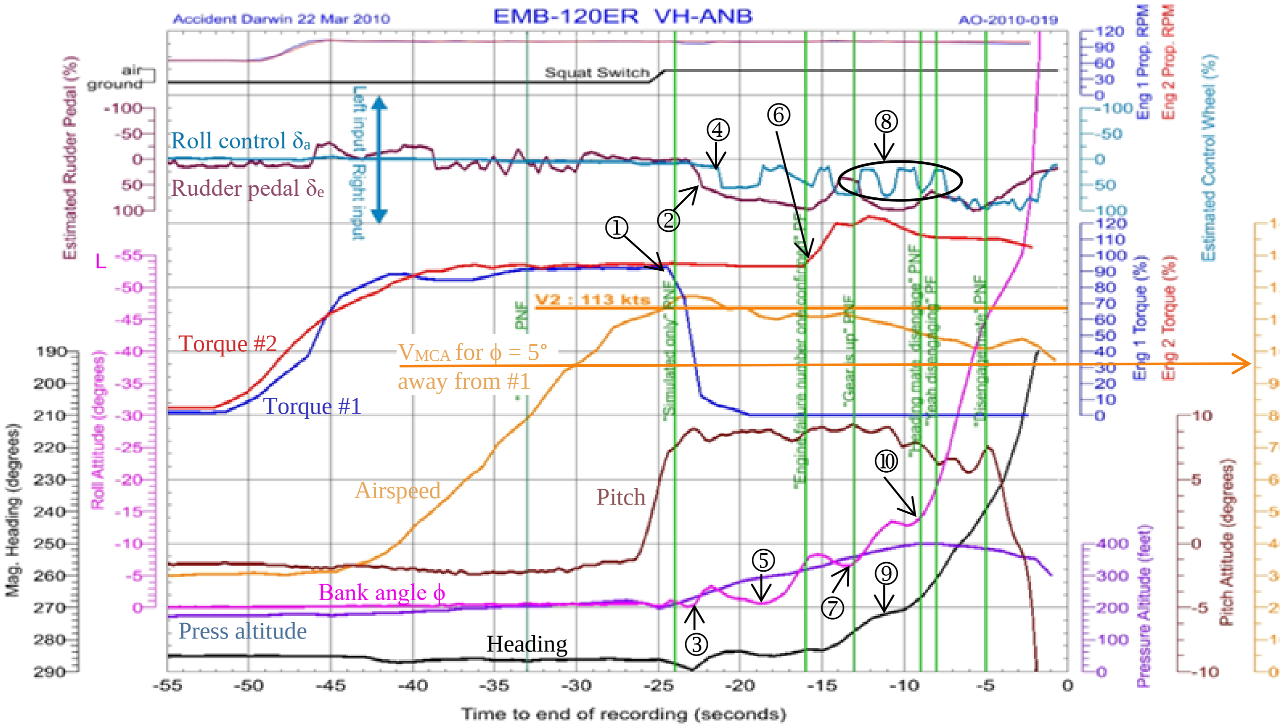

Figure 41. FDR data EMB-120ER takeoff accident while engine #1 idling.

*8.5.2.* ***Analysis.*** The power lever of engine #1 was retarded just after liftoff, event ① in Figure 41. The torque of both engines for takeoff was set to approximately 93%, as the FDR data in Figure 41 shows, for a reduced thrust takeoff. The idling propeller resulted in additional drag and a yawing moment that enlarged the thrust yawing moment of the operative engine #2.

The 2° heading change to the right might be caused by the small bank angle change just prior to the thrust decay, or by the torque effect. Then the airplane yawed 5° to the left as a result of the asymmetrical thrust yawing moment of engine #2. The yawing stopped because the pilot responded adequately with 50% rudder to the right (②). The pilot responded to the banking (③) with a roll control input to the right (④), after which the airplane rolled back to wings level (⑤). The airspeed slowly decreased, decreasing the side force generated by the vertical tail, so the pilot had to increase the rudder deflection to 100% for maintaining the heading (as from ②). The pilot returned the roll control wheel back to near zero, right after the wings were level again (⑤), so he obviously did not attempt to attain the favorable 5° bank angle away from the inoperative engine #1 to keep the actual $V_{MCA}$ low and reduce the drag to minimum (§ 3.1.1); the banking started to increase again. At event ⑥, the pilot increased the torque of engine #2 to 120%, but rather than maintaining the rudder at maximum deflection to counteract the increasing yawing moment, the pilot reduced the rudder to 30%, which caused the airplane to start yawing to the left. The increased thrust also increased the propulsive lift of the wing section behind propeller #2 resulting in a roll rate to the left (⑦), whereupon the pilot responded with varying, roll control inputs between 20 and 70% in magnitude (⑧). These inputs however, were not large enough to counteract the asymmetrical thrust rolling moment; the bank angle continued to increase to the left with some variations due to the varying roll control inputs.

The pilot again increased the rudder input to full rudder to the right, after which the yaw rate to the left slowed down a bit, but continued and could not be stopped anymore by the rudder alone (⑨). At that instant, the airplane was out of directional control. The continuing yawing, despite of maximum opposite rudder deflection is typically for what an experimental test pilot observes during flight-tests to determine $V_{MCA}$ when the airspeed decreases below $V_{MCA}$ (refer to § 5.3.3). The airspeed of 110 KIAS at that instant was however not the (standardized) $V_{MCA}$ of the airplane (97 KIAS with flaps 15°), but the *actual* $V_{MCA}$ which was 13 kt higher because the bank angle was not 5° away from the inoperative engine, but approximately 13° into the inoperative engine (§ 4.3). Shortly thereafter, the bank angle stabilized for a few seconds, but then continued to increase to the left (⑩). The airplane was out of lateral control as well, at an airspeed of 105 KIAS despite the increasing roll control input up to 100% to the right. The rolling continued and the nose went down. The airplane crashed, out of control.

8.5.3. Before the torque was increased from 93% to 120%, the one engine out climb was stable and controllable at an airspeed of 110 kt and a rate of climb of approximately 600 fpm at. It is difficult to say whether the aircraft would have continued the flight safely without the thrust increase, but the FDR data shows that neither the pilot, nor the checking captain was aware of the requirement to bank away from the inoperative engine when the (asymmetrical) thrust is increased. The propeller of the idling engine was not feathered, as was the case for determining the AFM-published standardized $V_{MCA}$, so the *actual* $V_{MCA}$ was for sure higher than the AFM-published $V_{MCA}$; a turn at low altitude would have led to control problems as well.

8.5.4. When throttle #1 was retarded to simulate an engine failure, the airspeed had already increased to $V_2$. $V_2$ is to provide a safety margin of at least 10% above the standardized AFM-published $V_{MCA}$ and 13% above $V_S$ (§ 6.5.2). While the pitch angle was near constant, the airspeed slowly decreased to 107 KIAS, into the 10% safety margin above $V_{MCA}$ (97 kt + 10% = 107 kt) when directional control was lost (⑨). As discussed above, the actual $V_{MCA}$ was higher because the 5° favorable bank angle was not attained and maintained. Therefore, the *actual* $V_2$ should have been equal to or higher than 1.10 × *actual* $V_{MCA}$ = 120 kt, because a bank angle of 5° was not attained and maintained away from the inoperative engine. The $V_2$ of 113 kt that was used was obviously not a safe takeoff speed for the way the airplane was controlled during this simulated engine failure, refer to § 6.5. It could not be determined whether the $V_2$ used was $V_{2MIN}$ or $V_R$ + a speed increment as determined in FAR/ CS 25.107 (c) (§ 6.5.2).

8.5.5. ***Manual review***. The safety report presents a number of quotes out of the EMB-120 Flight Operations Manuals. A few comments on these will be presented in the next paragraphs. The page numbers refer to pages in the Safety Report, ref. 19.

8.5.6. Page 4. *"The AFM procedure required that airspeed be maintained at $V_2$ (PIC's notes – $V_2$ +10)"*. In accordance with FAR/ CS 25.149, $V_{2MIN}$ is the higher of 1.1 $V_{MCA}$ (107 kt) or 1,13 $V_s$ (§ 6.5). $V_2$ may not be less than $V_{2MIN}$ and $V_R$ plus the speed increment attained before reaching 35 ft above the runway level. $V_2$ might be right and safe for engine failures during normal operations, when the propeller of the failing engine is automatically feathered, but not for training an engine failure when the torque is reduced to zero without feathering the propeller. That might be the reason that the Pilot in Command (PIC) noted $V_2$ + 10. For this flight, $V_2$ would then have been 113 + 10 = 123 kt, which would have been a safer airspeed. The PIC should also have added in his notes: bank 5° away from the inoperative engine, to keep the actual $V_{MCA}$ close to the standardized $V_{MCA}$ that is published in the AFM. It is recommended to review the AFM for this bank angle limitation.

8.5.7. *"The operator's procedures allowed for up to 110% torque on the operating engine, if required."* FDR data shows that the torque can be increased to 120% by moving the power levers forward. What would be the reason for the operator to allow a torque of up to only 110%? To preserve engine life? Was the AFM-published $V_{MCA}$ indeed determined using 120% torque, or were the engines more powerful than the engines that were installed during certification, which is sometimes the reason for a $V_{MCA}$ (and $V_2$) increment or a power decrement, if the size of the vertical tail is not increased? The $V_{MCA}$ that is published in the AFM must be based on the maximum power level that the pilot can set using the power levers; a procedural reduction, i.e. an allowance up to a thrust level that is lower than the maximum settable is dangerous and illegal (§ 4.7).

8.5.8. Page 15. According to the AFM, the take-off and maximum continuous power setting for a PW118A that was derated to a PW118 was 97% torque. When the derated procedure was used, a caution in the AFM stated:

> *IN THE EVENT OF ENGINE FAILURE ABOVE V1, THE TAKEOFF POWER SETTING ON THE OPERATING ENGINE MUST NOT BE CHANGED.*

This statement is worrying. It seems that the engines were indeed replaced with more powerful engines, while the $V_{MCA}$ and takeoff speed data in the AFM were not revised for the higher thrust. More powerful engines result in a higher $V_{MCA}$, and consequently in higher takeoff speeds, if the vertical tail and rudder are not enlarged as well. Engineers should de-rate engines that are more powerful, at the time of installation, to ensure that the maximum thrust yawing moment that an engine generates does not increase above the aerodynamic yawing moment that the control surfaces of the airplane were designed to generate. If true, this statement should not have been approved by the authorities, because it results (in this case resulted) in accidents after engine failure (§ 4.7).

8.5.9. Page 21. "The airborne minimum control speed, $V_{MCA}$ was defined in the EMB-120 Flight Operations Manual as "...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 center of gravity. In aircraft with auto-feathering, $V_{MCA}$ is calculated with a feathered propeller." Please refer § 7.3 where a similar inappropriate definition is discussed. The value does not only represent the most critical combination of power, weight, and center of gravity, but also the use of maximum rudder and a bank angle of 5° away from the inoperative engine. These even more critical parameters should have been included in the definition of $V_{MCA}$ and with the $V_{MCA}$ (and $V_2$) data in the EMB-120 Flight Operations Manual.

8.5.10. Page 35. In the EMB-120 AFM procedure for a takeoff with engine failure above $V_1$ and with 15° flaps, the following step is presented.

- *Retract flaps at $V_2$ + 20 KIAS at the level off height and accelerate to final segment speed or, if a close-in turn is performed, maintain the takeoff flaps and the airspeed at $V_2$ with a maximum bank of 15 deg.*

The last part of this procedure step suggests that it is safe to bank 15° to either side while the airspeed is $V_2$. As was explained in this report, banking away from the favorable bank angle, in this case 5° away from the inoperative engine #1, increases the actual $V_{MCA}$ above the standardized $V_{MCA}$ that is published in the AFM (§ 4.3), see also § 8.5.4 above. Bank angles of 15° at $V_2$ are not safe if any or all of the variables that have influence on $V_{MCA}$ happen to be at their worst-case values (§ 4).

*8.5.11.* Page 35. "*The manufacturer reported that the only cockpit action required by the crew from rotation (takeoff) to the level-off height was to retract the landing gear, an action normally performed on all takeoffs. The manufacturer's intent was that, when the aircraft was accelerated at the level-off height, take-off power could be readjusted if necessary.*

*The aircraft manufacturer advised that the procedure conformed to US Federal Aviation Regulation Part 25 section 25.111(c)(4), which stated:*

- *The airplane configuration may not be changed, except for gear retraction and automatic propeller feathering, and no change in power or thrust that requires action by the pilot may be made until the airplane is 400 feet above the takeoff surface."*

This procedure is out of FAR 25.111(c)4, which is for the certification of airplanes, not for operational use. During certification, the manufacturer has to prove that the airplane meets the climb (angle) requirements after engine failure without changing the configuration and the power or thrust. Does the manufacturer really mean that the power handles may not be advanced if the pilot notices that the airplane does not climb after liftoff (due to an accidental incorrect takeoff configuration, ice build-up, etc.)? Does the manufacturer really want the pilot to crash, rather than allowing advancing the throttles? This is a serious misinterpretation of an Aviation Regulation. Of course, the power may be increased below 400 ft, but the pilot should be made aware that, after engine failure, he needs to increase the rudder deflection and bank 5° away from the inoperative engine during the thrust increase, and make no turns until reaching a safe altitude (higher than 400 ft). Experimental test pilots safely perform this power increase and do not crash; airline pilots should be trained and capable of performing this as well.

*8.5.12. In respect of aircraft configuration changes during the simulation of one engine inoperative flight, section 25.111(c)(4) of US Federal Aviation Administration Advisory Circular AC 25-7C titled Flight Test Guide for Certification of Transport Category Airplanes explained that:*

> *(i) The intent of this requirement is to permit only those crew actions that are conducted routinely to be used in establishing the one-engine-inoperative takeoff path. The power levers may only be adjusted early during the takeoff roll, as discussed in paragraph 12b(2), and then left fixed until at least 400 ft above the takeoff surface.*
>
> *(ii) Simulation studies and accident investigations have shown that when heavy workload occurs in the cockpit, as with an engine failure during takeoff, the crew might not advance the operative engines to avoid the ground, even if they know the operative engines have been set at reduced power. This same finding applies to manually feathering a propeller. The landing gear may be retracted, however, as this is accomplished routinely once a positive rate of climb is observed. This also establishes the delay time to be used for data expansion purposes.*

Advisory Circular 25-7C is the Flight Test Guide for the *Certification* of Transport Category Airplanes, and is intended to be used by experimental test pilots and flight test engineers. This Advisory Circular is not to be used for writing operational procedures for use by airline pilots, as also stated in the previous paragraph. People whose expertise is not experimental flight-testing are obviously misinterpreting these Regulations that are not intended to be used by them.

8.5.13. Page 36. "Procedures in the operator’s Training and Checking Policy Manual for simulating engine failures during takeoff in EMB-120 aircraft complied with the guidelines set down in CAAP 5.23-1(1) and were approved by CASA. The technique that was taught to the PIC followed those procedures and used a zero thrust power setting for simulation of an engine failure with propeller auto-feathering. The operator’s Training and Checking Policy Manual gave direction to training and checking pilots for when and how the simulation of an engine failure was to be conducted. At the time of the accident Section 5.26 of that manual, titled Simulation of engine failures, stated:

> *The following are basic Company requirements for simulation of engine failure. Refer to the Manufacturer’s Operations Manual or the Company Training Manual for the aircraft type for more detailed instructions.*
>
> Turbo-prop engine failure shall be simulated by smoothly and slowly setting zero thrust."

The procedure in the last line might have caused confusion. *Setting zero thrust* sounds like setting zero torque. For training, it is required to set zero drag, i.e. set torque for zero thrust/ drag. During operations, captains sometimes decide to leave an engine idling (asymmetrical), which happened prior to the accident with a Saab SF-340B that was discussed in § 8.4. Recommended is to add a red radial line on the torque indicators at the torque setting for zero drag, just like at airspeed indicators of Part 23 airplanes to indicate $V_{MCA}$ (Figure 36 on page 55).
*Zero thrust should be set smoothly and slowly*. The training obviously is not aimed at demonstrating the dynamic response to a sudden engine failure and the dynamic $V_{MCA}$ (§ 5.4), but rather the static $V_{MCA}$ (§ 5.3 ).

8.5.14. Page 54. "$V_{MCA}$ was defined in the EMB-120 Flight Operations Manual as:

> *...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."*

As discussed in § 7.3, a $V_{MCA}$ definition like this one is definitely inappropriate. At $V_{MCA}$, the airplane is not *controllable* (if the variables that have influence on $V_{MCA}$ are at their worst-case values, § 5.2.4). By airplane design and flight-test definition,

$V_{MCA}$ is *the minimum flight speed at which the aircraft can only maintain straight flight*, provided a bank angle of exactly 5° is being maintained into the good engine and the rudder is, and/ or the ailerons are, fully deflected or up to a maximum force limit (§ 2.7.4). Hence, $V_{MCA}$ is not for a *maximum 5° bank*, but for exactly 5° bank toward the operative engine for this airplane, whether the engine is *critical* or not and fails *suddenly*, or while the thrust is slowly decaying. *The value presented* not only represents *the most critical combination of power, weight, and center of gravity*, but also includes the use of maximum rudder (and/ or ailerons) and a bank angle of 5° that is maintained into the good engine. In the *most critical combination* of the EMB definition of $V_{MCA}$, the *weight and center of gravity* are not changing during, and following an engine failure. Asymmetrical power, rudder deflection and bank angle do change, are under direct control of the pilot and have a much larger influence on $V_{MCA}$ and hence, are more critical to airplane control than *weight and center of gravity* (§ 4).

8.5.15. ***Conclusions.*** The AFM-presented $V_{MCA}$ and $V_2$ data might not have been valid for the airplane equipped with PW118A engines, but only for PW118 engines. The AFM-published $V_{MCA}$ and $V_2$ data were too low for engines that are more powerful and were too low for maintaining control after engine failure. This accident proved that takeoff safety speed $V_2$ was indeed not a safe takeoff speed after engine failure, and that the conditions that apply with $V_2$ (and $V_{MCA}$) were not observed/ applied. It also became clear that the engine failure procedures of the airplane manufacturer and/or the operator are far from safe for handling engine failures during takeoff, because they are not in accordance with the limitations and conditions that are applied for designing and flight-testing multi-engine airplanes. The control limitations and conditions that both the design engineers and the experimental flight-test crews used to design the vertical tail and conduct engine-out flight-testing were not included appropriately in the engine failure procedures and flight-crew training.

8.5.16. The simulated failed engine was set to zero torque, rather than to the torque setting for zero drag for not enlarging the yawing moment of the remaining engine to a value higher than for the engine failure alone. This zero-torque setting increased the actual $V_{MCA}$ to a value higher than the standardized $V_{MCA}$ in the AFM. In addition, the pilot did not attain and maintain the favorable bank angle of 5° away from the inoperative engine during increasing the torque to maximum, which increased the actual $V_{MCA}$ even further.

8.5.17. Both the pilot in command and the pilot under check did not understand the real meaning of $V_{MCA}$. No blame, their manuals and training were not right.

8.5.18. ***Cause of the accident.*** The probable causes of the accident were the inappropriate $V_2$ data and the inappropriate crew response to the simulated engine failure and inappropriate $V_{MCA}$ definition and engine failure procedures in the AFM. The initial slow heading change might not have been interpreted as an (approaching) loss of control, because manuals only write about a sudden failure. As for most accidents after a propulsion system malfunction, the pilots are not to be blamed. The engine failure procedures issued by the manufacturer, and/ or operator were obviously inappropriate, as was the pilot training for airplane control after engine failure. Procedures and training are the responsibility of the manufacturer, the operator, and the airworthiness authorities.

8.5.19. *Contributing factors* might have been the incorrect and incomplete $V_{MCA}$ and $V_2$ data in the AFM (which were for a less powerful engine) and the setting of zero torque, rather than zero drag (or zero thrust) on the simulated failed engine.

## 9. ANALYZING NON-FDR-EQUIPPED AIRPLANE ACCIDENT DATA

9.1. While analyzing non-FDR equipped airplane accidents, investigators have to rely on pilot and/ or witness reports with information of aircraft motions, engine noises, ground radar plots and on the results of the investigation of the wreckage and impact information, like engine controls and operation, propeller feathering and bending, instrument data and switch positions, etc. For this report it is assumed that already was determined that a failure occurred in the propulsion system and that the controllability needs to be analyzed. Two cases are presented of which only limited data were available, though enough to draw conclusions on the controllability after engine failure.

### 9.2. Accident Piper PA-31 Navajo

9.2.1. Shortly after takeoff, the left engine (#1) of this small twin-engine airplane quit operating for unknown reasons. The pilot feathered the propeller and returned to the airport for landing. During the turn from downwind to base leg, control was lost and the airplane crashed (ref. 20). The analysis below is also limited to airplane control.

9.2.2. During the turn at an altitude of approximately 200 ft AGL, witnesses reported hearing very loud engine noise and observed the left propeller to be stationary. The pilot might have increased the asymmetrical engine thrust to maximum for maintaining the required approach path. The airspeed must have been close to or at the final approach speed, which is not much higher than the standardized AFM-published $V_{MCA}$. During the final turn, which was into the dead engine, while the power of the other engine was high, the *actual* $V_{MCA}$ that the pilot experienced in-flight must have been much higher than the standardized AFM-published $V_{MCA}$, as was explained in § 4.3 above and summarized in the next paragraph.

9.2.3. If the thrust of the operative engine is not maximal during a turn, the thrust yawing moment, and there with the required rudder deflection to counteract that thrust yawing moment, are not maximal, hence, *actual* $V_{MCA}$ remains low and no control problems will occur. However, if the thrust of the remaining engine was high, or was increased during the turn to final approach for maintaining the required approach path, a larger rudder deflection was required to counteract the increased thrust yawing moment for maintaining directional control at the given airspeed. At low altitude, the airspeed cannot easily be increased, so increasing the rudder deflection is the only way to counteract the increase of the thrust yawing moment.

9.2.4. The bank angle to the left during the final turn caused a side force ($W \cdot \sin \phi$) to the left that added to the side force generated by the rudder that was required to counteract the engine thrust yawing moment (§ 2.10 on page 20). The sum of the side forces to the low wing side was now increased; the airplane started a sideward acceleration to the left that increased until the resulting sideslip would generate a side force to the right would be large enough to balance the side forces acting on the airplane. This sideslip cannot be avoided while banking into the inoperative engine, but only by rolling the airplane to a bank angle of 5° away from the inoperative engine (§ 2.4.7 above). The unavoidable sideslip during the increasing banking into the dead engine for the final turn, generated high drag that, on an airplane type like the PA-31, cannot be overcome by attaining and maintaining maximum asymmetrical thrust; a sure rate of descent cannot be avoided either.
In addition, the ailerons might also already have lost adequate control power to overcome the propulsive lift of engine #2 due to the decreased airspeed. The pilot must have been unable to roll the airplane back to wings level. Directional control was lost and, most probably, lateral control as well.
The actual $V_{MCA}$ must, in this case, have increased to a value much higher than the standardized AFM-published $V_{MCA}$, which was the consequence of not maintaining a small (5°) bank angle away from the inoperative engine while the power setting was high or increased to maximum thrust. This increase of actual $V_{MCA}$ above the indicated airspeed must have led to an uncontrollable airplane instantaneously. A recovery at the low final turn altitude and while maintaining a high power setting on the opposite engine was not, and will never be, survivable.

9.2.5. The airspeed indicator of this Part 23 airplane must have presented a red radial line indicating $V_{MCA}$ (i.a.w. FAR 23.1545). The pilot will have maintained an airspeed higher than this redlined $V_{MCA}$. However, his multi-engine rating training, the airplane manuals and the placards on the instrument panel most probably never made him aware that the redlined $V_{MCA}$ is valid only if the bank angle is the same as was used to design the vertical tail and to determine $V_{MCA}$, i.e. during *straight flight* when the thrust is high (§ 4.3.11). A manufacturer may select a fixed bank angle of maximum 5 degrees (away from the failed engine) to calculate the required size of the vertical tail and to determine (the redlined) $V_{MCA}$, but there is no requirement to publish the actual bank angle used for the redlined $V_{MCA}$ to be valid with the $V_{MCA}$ in the

AFM (yet). Five degrees away from the failed engine will always be safe, though, although the drag might not be minimal (§ 2.4.6).
If indeed the power of the operative engine was high or was increased during the final turn, the actual $V_{MCA}$ will have increased above the actual indicated airspeed, after which control could not be maintained. The vertical tail was not designed large enough to maintain control during turns at this airspeed while an engine is inoperative.

9.2.6. ***Manual review***. A flight or operating manual was not available for review. The aviation occurrence report (ref. 20 did not contain any manual information suitable for review, except that some actions out of the emergency procedures were included in the report, in which no reference was made to the required bank angle for maintaining a positive rate of climb and for the validity of the AFM-published $V_{MCA}$.

9.2.7. ***Cause of the accident.*** The accident might have happened because during the final turn the power was either high, or was increased to maintain the approach path. These conditions increased the *actual* $V_{MCA}$ to a value much higher than the standardized AFM-published and redlined $V_{MCA}$ on the airspeed indicator, and higher than the indicated airspeed. Loss of control became unavoidable. Under these circumstances, control can only be regained by quickly increasing the speed or, if the altitude is low, by decreasing the power of the operative engine temporarily just a little bit to decrease the yawing moment, after which *actual* $V_{MCA}$ will decrease as well and control might be regained. Power can be increased again as soon as straight flight with a bank angle of 5 degrees away from the inoperative engine is established. As was shown in the accident analysis using FDR data in § 8.3, the thrust needed to be reduced to 80% for the controls to become effective again (§ 8.3.10).

9.2.8. The pilot is not to be held responsible though; AFMs, student pilot textbooks and flight schools do not warn pilots for this (actual) $V_{MCA}$ increase. There are no warnings to avoid turns when the asymmetrical power setting is high and the airspeed low. The loss of control after engine failure or while an engine is inoperative is a long forgotten but still very actual and life-threatening 'phenomenon'. Nevertheless, all experimental test pilots and flight-test engineers, who are trained at one of the formal Test Pilot Schools, know about this, because it is observed every time they determine the $V_{MCA}$ of a multi-engine airplane during experimental flight-testing (refs 3, 5, 6, 10, 11, 12; see also § 5.3 above).

9.2.9. ***Recommendations***. Improve training and operations by improving textbooks, training programs and AFMs by adding the following. The $V_{MCA}$ that is published in the AFM and that is redlined on the airspeed indicator is a standardized $V_{MCA}$ that is valid, and provides safety only during straight flight while maintaining a bank angle of 5 degrees away from the inoperative engine. When an engine fails during takeoff, maintain straight flight while immediately attaining the small 5-degree bank angle away from the inoperative engine until reaching an altitude at which the power can be reduced a little for making safe turns. During the turns, some altitude will be lost because of the increase of drag, but control will be maintained.
When an engine is inoperative, avoid high thrust settings during turns while the airspeed is low. Plan ahead if an engine-out landing becomes necessary; it is much safer to perform a long straight in approach. If an increase of (asymmetrical) engine thrust is required for maintaining the approach path, it is easier and much safer to first attain a small bank angle and only then increase the asymmetrical thrust while maintaining a straight flight path.

9.2.10. A recommendation should also be that FAR/ CS 23 should be amended to require manufacturers to publish in AFMs the bank angle for which the published $V_{MCA}$ is valid, and to amend engine emergency procedures to include the bank angle requirement during high asymmetric thrust settings.

### 9.3. Accident Mitsubishi MU-2B-60

9.3.1. Shortly after takeoff, the left engine (#1) failed. The pilot returned for landing via a left-hand circuit; the left propeller was feathered. The airplane did overshoot the final approach of runway 35R and was cleared to the next runway 28. A witness heard an aggressive throttle; the airplane made an immediate sharp bank to the left and descended to the ground. The landing lights were then seen turning down toward the terrain. The airplane crashed; the two souls onboard were fatally injured, ref. 21.

9.3.2. Obviously, a (partial) go-around was initiated to reach the next runway for which the (asymmetrical) power setting had to be increased. Furthermore, a turn to the left, into the dead engine, was required to approach runway 28. These must have been the ingredients for the loss of control, due to the increase of asymmetrical thrust at low speed causing the increase of the actual $V_{MCA}$ above the indicated airspeed of the airplane, and the loss of performance. The thrust yawing moment generated by engine #2 needed to be counteracted by a rudder deflection to the right. The side force generated by the rudder also results in a sideward acceleration to the left that normally should be compensated by a small bank angle away from the failed engine, in this case to the right. If this bank angle was not attained and maintained, the rudder generated side force, enlarged by side force $W \cdot \sin \phi$, caused a sideslip to the left that increased until side force due to sideslip was equal to side force $W \cdot \sin \phi$ (§ 2.10 above). This sideslip increased the drag and reduced the remaining one engine inoperative climb performance or resulted in a rate of descent.

9.3.3. One of the steps in the engine emergency procedures was:

> *Power Lever (Operating Engine) - Set as Required to Maintain Airspeed and Desired Flight Path.*

The recommended airspeed (flaps up) was $V_{xse}$ =140 KCAS, with flaps 5º $V_{xse}$ =130 KCAS and when landing is assured with flaps 20º, $V_{xse}$ = 125 KCAS and 110 KCAS when over the runway. $V_{MCA}$ was published as 99 KCAS.
No warning was presented to attain and maintain a small bank angle away from the inoperative engine as the asymmetrical power is increased, to keep the actual $V_{MCA}$ low. An increase of power increases the thrust yawing moment $N_T$ and increases the requirement for rudder input to counteract the yawing to be able to maintain the heading. The lower the airspeed, the larger rudder deflection is required. Rudder deflection also causes in a sideward acceleration to develop. A small bank angle of 5° (as determined by the manufacturer) away from the inoperative engine can be used to reduce the resulting sideward acceleration and sideslip and therewith to reduce the drag and maximize takeoff or go-around performance (§ 4.3). A small bank angle of 5° away from the inoperative engine not only decreases the drag, but also decreases the actual $V_{MCA}$. If the small bank angle is being maintained while the power setting is maximal and the rudder is deflected to stop or prevent yawing, the actual $V_{MCA}$ will never be higher than the standardized $V_{MCA}$ that is published in the AFM. These are the most important conditions under which the vertical tail was designed and the standardized $V_{MCA}$ was determined. However, if the small bank angle is not maintained and the rudder is not deflected to prevent yawing, the actual $V_{MCA}$ can easily increase above the indicated airspeed; the resulting sideslip increases the drag considerably. Then the airplane is out of control and turns and slips into the direction of the inoperative engine in a descending flight path.

9.3.4. ***Conclusion***. Control was lost because the favorable 5-degree bank angle away from the inoperative engine was not attained and maintained while increasing the asymmetrical power for the go-around; the *actual* $V_{MCA}$ must have increased above the indicated airspeed resulting in the sharp bank to the left, the loss of control and the crash.

9.3.5. ***Cause of the accident.*** The cause of the accident was the pilot's failure to maintain a small bank angle (max. 5 degrees) away from the inoperative engine while the power setting was increased or was high and the airspeed was low. The AFM-published $V_{MCA}$ was 99 KCAS, but the actual $V_{MCA}$ varies with bank angle at high asymmetrical power settings. If maximum thrust is set on the operative engine while the bank angle differs from the bank angle used to determine $V_{MCA}$, then the actual $V_{MCA}$ might have increased to a higher value, even above the indicated airspeed after which control was lost. In addition, the increased airflow over the wing behind the operative propeller (propulsive lift) caused a rolling moment into the dead engine. Control could not be regained because of the low altitude and the high asymmetrical power setting. The one engine inoperative performance deteriorated because the drag increased due to not maintaining the favorable bank angle.

9.3.6. The pilot however, is not to be blamed. This accident was also caused by an incomplete and deficient engine emergency procedure, by inadequate pilot training on the subject of engine failures, and by imperfections and errors in FAR's and other regulatory publications.

### 9.4. Accident DHC-6-100 Twin Otter

9.4.1. A De Havilland DHC-6-100 airplane, crashed into trees and terrain after takeoff. Witnesses at the airport reported that, shortly after the airplane lifted off from the runway, flames emitted from the airplane's right engine.
Data below are copied from the NTSB Aircraft Accident Summary Report, ref. 22. This report limits itself to analyzing the controllability after engine failure.

9.4.2. According to photographic evidence provided by a witness, the pilot taxied the airplane onto runway 24 from the intersecting taxiway, which is about 1,700 feet from the runway's west end, and began a takeoff roll to the west from that location, rather than using the runway's entire 4,500-foot length. Photographic evidence depicting the airport windsock showed that the airplane departed into a moderate headwind. Witnesses at the airport reported seeing the airplane take off and climb to about treetop height. Several witnesses reported hearing a "poof" or "bang" noise and seeing flames and smoke coming from the right engine. One witness reported that, after the noise and the emergence of flames, the right propeller was "just barely turning." Photographic evidence showed that, at one point after the flames occurred, the airplane was about one wingspan (about 65 feet) above the runway. One witness estimated that the airplane climbed to about 150 feet.

9.4.3. As a photograph in the accident investigation report (ref. 22) illustrates, the airplane's rudder was not deflected and its wings were not banked toward the operative engine (as required by procedure, see § 9.4.20 below), but were rather a few degrees toward the failing engine. Witnesses' descriptions of the flight indicated that the pilot allowed the airplane to drift to the right (toward the inoperative engine) before it nose-dived into the ground.

9.4.4. Witnesses reported that the airplane lost some altitude, regained it, and then continued to fly low above the treetops before turning to the right and disappearing from their view behind the tree line. Another witness in the backyard of a residence northwest of the airport reported that she saw the airplane flying straight and level but very low over the trees before it dived nose first to the ground.
The airplane impacted trees and terrain and came to rest vertically, nose down against a tree behind a residence about ½ mile northwest of the end of runway 24. A sketch of the runway and accident site is presented in Figure 42 below.

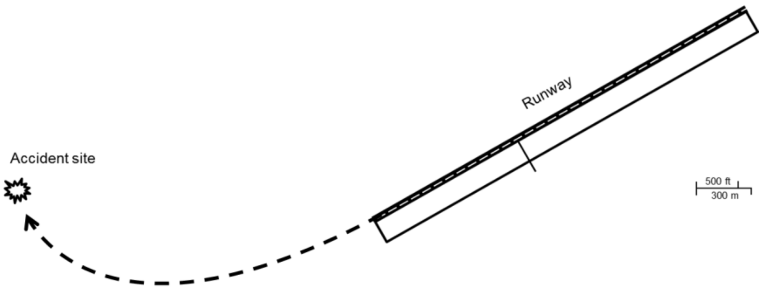

Figure 42. Accident site Twin Otter and takeoff runway 24.

9.4.5. The airplane was powered by two Pratt & Whitney Canada PT6A-20, 550-horsepower engines equipped with three-bladed, single-acting, hydraulically operated, constant-speed, reversible Hartzell propellers with feathering capabilities. Examination of the wreckage, including both engines and propellers, revealed that the right engine's compressor turbine disk was intact but that its attached blades were fractured; the damage observed within the engine resulted in the loss of engine power. No evidence of any other pre-impact conditions that would interfere with normal operations was found during examinations of the airplane, engines, propellers, and components.

9.4.6. The report does not present data of airplane weight and location of the center of gravity. According to a performance assessment provided by the airplane's current type-certificate holder, given the weather conditions at the time of the accident, airport altitude and calculated weight for the accident airplane, the airplane should have been capable of a positive single-engine climb rate of about 300 feet per minute if the pilot had configured the airplane properly according to the published procedures by feathering the propeller on the failed engine and attaining the recommended airspeed.

9.4.7. Although the accident airplane was equipped with a propeller autofeather system designed to automatically feather the propeller of an underpowered engine, the system was deactivated. With the system deactivated, the pilot would need to manually position the propeller-control lever of the failed engine to the “feather” position to feather the propeller blades. Because of the impact damage to the cockpit propeller-lever controls, it was not possible to determine their pre-impact positions. However, post-accident examination of the right propeller assembly revealed that the blades were at high angles at impact, which is consistent with a feather or near-feather condition.

9.4.8. The airplane was originally certificated without an autofeather system. The airplane’s published emergency procedures, which were available to the pilot in the cockpit, correctly indicated the procedure for feathering the propeller without the autofeather system. The accident airplane was modified with a propeller autofeather system, which, according to the airplane’s AFM, is designed to “automatically feather the propeller of an underpowered engine when a decrease in torque to 13 [to] 11 [pounds per square inch] is detected. However, the autofeather system had been inoperative since the operator acquired the airplane 5 years earlier, and its deactivated status was placarded “DEACTIVATED” in the cockpit; therefore, the pilot was likely aware of the discrepancy.

9.4.9. ***Analysis***. This analysis is limited to the controllability aspects. Please refer to the accident investigation report, ref. 22, for technical aspects.

9.4.10. From the picture in the accident investigation report, it became clear that at the instant the picture was taken, the rudder was not deflected and the bank angle was not into the good engine, as the engine emergency procedure describes, but rather a few degrees to the wrong side, while flames were visible. This could also mean that the dynamic effects of the engine failure were yet to begin and that the engine thrust was not decreasing yet.

9.4.11. If rudder control is not applied while the thrust of a failing engine is decreasing, the asymmetrical thrust results in an increasing yawing about the center of gravity until the yawing moment due to sideslip (weathercock) equals the asymmetrical thrust moment. The result is a sideslip to the left, with the 'wind in the left ear'. Sideslip means drag which might prevent the airplane from accelerating to or maintaining the required climb speed; the rate of climb decreases. As long as the propeller of the failed engine was not yet manually feathered, the total thrust yawing moment, and therewith also the sideslip, was higher; manual feathering takes time. In the meantime, the side force due to sideslip must already have started to displace the airplane to the right. Witnesses’ descriptions of the flight indicated that the pilot allowed the airplane to drift to the right before it nose-dived into the ground.

9.4.12. Rudder deflection is required to establish an improved, more favorable balance of forces. Rudder deflection decreases the sideslip, but then the drag will not be as low as possible. Lowest drag can be achieved only when the bank angle is 5 degrees away from the inoperative engine, or the number of degrees determined by the manufacturer (§ 4.3).

9.4.13. The pilot must have noticed the increasing heading away from the runway heading and must have deflected the rudder to the left, while trying to keep the wings level. Nevertheless, the airplane seemed not to have responded to these control inputs, which would be the case if the airplane was already out of directional control, because the *actual* $V_{MCA}$ increased above the indicated airspeed (or the indicated airspeed decreased below the *actual* $V_{MCA}$). The *actual* $V_{MCA}$ was higher than the AFM-published $V_{MCA}$, because the bank angle was not maintained 5 degrees away from the inoperative engine and the rudder might not have been fully deflected while the thrust on the operative engine was high (§ 4.3, § 4.8).

9.4.14. If the heading after engine failure cannot be maintained, i.e. the rudder does not have the authority to maintain directional control, then the *actual* $V_{MCA}$ of the airplane increased above the indicated airspeed. Typical for this type of loss of control is that the heading increases despite opposite rudder input. If the rudder deflection is less than maximum or zero, the *actual* $V_{MCA}$ of the airplane is higher than the standardized $V_{MCA}$ published in the AFM and placarded in the cockpit (§ 4.8).

9.4.15. From the location of the accident site, to the right of the extended runway centerline (Figure 42), it is obvious that straight flight after engine failure was or could not be maintained. Directional control must have been lost already shortly after engine failure.

9.4.16. The ailerons should normally be capable of providing adequate lateral control, unless the rolling moment due to propulsive lift (of the wing section behind the operative propeller) is higher than the aileron control power for the given airspeed. Then lateral control is also lost.

9.4.17. As was included in the accident report, witnesses' descriptions of the flight indicated that the pilot allowed the airplane to drift to the right (toward the inoperative engine) before it nose-dived into the ground. If the bank angle is not maintained at 5 degrees away from the inoperative engine (in this case to the left), a sideslip to the right cannot be avoided. If, in addition, a bank angle is allowed toward the inoperative engine, the side force due to bank angle and weight ($W \cdot \sin \phi$) increases the sideslip even more. If the sideslip angle increases above the (horizontal) stall angle of attack of the vertical tail with rudder, the vertical tail will stall (Figure 7). If this happens, the yawing moment that was balancing the asymmetrical thrust yawing moment no longer exists, whereupon the nose of the airplane starts turning to the right, toward the ground, because the drag increases considerable as well. A catastrophe cannot be avoided if this takes place at a low altitude (and sustained asymmetrical thrust).

9.4.18. The author of this report conducted engine out flight-testing in this type of airplane and proved that the airplane could continue to fly safely while one engine was inoperative and to climb on runway heading. The angle of sideslip difference between wings level and a bank angle of 5° away from the inoperative engine was 14 degrees. The difference between $V_{MCA}$ with wings level and $V_{MCA}$ with a bank angle of 5° in the tested configuration was 5 kt. $V_{MCA}$ with flaps 20 was higher than the stall speed.

9.4.19. ***Manual review***. An AFM was not available for review, but the accident report presented the engine emergency procedure and a $V_{MCA}$ definition, which are reviewed below.

9.4.20. *Engine emergency procedure*. According to section 3.1 of the emergency procedures of the airplane's AFM, which was found in the wreckage, the emergency procedures for an engine failure during takeoff include:

> *If engine failure occurs above $V_{MC}$ and a decision is made to continue the takeoff, proceed as follows:*
>
> - *Maintain heading by applying rudder and lowering wing against the live engine as necessary and lower nose to hold desired airspeed.*
> - *Advance power levers.*
> - *Power lever of failed engine - IDLE.*
> - *Propeller lever of failed engine - FEATHER.*
> - *Hold 71 knots IAS if flaps at 30°, 83 knots IAS if flaps at 0°.*
> - *When clear of obstacles, the flaps should be retracted in increments and the airspeed increased appropriately per the above schedule in order not to lose altitude during retraction. Best single engine rate of climb is achieved with flaps 0° at 83 knots IAS.*

9.4.21. A few remarks to this procedure:

- *If engine failure occurs above $V_{MC}$*. It is not clear whether $V_{MCG}$ or $V_{MCA}$ is meant here. If $V_{MCA}$ is the decision speed to continue the takeoff, the airspeed at lift off after engine failure will still be very close to the *actual* $V_{MCA}$ because the wings are still level. It will be required to immediately attain and maintain a small bank angle away from the inoperative engine.
- *Maintain heading by applying rudder and lowering wing against the live engine as necessary and lower nose to hold desired airspeed*. Good point, but what is *lowering wing against the live engine as necessary*? This should be replaced with: attain and maintain a bank angle of 5 degrees away from the inoperative engine (or into the live engine), or a bank angle as opted by the manufacturer (that was used to design the vertical tail because then the sideslip, hence drag is as low as possible).
- *Advance power levers*. In addition, rudder deflection needs to be increased while advancing the power levers to prevent yawing.
- Added should be not to turn the airplane, but maintain straight flight while maintaining the small bank angle, until reaching a safe altitude.

9.4.22. Although engine emergency procedures of some airplane's present guidance on the use of the small bank angle, this often comes too late in the procedure, but not here. That is quite good, but if pilots were not trained for this on small twins, this does not mean anything to them.

9.4.23. *$V_{MCA}$ definition*. A footnote (No. 11) in the accident report presents a definition of $V_{MC}$: "According to FAA definitions, $V_{MC}$ is the minimum airspeed at which the airplane could remain controllable with its critical engine inoperative; for twin-engine airplanes, the critical engine is the engine in which a failure would have the most adverse effect on directional control. On the DHC-6-100 airplane, which has engines that both rotate in conventional, clockwise rotation as viewed from the pilot’s seat, the left engine is the critical engine."
It is not clear whether this definition is copied out of the AFM or out of another source; is this also the definition of the airplane manufacturer?

9.4.24. A few remarks to this definition:

- *Vmc* (meant will be $V_{MCA}$) is not only the minimum airspeed for maintaining control *with the critical engine inoperative*, but for any inoperative engine. The critical engine is shut down during flight-testing to determine $V_{MCA}$ because this $V_{MCA}$ is a little higher than $V_{MCA}$ after shutting down the other engine. Any inoperative engine has its own *actual* $V_{MCA}$.
- The last sentence suggests that the failed engine, which was not the critical engine, did not have *the most adverse effects on directional control*. This might be the reason that important data, like $V_{MCA}$, center of gravity, etc. is missing in the report.
  Anyone of the two engines has, after failure, near identical effects on directional (and lateral) control, though in opposite direction. The differences are the opposite required control inputs, a little different *actual* $V_{MCA}$ and a little different yaw rate immediately after the failure.
- The *criticality* of an engine does not belong in an AFM definition; only a single emergency procedure applies after failure of either engine. The effect of the longitudinal and lateral location of the center of gravity and the huge effect of bank angle on $V_{MCA}$ are not mentioned; these are much larger than the difference between the critical and the other engine (§ 4.5). The AFM-published $V_{MCA}$ is safe after failure of any engine and with the other engine generating maximum thrust, with any center of gravity, but only while maintaining a small favorable bank angle and with the rudder deflected for stopping the yawing, i.e. for maintaining the heading.

9.4.25. *Missing data*. Many variables have influence on the minimum control speed $V_{MCA}$, as was discussed in § 4. For a valuable analysis, the actual value of these variables should have been included in the accident investigation report.

9.4.26. The autofeather system was labeled "DEACTIVATED" (§ 9.4.8). It is not made clear in the accident report whether the published $V_{MCA}$ was for an activated or a deactivated autofeather system. The $V_{MCA}$ with a deactivated system is higher than $V_{MCA}$ with an operative (and armed) autofeather system.

9.4.27. *Training*. It will never be known whether the pilot was aware of the engine failure at the instant the picture showing the not-deflected rudder was taken. The bank angle was not into the operative engine, as the engine emergency procedure requires. However, if the pilot never trained the failure of engine #2, the non-critical engine in terms of the accident report, then the wings-level attitude in the picture can be explained, but still is not correct.

9.4.28. ***Cause of the accident***. The analysis presented above is limited, because quite some relevant data is missing in the accident investigation report. Based on the information provided and on the experimental flight-test knowledge of the author of this report, the conclusion is that the airplane was out of directional control already shortly after liftoff, because the airplane obviously could not maintain runway heading after engine failure. The pilot obviously did not bank into the live engine and might not have realized that $V_{MCA}$ is only valid, and that control can be maintained only, if a bank angle of 5 degrees is maintained away from the failed engine. Not maintaining this bank angle (while the thrust of the remaining engine is maximal) results in an increase of the $V_{MCA}$ to some higher *actual* $V_{MCA}$, to a sideslip and hence, drag. If indeed the *actual* $V_{MCA}$ increased above the indicated airspeed due to a bank angle away from the favorable 5 degrees bank angle, control was lost from which recovery at low altitude was not possible.
The pilot did not follow the engine emergency procedure that was published in the AFM (as included in the accident investigation report).

9.4.29. Most probably though, the pilot is not to be blamed. Most pilots, their instructors and accident investigators as well, were not aware of the design and flight-test techniques of airplanes and what the real value is of minimum control speed $V_{MCA}$, prior to reading this report.

## 10. CONCLUSIONS

10.1. Many papers and reports, including accident investigation reports, were written on airplane control after engine failure but still, accidents continue to happen. This was reason for Avio*Consult* to review accident reports, multi-engine AFMs, textbooks and aviation Regulations on the subject of controllability while flying on asymmetrical thrust. As a result, many imperfections and even deficiencies were found. Consequently, by reading (only) these imperfect documents, pilots, instructors, tutors, writers, etc. receive an incomplete and hence incorrect comprehension of $V_{MCA}$, which definitely must have contributed to many engine failure related accidents in the past.

10.2. Throughout this report, many conclusions were already presented; these will not be repeated here, only the most important ones.

10.3. The standardized minimum control speed $V_{MCA}$ that was used to size the vertical tail and that is published in AFMs and used by pilots of multi-engine airplanes is in reality, i.e. during actual flight with an inoperative engine, not a constant number as the manuals might suggest and pilots assume it is. $V_{MCA}$ varies considerably with bank angle, control inputs and power setting to some actual value. The standardized $V_{MCA}$ that is published in AFMs is determined while maintaining straight flight using the worst case of many variable factors that have influence on $V_{MCA}$ ànd a small 3° to 5° bank angle away from the inoperative engine, at the option of the applicant (the manufacturer), and while the power setting is maximum available takeoff. The actual $V_{MCA}$ might increase more than 60 knots, depending on airplane type, above the published $V_{MCA}$ if the bank angle is not maintained at the opted number of degrees away from the inoperative engine, which might lead to an uncontrollable airplane and consequently to a calamity. The influence of bank angle on $V_{MCA}$ is not made clear in AFMs (may be except for a very few), aviation Regulations and most textbooks, etc. (refer to § 4 and § 5 above).
The $V_{MCA}$ published in AFMs is a minimum control speed for maintaining straight

flight only, certainly not for maneuvering and is only valid as long as the same small bank angle that was used to determine $V_{MCA}$ is indeed maintained.

10.4. Takeoff safety speed $V_2$ is used on Part 23 Commuter and Part 25 airplanes. It is supposed to provide safety during takeoff, even after engine failure. $V_2$ is calculated during preflight (or by the on-board computers) using $V_{MCA}$ and stall speed $V_S$, and is normally the greater of 1.1 × $V_{MCA}$ and 1.08 to 1.13 × $V_S$ (FAR/ CS 25.107). In § 6 an example was given where actual $V_{MCA}$ at high takeoff gross weight increased with 71 kt to 190 kt, which is 60% above the preflight calculated $V_2$ (119 kt) after banking only 5 degrees into the failed engine. If the pilot would attempt to maintain equilibrium flight with this bank angle, the airplane would run out of control and crash. The $V_2$ published in AFMs is in general not a safe takeoff speed after engine failure, unless the same bank angle is applied that was used to size the vertical tail and determine $V_{MCA}$ (which is a bank angle between 3° and 5° away from the inoperative engine at the option of the applicant, the manufacturer of the airplane) and straight flight is maintained as well. 'Unfortunately', no requirement exists in Regulations to list this required bank angle with $V_{MCA}$ or with $V_2$ data in AFMs.

10.5. Modern avionics provide the pilots with many warnings, cautions and alerts if operating limitations are approached. But the most important speed limitation that even becomes life threatening after engine failure is not included in the warning systems. Pilots are not alerted of approaching the *actual* air minimum control speed $V_{MCA}$ yet, while all of the data that is required to calculate an actual air minimum control speed is available in the on-board computers. Advices on safe bank angles for the actual airspeed are not presented.

10.6. Turn-rate indication is not presented anymore on many modern electronic cockpit displays. The slower moving heading scale has to be used for detecting the yaw rate caused by engine failure, which delays the early detection of a propulsion system malfunction and increases the reaction time of the flight crew (if under Instrument Meteorological Conditions), which might lead to recovery problems.

10.7. Additional flight-testing will be required to acquire data of the effect of bank angle and weight on minimum control speeds of individual airplane types in order to be able to continuously calculate and display the actual air minimum control speed $V_{MCA}$ and takeoff safety speed $V_2$ in-flight. This will cost money, but might save lives and avoid lawsuits in the future too.

## 11. RECOMMENDATIONS

11.1. Recommendations from this report that could also be used in accident investigation reports to prevent accidents after engine failure could include, but should not be limited to:

1. Include in FAR/ CS 23 (§ 23.1563) the requirement to list the bank angle for which the indicated and/ or placarded $V_{MCA}$ is valid on the same placard or on a separate placard near the airspeed indicator (§ 7.5);
2. Include in FAR and CS 23 and 25 and in the Flight Test Guides the requirement for testing the effect of bank angle on $V_{MCA}$ prior to and during certification and add these data to AFMs to convince pilots of the fact that a small bank angle has great effect on $V_{MCA}$ and V2. Consider also to require data on the differences in $V_{MCA}$ with forward center of gravity and with failure of the engine opposite of the critical engine. Properly informing pilots about these effects might help prevent fatal accidents while an engine is inoperative (§ 4.3, § 6);
3. Review and if necessary, improve flight and operating manual texts on $V_{MCA}$ and $V_2$, in the definitions as well as in numbers, charts and legends (§ 7);
4. Review and if necessary, improve the publishing of appropriate conditions for maintaining maximum n-1 climb performance (§ 7.8.2);
5. Review and if necessary, rewrite flight crew training textbooks on $V_{MCA}$ (§ 7.6);

6. Review in-flight as well as in-classroom training for engine-out, and improve as necessary to be in agreement with the way that airplanes are designed and flight-tested (§ 7.7);
7. Review and if necessary rewrite simulator training syllabi for engine failures and for simulated flight with an inoperative engine to be also in agreement with the way that airplanes are flight-tested (§ 7.7, § 5.3, § 5.4);
8. To increase pilot awareness and therewith reduce accidents when an engine is inoperative, implement bank angle and rudder advisories to electronic displays using on-board dynamically calculated actual takeoff data and add warnings and alerts for approaching the actual $V_{MCA}$ and/ or actual $V_2$ similar to the existing $V_S$ warnings and alerts (§ 7.4);
9. Review operational requirements for departure procedures for reduced turn capability after failure of left and right engines at low speed (§ 6.5.15, § 7.6.3);
10. Review the consequences of engine failures for airport operations from parallel runways or from runways in mountainous terrain (§ 2.7.6);
11. To 'expedite' the detection of a malfunctioning propulsion system, yaw-rate indication should be or be made available again (§ 7.6.3);
12. Add a radial line on the power or thrust indicators to indicate the thrust or torque for zero drag/ zero thrust for a realistic asymmetrical thrust yawing moment during engine-out training (§ 8.5.13).

11.2. Although not reviewed and discussed in this report, the following actions are strongly recommended as well in order to improve aviation safety:

13. Review and if necessary, rewrite airplane accident investigation methods and techniques using the facts presented in this report;
14. Review and if necessary, rewrite multi-engine rating exams, test rides and proficiency programs and sequences;
15. Review and if necessary, modify spoiler assisted roll control during takeoff on spoiler equipped airplanes and flight control systems on fly-by-wire jets;
16. Rewrite the flight safety audit checklist, etc., etc. ■

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Engine failures or, in general, propulsion system malfunctions of multi-engine airplanes continue to result in serious incidents and fatal accidents all across the globe quite frequently, although the airplanes were designed, flight tested and certificated to continue to fly safely. Most flight instructors, (airline) pilots and accident investigators explain the minimum control speed in the air (VMCA) and the remaining performance after engine failure of multi-engine airplanes in a different way than airplane design engineers, experimental test pilots and flight test engineers do. This report tries to bridge the obviously existing knowledge gap on the subject of airplane control after engine failure between the design engineers, experimental test pilots and flight-test engineers – supported by aviation regulations – on one side, and other pilots, flight instructors as well as airplane accident investigators on the other side.

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