Controllability of a Boeing 747-258F After Separation of Two Engines

4 October 1992, Amsterdam

Including The Theory of Engine-Out Flight

And

Systemic Errors in Controlling Multi-Engine Airplanes When Engine(s) Failed

Limited To Flying Qualities, Handling and Performance

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Harry Horlings

Graduate FTE USAF Test Pilot School

Avio*Consult*

Colophon

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The most recent version of this report with working URLs (links) can be downloaded from the Accidents Page of the website of Avio*Consult*: https://www.avioconsult.com. This is version 2025-03-26.

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Harry Horlings is Lt-Col ret. of the Royal Netherlands Air Force, former Chief Operational Research and Evaluation (experimental flight-test), and is graduate Flight Test Engineer of the USAF Test Pilot School, Edwards Air Force Base, CA, USA (1985). He has been appointed Officer in the Order of Orange-Nassau by the King of the Netherlands for rendering outstanding services of national and international importance for increasing aviation safety.

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13. ABSTRACT (Maximum 200 words)

During the past 25 years, more than 400 accidents occurred after a propulsion system malfunction of small and large multi-engine airplanes, causing over 4,000 casualties. Such accidents occur because pilots are not made aware of the flight limitations that apply when engine(s) is/are inoperative and hence, maneuver their airplane without realizing that the control surfaces of the airplane are not sized large enough to maintain the equilibrium of forces and moments that act on an airplane. Regulations require manufacturers to publish the lowest speed which can be obtained during straight flight while maintaining a small bank angle for minimum drag, at maximum asymmetrical thrust, and with full lateral or directional control deflection; this speed is called the minimum control speed (V_{MC}). However, regulations do neither require publishing the bank angle for which the V_{MC} is valid, nor making pilots aware of the huge increase of V_{MC} in the Air (V_{MCA}) when bank angles to either side are attained when the asymmetrical thrust is, or is increased to maximum.
This report provides V_{MCA} knowledge as taught at aeronautical universities and test pilot schools, analyses the Boeing 747-258 accident, and recommends improvements for pilot training, manuals, accident investigations, and Aviation Regulations.

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1. Executive Summary

1.1. Introduction

1.1.1. On 4 October 1992, a Boeing 747-258 freighter lost its two right-wing engines shortly after takeoff from Schiphol Airport, Amsterdam while climbing passing 6,500 ft. Engine #3 separated from the wing due to a fuse-pin failure in its pylon and knocked engine #4 off the wing as well. Twenty-eight seconds later, the pilots initiated a right hand turn back to the airport which ended too close to the runway threshold and too high, making another descending turn necessary to position correctly for the approach to the requested runway. When, during this turn, the thrust of the left engines was increased to maximum, the airplane continued to roll uncontrollable and collided with an apartment building in a suburb of Amsterdam with the wings near vertical. While this accident occurred 32 years ago, it received renewed attention in the media in 2023.

1.1.2. This engine failure related accident is definitely not one of a kind. Since 1996, more than 400 accidents after a propulsion system malfunction with small and large multi-engine airplanes were reported on the Internet alone, resulting in more than 4,100 casualties. Neither of the pilots were obviously aware of how to prevent an accident after engine failure, nor were the accident investigators of several Transportation Safety Boards across the globe.

1.1.3. Being a graduate flight test engineer of the USAF Test Pilot School (85A), and having the privilege of possessing high-level knowledge on the subjects of performance and flying qualities, and experience with engine-out flight, I could not comprehend why such accidents occur. The experimental test pilots of airplane manufacturers, usually also graduates of a test pilot school, conduct flight-tests while one or two engines are made inoperative, and determine the speed limitations and flight restrictions that apply, after which these limitations are published in Airplane Flight Manuals for use by airline pilots, once the airplane is in operational use.

1.1.4. Experimental test pilots do not crash when one or more engines are inoperative, so I considered it my duty and responsibility to research many reports of accidents after engine failure, to find out why so many airline pilots lose control of their airplane after an engine failure. My conclusion is that airline pilots, and also accident investigators, are not at all made aware (anymore) of the real value of the limitations and of the flight restrictions that apply while one or more engines are inoperative in-flight.
Airplane design engineers are allowed to limit the size of the aerodynamic control surfaces vertical tail with rudder and the ailerons, as approved and defined in Federal Aviation Regulations and EASA Certification Specifications § 25.149 and § 23.149, and equivalent in other countries, for maintaining control during ***straight flight*** only, while one engine is inoperative and when the ***asymmetrical thrust is or is increased to maximum***, while also ***maintaining a small bank angle*** but not more than 5° away from the inoperative engine(s). Experimental test pilots subsequently determine the lowest airspeed which can be obtained during straight flight while maintaining the small bank angle with full directional and/or lateral control deflections and with maximum thrust on the engine opposite of the inoperative engine. This airspeed is called the *minimum control speed* (V_{MC} or, as used today and in this report, V_{MCA}), and is to be published in the Limitations Section of the Airplane Flight Manual for use by pilots. However, manufactures do not publish the above-mentioned flight restrictions (**straight flight, small bank angle**) that come with V_{MCA}, and that are required for the published V_{MCA} to be valid, in their flight and training manuals; Federal Aviation Regulations and EASA Certification Specifications and equivalent do not require them to do so. So, pilots are not made aware of these restrictions and do not hesitate to turn at maximum asymmetrical thrust, and/or increase the thrust to

maximum during a turn, after which they lose control of their airplane, because the rudder and ailerons are not sized large enough to maintain an equilibrium of forces and moments during a turn. Design engineers only use one V_{MCA}, pilots will have to deal with many different actual V_{MCA}'s after engine failure.

1.1.5. I started writing papers to explain the controllability of an engine-out airplane to pilots and investigators 22 years ago, and wrote recommendations that should indeed prevent accidents. The papers are published on my website, and were presented during symposia, in seminars and in aviation magazines in several countries. But this work seems not to have been very effective. Most professional aviators smiled politely and forgot or denied it; "*never heard of, can't be true*". They resist because they obviously cannot explain the equilibrium of forces and moments that is required to keep an engine-out airplane aloft; they are suffering from a deficit of scientific knowledge. My work is based on the wisdom of science and experience, not on opinion and ignorance. One day they will accept, also because they themselves don't want to get killed because of unawareness, and leave their next of kin behind in mourning. As philosopher Arthur Schopenhauer once said: *"Every man takes the limits of his own field of vision for the limits of the world"*.
The effect of bank angle and weight on $V_{MC(A)}$ is once again explained in § 3 below. This report might widen up the limits of the field of vision of (denying) pilots and investigators, and also of others who are responsible for the safety of pilots and their passengers.

1.1.6. My papers, and this report as well, were written using the theory of engine-out flight and of the prediction of V_{MCA} prior to conducting (experimental) flight tests, as taught at aeronautical universities and at test pilot schools, of which the entrance level usually is an MSc degree in engineering or a BSc plus entrance exam. Every student of a test pilot school learns how to control an engine-out airplane, and what the real value is of the published minimum control speed of multi-engine airplanes that is published in Airplane Flight Manuals, and what the flight restrictions, the do's and don'ts, are when one or more engines are inoperative in-flight.
This report, and the other papers by Avio*Consult*, also teach how to prevent accidents after engine failure to airline pilots, accident investigators, aviation regulators and inspectors of FAA and EASA and equivalent organizations across the globe.

1.1.7. This report is also written as a citizen's report to ICAO, because it addresses deeper systemic errors and causes, and draws safety recommendations that are of global concern, which none of the TSB's across the globe adequately did in the 400 reviewed reports of accidents after engine failure.

1.2. Main Conclusions

1.2.1. The pilots were not made aware of the maneuver limitations that apply when one or more engines are inoperative in-flight. The accident investigation report proves that the investigators analyzing the controllability were not (made) aware either. The recommendations in the report did not result in the prevention of engine failure related accidents. The main conclusion of such accidents is lost, forgotten, or unknown knowledge on engine-out flight.

1.2.2. US Federal Aviation Regulations, EASA Certification Specifications, and equivalent do require minimum control speeds for engine-out flight to be published in airplane flight manuals, but do not require to include the bank angle and the maneuver limitations that apply for the speed limitations to be valid. This is a major deficiency of global concern.

1.2.3. In general, airplane manufacturers, flight schools and airplane operators do not include the maneuver limitations that apply for the airspeed limitations to be valid in airplane flight, operating and training manuals and in engine-out training syllabi. The manuals and training materiel are not written by competent writers, and are not adequately reviewed either.

1.2.4. The pilot of the subject Boeing 747, while two engines had separated off the right wing and while in a 25° banked right turn at an airspeed of 260 kt, increased the thrust of both left-wing engines to maximum, after which control was lost – by definition, as every experimental test pilot with a high engineering-level background will confirm.
Just prior to the thrust increase, the rudder and ailerons were already near maximum deflected, which is a strong warning signal of an impending loss of control. The pilot increased the thrust during a turn, while he should have attained straight flight first. The pilot was obviously never made aware that straight flight should be maintained when the asymmetrical thrust is or is increased to maximum, neither in the Airplane Flight Manuals, nor in Training Manuals or in simulator training. The control surfaces of the airplane do not need to be designed large enough to provide for the forces and moments required to maintain the equilibrium of the forces, including the gravitational forces, and of the moments that act on the airplane during turns at high asymmetrical thrust levels.

1.2.5. Engines are not perfect, and may occasionally fail. To compensate for such a failure, procedures are developed and limitations are published, for pilots to use.
More than 40 years ago, manuals still did include such limitations, but somehow this life saving information was eliminated, most probably by people who are not competent at a high enough engineering level and do not really understand the physics of engine-out flight. The authoritative approval of manuals by FAA, EASA and equivalent organizations failed as well. The field of vision of manual writers, manual reviewers, flight instructors and accident investigators, but also of aviation regulators and inspectors, has become too limited.

1.2.6. Most pilots and accident investigators are convinced that an airplane only has one V_{MCA}, the V_{MC} published in the Airplane Flight Manual. Although this standardized $V_{MC(A)}$ is indeed a fixed number, the *actual* V_{MCA}, being the V_{MCA} that a pilot will experience in-flight, is definitely not. The ***actual* $\mathbf{V_{MCA}}$** varies with the many factors that have influence on the equilibrium of lateral and directional forces and moments acting on the airplane, such as asymmetrical thrust level, asymmetrical drag, bank angle, the amount of controls deflection, the position of the center of gravity (lateral and longitudinal), the weight of the airplane and other factors such as damaged or lost control surfaces or engines, open cargo doors or an inadvertently deployed thrust reverser. The difference between the published standardized $V_{MC(A)}$ and the *actual* V_{MCA} that the pilot will experience in-flight can be very large. Every experimental test pilot knows from experience that when keeping the wings level, the *actual* V_{MCA} can be already ≈ 6 kt higher than the published V_{MCA} for a small twin engine airplane, but 30 kt or more for a large airplane. When the bank angle increases to either side, the *actual* V_{MCA} will increase to an even much larger value. Regrettably, as mentioned before, regulations do not require the bank angle, for which the published $V_{MC(A)}$ is valid, to be included with this airspeed limitation. Furthermore, the increase of the *actual* V_{MCA}, while banking to either side, is not required to be communicated to pilots either.

1.2.7. When two engines on the same wing are inoperative (n − 2) on 4- or more engine airplanes, the minimum control speed also increases considerable. The requirement to publish this minimum control speed (V_{MCA2}), that needs to be observed in anticipation of, and after a second engine failure, was inappropriately deleted from civil regulations many years ago, while an *actual* V_{MCA2} still exists, such as during this flight.

1.3. Main Recommendations of Global Concern

1.3.1. This report addresses the required knowledge on engine-out flight and on the investigation of accidents after engine failure, and recommends improvements of Aviation Regulations, pilot manuals, and pilot and investigator training.

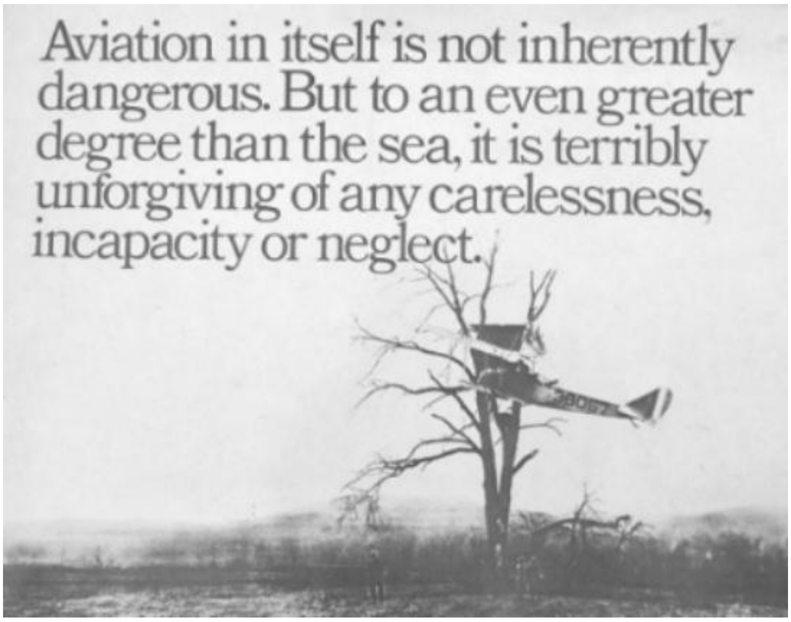
1.3.2. All current Airplane Flight Manuals, Airplane Operating Manuals, Training Manuals of all multi-engine airplanes built across the globe and relevant Aviation Regulations should be reviewed and improved as soon as possible by a competent, knowledgeable, and multi-disciplinary team of aviators, graduates of a test pilot school, aeronautical engineers, and other specialists, capable of comprehending the higher-level knowledge of engine-out flight as taught at aeronautical universities and test pilot schools, to prevent future fatal accidents after the failure of an engine. In the meantime, a notice of some kind should be issued to inform all multi-engine pilots as soon as possible of the limitations that apply when the thrust is asymmetrical, to prevent accidents. Avio*Consult* included suggestions to review and improve manuals and engine-out training in its papers (see website). When these recommendations are followed, no more accidents after engine failures will occur.

1.3.3. The FAA, EASA and equivalent rule making organizations, as well as the NTSB and other accident investigating TSBs should consider increasing the required aeronautical engineering knowledge level of their rule makers and inspectors, respectively air safety and accident investigators, on the subjects of airplane performance and flying qualities, especially on the subject of engine-out flight, to prevent aviation from drifting into failure any further.

1.3.4. ICAO is strongly recommended to include in the *Manual of Aircraft Accident and Incident Investigation, Doc 9756 Part III Investigation*, a chapter on the investigation of the controllability of airplanes after a propulsion system malfunction.

1.3.5. ICAO is also recommended to include a chapter on the investigation of manuals used by pilots and flight training organizations in the same manual.

1.3.6. ICAO is recommended to review other recommendations in this report that might also be of global concern.



2. Objective Of This Report

2.1. This accident happened 32 years ago, but obtained renewed attention after documentaries were aired on public TV recently. Earlier, National Geographic Channel broadcasted an episode of this accident in their series Air Crash Investigation. In these 32 years, not only this Boeing 747 crashed after engine failure; worldwide more than 400 accidents with small and large multi-engine airplanes were reported on the Internet alone, at a rate of approximately one per month, killing more than 4,000 crew and passengers. So, the question is why did this airplane, and why do still so many other multi-engine airplanes crash after the failure of one or more engines, while airplanes are well-designed and certificated in accordance with established Aviation Regulations, Airworthiness Standards, and/or Certification Specifications, are thoroughly flight-tested, and its operating limitations are published by Aviation Authorities in the Type Certificate Data Sheet and by manufacturers in the Flight Manuals of the airplanes, after approval by Authorities, for use by pilots. The answer was not given in any of the reviewed accident investigation reports. Experimental test pilots and their crew do not crash when evaluating the flying qualities and airplane handling when one or more engines are intentionally made inoperative prior to and during certification. So why do airline and commercial pilots still do so often when an engine fails? Something must be wrong; it is worthwhile to find out what, and recommend improvements. Therefore, Avio*Consult* started researching such accidents using experimental flight-test knowledge, reviewed more than 400 accident reports (ref. 4), and is convinced to have found the real cause, after which articles and papers were written and presented, supplemental accident analyses conducted, and Authorities informed.
This Boeing 747 accident is regrettably another 'excellent' example of the shortfall in knowledge of flight while an engine is inoperative, not only of pilots, but also of accident investigators, which is the reason why this report is written after all these years.

2.2. The writer of this report is a graduate Flight Test Engineer of the USAF Test Pilot School, Edwards AFB, CA (class 85A). The very few Test Pilot Schools (TPS) across the globe provide the highest level of experimental flight-test training. In 1985, the entrance level for experienced pilots and engineers was an MSc degree in engineering or a BSc and an entrance exam. TPS's were founded already during and following World War II because so many expensive prototype airplanes were lost during flight-testing, and their crews killed, due to their lack of higher-level engineering knowledge and experience required for experimental flight-testing. Test Pilot Schools teach aircraft performance, flying qualities, airborne systems, and flight test management and are bridging the gap between airplane operating and engineering expertise. Course duration is 12 months. Students receive academics at engineering MSc level about 50% of the time, and flight-test training and experience in some 24 different types of airplanes and/or helicopters: fighter jets, single- and multi-engine propeller and turbojet/turbofan transport airplanes, helicopters, gliders, and in 5 different flight simulators. Weekly exams, 32 written flight-test reports throughout the year and a final exam ensure that the required training level is achieved.
Always part of the curriculum of a TPS is flight-testing multi-engine airplanes while one or more engines are intentionally made inoperative, to not only determine the Minimum Control Speed in the Air (V_{MC} or V_{MCA})[1], being the lowest (Calibrated) airspeed[2] which can be obtained with full control deflections and maximum thrust, but also to evaluate the

[1] Regulations continue to use abbreviation/symbol V_{MC}, the V_{MCA} in the takeoff configuration. V_{MCA} (V_{MC} in the Air, or Airborne) is commonly used today, also because a V_{MCA} applies in anticipation of and after an engine failure during the whole flight, not only during takeoff. The existing minimum control speeds are: V_{MCG}, V_{MCA}, V_{MCA2}, V_{MCL}, V_{MCL2}.

[2] This report uses airspeed, as short for Calibrated Airspeed. All airspeed limitations in an Airplane Flight Manual (AFM) are and should be in knots Calibrated Airspeeds (KCAS), rather than in knots Indicated Airspeeds (KIAS), because the manual writer cannot know the instrument errors of airspeed indicators (ASI) in each individual airplane of the same type, with the same AFM. An FDR records KCAS, because there is no camera in a cockpit that records the IAS. IAS = CAS ± instrument errors.

handling qualities of the engine(s)-out airplane during takeoff, cruise flight, approach, and go-around. Hence, the writer of this report believes to be fully qualified to write about the subject, and conduct the analysis of the controllability of the subject Boeing 747 accident.

2.3. The sole objective of the investigation of an accident or incident shall be the prevention of accidents and incidents, as is defined by ICAO in Annex 13 to the Convention on International Civil Aviation, Doc 7300 (ref. 5). Regrettably, neither the Aircraft Accident Report of this Boeing 747 accident (ref. 1), nor reports of other Transportation Safety Boards (TSB) did contribute to the prevention of accidents and incidents after engine failure, neither in The Netherlands, nor across the globe. Only two years after this accident, in 1994, a Saab SF-340 returned to Schiphol Airport, following an oil pressure failure in one of the engines, and crashed during a one-engine-inoperative go-around that became necessary when the airplane drifted away from the runway centerline just prior to touchdown. In 1996 a C-130 crashed at Eindhoven Airport following the failure of the two left engines during a go-around. A few years later, a PA-44 crashed during engine-out training, and a BN-2 and a DC-3 ditched in the sea after failure of one engine. Because worldwide still every month small or large multi-engine airplanes crash after an engine failure, nothing was learned from previous accidents and from the investigations that should prevent such accidents, obviously. Still, nobody wants to get killed during an accident that easily could have been prevented; something needs to be done, and can be done.

2.4. While reviewing the accident investigation reports of engine-failure related accidents, it was noticed that pilots do not control their airplane after engine failure in compliance with the limitations and restrictions that airplane design engineers are allowed to apply during sizing the vertical tail (fin) with rudder and the ailerons of their multi-engine airplane. The significance, knowledge and awareness of these limitations and restrictions are obviously not passed on anymore to (airline) pilots, but only at test pilot schools. Accident and/or safety investigators are not made aware either, nor are flight training and flight manual approving authorities.

2.5. During the past 22 years, many papers on the subject were presented by Avio*Consult* to many organizations in Europe and USA. Articles were published in aviation magazines and on pilot forums, and supplemental analyses were written of accidents when the investigating Transportation Safety Boards did not describe the controllability of an airplane after engine failure correctly, i.e. in compliance with the airplane design courses taught at aeronautical universities and with flight test techniques taught at test pilot schools. These papers are also published on the website of Avio*Consult.* A video on YouTube (ref. 6) summarizes the controllability after engine failure, and briefly analyzes two accidents.

2.6. The objective of this Boeing 747 accident analysis is not only to analyze the controllability after engine failure, but also to renew the long-forgotten knowledge on flight with an inoperative engine for readers (§ 3), and to report systemic errors that are of global concern to ICAO, and to whom it may concern.
The analysis is conducted in accordance with the airplane design methods as taught at aeronautical universities and with the flight test techniques as used by experimental test pilots during experimental flight-testing the airplane to determine the minimum control speeds and the engine-out flying qualities as defined and described in FAA and EASA aviation regulations and certification specifications, and in FAA and EASA flight test guides.
This analysis of the controllability of the subject Boeing 747 in § 5 below is written as a supplement to the Aircraft Accident Report 92-11 published by the Netherlands Aviation Safety Board (NASB – ref. 1), but is limited to performance and control.

2.7. Below in § 3, the theory of airplane control after engine failure is explained in a detail necessary to analyze the controllability of an airplane after engine failure. In § 4 some factual data are repeated from the references, as required for this limited analysis.

The controllability of the Boeing 747 airplane after the loss of two engines, during the final phase of the flight, is then analyzed (§ 5), and conclusions are drawn (§ 6), and recommendations presented that will indeed improve safety (§ 7), if applied.
The required data for this analysis was found partly in the accident report (ref. 1), but since Flight Data Recorder (FDR) data was not included in that report, these were requested from the Dutch National Archives (but not received yet). FDR data was also obtained in less detail from NLR report NLR-TP-2003-392 (ref. 2), and from a yearbook of the Netherlands Association of Aeronautical Engineers (NVvL – ref. 3).

2.8. Readers resisting the explained controllability after engine failure and the analysis of the accident as presented below should read the airplane design books of aeronautical university and test pilot school course books, as well as the FAA and EASA Flight Test Guides, for which download links are provided on the website of Avio*Consult* (.com). These formal documents were also the basis for writing papers on the subject, and for supplemental analyses of several accidents and incidents after engine failure, including this report, which are downloadable for free from the website of Avio*Consult*.
If readers take their personal responsibility for preventing accidents seriously, they must read this report, as well as the referenced manuals and books, and subsequently initiate appropriate measures to improve the safety of flight after engine failure. Pilots don't want to get killed because life-saving lessons on engine-out flight were withheld from them, neither do their passengers. Together we can make aviation safer, and prevent people, including our own next of kin, from getting killed in unnecessary accidents.

3. Airplane Control After Engine Failure, in General

The theory on engine-out flight as presented below is not taught to most (airline) pilots anymore during the past 40 – 50 years, with hundreds of recurring fatal accidents as a consequence. Nevertheless, aeronautical universities and test pilot schools still do. Test pilot school graduates do not crash during experimental flight-testing while one or more engines are intentionally made inoperative. Please learn from this paper on how to prevent unnecessary fatal accidents after engine failure, rather than discarding it, for your own benefit.

3.1. Flight With Inoperative Engine(s)

3.1.1. ***Introduction***. When reviewing multi-engine rating courses by flight schools, and also courses on the subject of control and performance of multi-engine airplanes after engine failure by certified flight instructors which they publish on the Internet or in YouTube videos, it becomes very clear that there is a huge knowledge gap between pilots and accident investigators on one side, and aeronautical engineers, experimental test pilots and flight test engineers on the other.
To bridge this knowledge gap and improve the analyses of this Boeing 747 and similar accidents and therewith prevent accidents, Avio*Consult* wrote several papers[3] as well as the already mentioned supplemental accident analyses[4].

[3] https://www.avioconsult.com/downloads.htm.
[4] https://www.avioconsult.com/accidents.htm

3.1.2. Multi-engine airplanes are designed and flight-tested to be able to continue to fly and land safely after the loss of thrust of one engine or, if the airplane is powered by four or more engines, after the loss of thrust of two engines of the same wing.
Following a propulsion system malfunction, the thrust of the remaining engine(s) cause(s) a rotation about the center of gravity, called a yawing moment[5], which in-turn results in a large sideslip and hence, much drag, which reduces the rate of climb, or causes a descent. The pilot must therefore counteract the thrust yawing moment using the rudder, and counteract the banking, which is a side effect of the yaw rate, the sideslip, and the rudder deflection, using the ailerons, and expects the controls to be effective.

3.1.3. Below, a brief summary is included of the theory of airplane control after engine failure and of the (FAA and EASA) flight test techniques used to determine the minimum control speed V_{MCA} and to evaluate the flying qualities of an engine-out airplane as taught by Prof. Dr. Ir. Jan Roskam (ref. 9) and other aeronautical universities, and at Test Pilot Schools. An academic-level course of the USAF Test Pilot School on flying qualities is available for free download from the US Archives (ref. 10); engine-out is in Part 2, chapter 11.

3.1.4. ***Forces and Moments Acting on An Airplane.*** When pilots explain the forces acting on an airplane during turns, they refer to the horizontal centripetal (side) force that acts on the airplane while banking, as shown in Figure 1. This force acts in the so-called earth referenced coordinate system, in which the horizontal axis is always parallel to the local surface of the earth, and the vertical axis always points towards the center of the earth. The centripetal force is the horizontal component of the Lift of the wings, and acts in the aerodynamic center which is normally aft of the cg. The gravitational force that acts on the airplane, the Weight (W), acts in the cg along the vertical axis and has no horizontal component in this axis system. The vertical component of the lift (dotted line) needs to be equal to the Weight to maintain altitude; the pilot controls the required lift for maintaining level flight with the elevator.

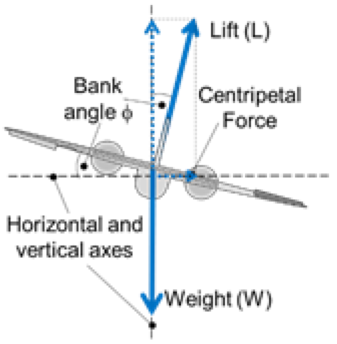


Figure 1. Centripetal force in flat earth referenced coordinate system.

3.1.5. When an engine is inoperative, i.e. when the remaining thrust causes an asymmetrical thrust yawing moment, a counteracting moment is required generated by the rudder to act against the asymmetrical thrust; this is achieved by the pilot pressing the appropriate rudder pedal. The generated rudder side force also causes a sideward acceleration, hence a sideslip, that generates an opposite side force on the vertical tail. The distribution of forces and moments that act on the airplane has changed considerable, and is also different for turns into and away from the inoperative engine; the rudder generated side forces then act in the same direction as, or against the centripetal force. These additional force components and moments make the use of this coordinate system a bit more complicated. The resulting centripetal force after engine failure is not the centripetal force when all engines are operating. Therefore, a prerequisite for using this earth referenced coordinate system is that the flight is coordinated, i.e. no asymmetrical thrust or drag is affecting the lateral and directional forces and moments that act on the airplane. Test pilots also use this axis system for turn performance, but it is not adequate for analyzing lateral-directional controllability after failure of one or more engines, or any other asymmetrical configuration, such as a large wing weight imbalance or asymmetrical drag.

[5] A moment (ft-lb, Nm) is the multiplication of a force (lb, N) and its perpendicular distance (ft, m), also called arm, from the center of gravity, producing a rotation (about its axis). In this case, the thrust yawing moment generated by an engine is the thrust of the engine times the distance of the engine to the center of gravity.

3.1.6. An example is also the knife-edge maneuver, straight flight with a bank angle of 90° as often performed by fighter airplanes during airshows. Despite of the large bank angle, the airplane does not turn, there is no acting centripetal force. Pilots, using the earth referenced coordinate system, will have a difficult time explaining the knife-edge maneuver when de wings obviously do not produce a lift component that keeps the airplane in the air; the sideslip side force, caused by deflecting the rudder, and a component of the engine thrust then do; the rudder controls the altitude, and the role of the elevator changed as well.

3.1.7. Therefore, during analyzing lateral and directional control after the failure of one or two engines, i.e. when the flight is no longer coordinated, airplane design engineers and experimental test pilots do not use the earth fixed coordinate system, but the body axes coordinate system for analyzing the effects of bank angle, rudder and aileron deflections, and sideslip. The body axes system is briefly explained next.

3.1.8. ***The body axes system*** makes it easier to show and explain lateral and directional forces and moments that act on an airplane, and to calculate these using the lateral-directional equations of motion. The three body axes are attached to the airframe, move with it, and run through the cg; the longitudinal x axis through nose and tail, the lateral y axis left and right through or parallel to the wings, and the z body axes vertical, parallel to the vertical tail, all three perpendicular to each other, as shown in Figure 2 (except for the longitudinal x axis which is not used for lateral-directional purposes). In this system, the side forces act in the direction of the y axis, rather than parallel to the horizon. Bank angle ϕ is the angle between the z body axis and the direction of the center of the earth which is also the angle between the y axis and horizon.

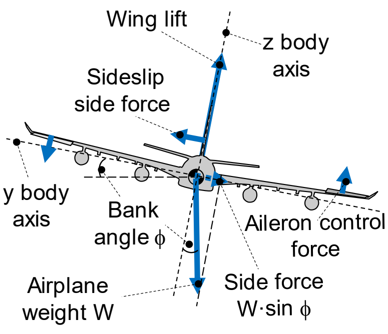


Figure 2. Lateral and side forces in body axes coordinate system.

Gravity, rather than wing lift, plays the most significant role in the body axis system. The gravitational attraction between the mass of the earth and the mass of the airplane tries to accelerate the airplane in the direction of the center of the earth all the time, whatever the attitude of the airplane in the sky is. This is shown by the Weight vector (W) in Figure 2 that acts in the center of gravity; its lateral component, side force W·sin ϕ, acts along the y body axis, in the same direction as the bank angle.

The lift of the wings has no lateral component in the body axes system, because the lift acts in the direction of the z body axis. If the lift is equal to the opposite z axis component of the weight (W·cos ϕ), the airplane will not descend. In this axes system, the horizontal component of the vectorial sum of side force W·sin ϕ and the other side forces, like the sideslip and rudder side forces if the thrust is asymmetrical, is the 'centripetal force'.

Using the body axes system, it will not only be possible to explain the knife-edge maneuver, but also to analyze the forces and moments acting on an asymmetrical powered airplane (at increasing bank angles). In Figure 2, only the most important forces are shown. Below, the side forces and yawing moments after engine failure will be further explained.

3.1.9. ***Control authority and equilibrium***. When an engine fails, the airplane yaws and rolls. The rudder has to be used to counteract the asymmetrical thrust and other yawing moments, and the ailerons to counteract roll effects. The counteracting forces generated by these aerodynamic control surfaces are proportional to the square of the airspeed (V^2), to the area of control surface (S) and to their deflection, and to a few other parameters such as air density (altitude), the lift coefficient (C_L) of the airfoil and its angle of attack (α) or angle of sideslip (β) to the incoming free airstream. Hence, airspeed has a large quadratic effect on the forces and moments generated by the aerodynamic control surfaces.

The thrust of turbo(fan) engines does not change with airspeed, but only with altitude, or more specific, with the density of the air, so the lower the airspeed, the larger the control surface deflections need to be for generating adequate counteracting forces and moments against the asymmetrical thrust yawing moment for maintaining equilibrium flight[6].

3.1.10. ***Minimum Control Speeds***. For the given size of the vertical tail with rudder (S) there is a speed (V) below which the rudder generated side force and the resulting yawing moment are not large enough anymore to counteract the asymmetrical thrust yawing moment after the loss of thrust of one or more engines, as well as the other forces and moments such as those produced by a sideslip, or asymmetrical drag such as by a deployed thrust reverser, etc. Below this speed, the heading can no longer be maintained; directional control will be lost.
Similarly, for the given size of the ailerons and the roll control power of other devices such as roll assisting spoilers, there is also a speed below which the generated lateral (roll) control forces and resulting rolling moments are not large enough anymore to counteract the rolling moments due to sideslip, due to the side effects of rudder deflection, due to the loss of lift because of wing damage, due to a partial loss of hydraulic power to actuate control surfaces, or due to the lateral displacement of the center of gravity (cg) caused by a lateral fuel imbalance in the wing tanks or by the loss of the weight of engines and pylons. Below this speed, despite maximum deflection, the ailerons do not produce the control power anymore required to counteract the rolling tendency; the demanded bank angle can no longer be maintained; lateral control will be lost.

3.1.11. The airspeed at which either directional or lateral loss of control or both occur is called *Minimum Control speed* V_{MCA}. V_{MCA} is the lowest speed which can be obtained with either full lateral or directional control deflection (whichever comes first) when the asymmetrical thrust is maximum. As mentioned above, many factors have effect on the balance of forces and moments, not only the factors already mentioned in the previous paragraph, but also the position of the center of gravity, the actual thrust level of the engines, the weight of the airplane, the actual amount of rudder and/or aileron deflections and, last but not least, the effect of bank angle. Below, it is explained that bank angle also has a very large, though forgotten effect on the magnitude of V_{MCA}. All of these many factors affect the balance of lateral and directional forces and moments and therefore have effect on the airspeed required to maintain the equilibrium, hence on the *actual value of* V_{MCA}. Each actual value of each individual factor affects the *actual* V_{MCA}.

3.1.12. It would be impossible to determine and publish all actual V_{MCA}'s of an airplane in a large table, which would be very costly and the use of which by pilots would be prone to errors. Therefore, both FAR and EASA CS 25.149 and equivalent require only one V_{MC} of an airplane to be determined and published as limitation in the Airplane Flight Manual: the V_{MC} while maintaining ***straight flight*** after failure of one (outboard) engine (n-1) while the opposite engine is generating the maximum thrust that the pilot can set from the cockpit, and while banking a small bank angle from the inoperative engine. This bank angle is determined by the manufacturer, is maximum 5° and reduces the sideslip to a minimum, resulting in minimum drag and hence maximum Rate of Climb. A few more conditions apply which are explained below. This *standardized* V_{MC} is already calculated and used by the airplane design engineer to size the fin, rudder, and ailerons and is the V_{MCA} that applies to takeoff; takeoff speeds V_R and V_2 are calculated using this *standardized* V_{MC}. There is no regulatory requirement to size the control surfaces large enough to maintain control during turns when the thrust is maximum asymmetric, although there are turn performance requirements at airspeeds higher than V_{MC}. This report uses V_{MCA} rather than V_{MC}.

[6] Steady equilibrium flight, whether during straight flight or during turns, can only be achieved when both the sum of the forces and the sum of the moments acting in each of the three individual body axes are equal to zero.

3.1.13. When on a four or more-engine airplane two engines on the same wing are inoperative (n−2), V_{MCA2} is the 'acting' minimum control speed. V_{MCA2} is also to be observed after failure of one engine, in anticipation of a second engine to fail, just like V_{MCA} applies in anticipation of the first engine to fail. V_{MCA2} is significantly higher than V_{MCA} because the yawing moment generated by two remaining engines on the same wing is much larger. Some manufacturers still present V_{MCA2} in their manuals, although the requirement to determine V_{MCA2} was regrettably deleted from civil aviation regulations many years ago, but not from military regulations. Nevertheless, V_{MCA2} continues to play an important role when two engines are inoperative on, or are separated from, the same wing.
Surprisingly, FAR and CS 25.149 do require not only a Minimum Control speed for approach and Landing for one engine inoperative (V_{MCL}), but also a V_{MCL2} for airplanes with 3 or more engines, both of which the military don't require, because these are not considered being of use.

3.1.14. Hence, V_{MC}'s are important design parameters that are already determined and used at the drawing board for sizing the vertical tail (fin) with rudder and the ailerons of an airplane, and are also important for pilots as the lowest airspeed for being able to maintain *straight flight* after engine failure, when the asymmetrical thrust and either rudder or aileron deflection are maximum.

3.1.15. The published V_{MCA} does however not take the separation of engines and other asymmetrical configurations into account, but a symmetrical airplane about the x-z plane. A weight imbalance between both wings, or severe damage to one of the wings requires a roll control input to counteract, after which less control travel is available for lateral control. Hence, the *actual* V_{MCA} after the separation of engines is higher than the AFM-published V_{MCA}. This, by the way, would also be the case when wing fuel imbalance exceeds the limits, or a thrust reverser inadvertently deploys in-flight.
The *actual* V_{MCA} is not displayed in the cockpit, its magnitude is not known; only a standardized V_{MCA} for straight flight is published. The actual V_{MCA} that a pilot will experience in-flight varies with many variables/ factors, including the bank angle, which will be discussed below. But, as already mentioned above, there are strong 'signals' for the pilot-flying to recognize that the *actual* V_{MCA} is increasing, which are large, near maximum deflections of either rudder or aileron, or both. Then the *actual* V_{MCA} is near the (indicated) airspeed and hence, the loss of control is imminent. This condition "screams" at the pilot: *increase your speed now, loss of control is impending*.
The real, the *actual* value of V_{MCA} is subject of the next paragraphs.

3.1.16. ***Actual V_{MCA}***. When engine(s) fail or are inoperative, the remaining engine(s) generate a thrust yawing moment that yaws the airplane into the direction of the failed engine(s) (T_3 and T_4 in Figure 3 below).
When an engine is inoperative or idling, its spillage drag increases the yawing moments. The thrust-bending side forces of the operating engines (not drawn) when the sideslip is not zero have effect as well; this side force of the inboard engine intake acts in front of the cg, of the outboard behind the cg, their moments are opposite but with a different moment arm. When, as happened in this case, engines separated from the wing, there is no spillage drag, and the thrust yawing moments will be smaller. A damaged wing however, generates more drag and will also enhance the thrust yawing moments.
The yawing continues until an equilibrium is achieved of yawing moments due to the resulting sideslip, as generated by the vertical tail (weathercock), and by other side forces. The sideslip angle will be considerable, and hence the drag will be high; climb performance might be lost. The thrust yawing moment can and must be counteracted by the pilot with a rudder input that generates a yawing moment due to rudder deflection. The rudder side force that generates this yawing moment also causes the airplane to accelerate sideways; the sideslip reverses to the other side. The sideward acceleration continues

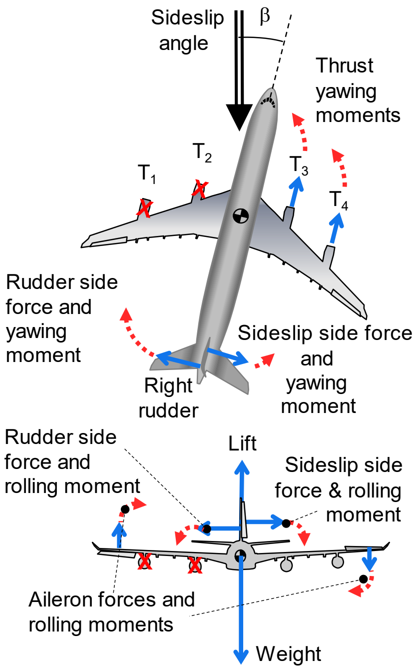


Figure 3. Equilibrium of directional and lateral forces and moments, engine 1 and 2 inoperative; wings level.

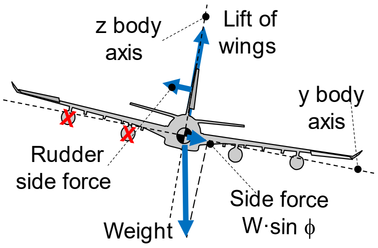


Figure 4. A small bank angle into the good engines replaces the sideslip side-force; sideslip, hence drag is minimal.

to increase until the resulting sideslip side force equals the rudder and other side forces, as shown in Figure 3. The drag is definitely not minimal but an equilibrium, i.e. directional control, is re-established. If an equilibrium cannot be established, the sideward acceleration continues and control will be lost. In the body axis system shown in Figure 2, the sum of the forces in the z axis, the Lift and the weight component $W \cdot \cos \phi$, need to be zero (not a problem at higher speeds), and the sum of the rudder side force and the sideslip- and other side forces in the y axis, need to be zero as well for an equilibrium to be maintained. As shown in Figure 3 with red dotted arrows representing the moments, the sum of the lateral moments (about the cg) caused by the rudder and the sideslip side forces, by the wing lift when the cg is displaced, and by the deflected ailerons must also be zero for equilibrium.

3.1.17. The large sideslip also causes much drag. To reduce the sideslip, and therewith the drag, a small bank angle into the good engine can be used. Regulations FAR/CS 25.149 allow the design engineer to use a small bank angle of maximum 5° (away from the failed engine) during sizing the vertical tail. A small bank angle (ϕ) causes a component of the weight (W) to act as a side force ($W \cdot \sin \phi$) in the center of gravity along the Y (lateral) body axis (Figure 4). Side force $W \cdot \sin \phi$ replaces the side force due to sideslip (shown in Figure 3), and thus reduces the sideslip and hence the drag to a minimum when it is equal to the rudder side force. The rudder remains required to counteract the asymmetrical thrust. Because side force $W \cdot \sin \phi$ acts in the cg, its moment arm is zero; it causes no lateral or directional moments. In addition, a small bank angle has another favorable effect. Because the rudder no longer has to overcome the thrust yawing moment as well as the sideslip yawing moment, its deflection can be smaller. The design engineer is allowed to use maximum rudder deflection, so the airspeed can be reduced until the rudder is again maximum deflected, hence, the V_{MCA} while maintaining a small bank angle is lower than when maintaining wings level, and the sideslip, the drag, is reduced to a minimum. This difference in V_{MCA} with the wings level and with the small favorable bank angle ≤ 5° away from the failed engine can be between 6 and 30 kt for different types of airplanes. The design engineer already determines V_{MCA} at the drawing board and uses it for sizing the control surfaces. More conditions exist, which will be discussed below. Airplane design Professor Dr. Jan Roskam (KU) wrote in an airplane design book (ref. 19): *"The $V_{MC(A)}$ value ultimately used ties takeoff performance to engine-out controllability"*: both drag and V_{MCA} are lower.

3.1.18. A larger vertical tail reduces the required airspeed for generating the side force to act against the asymmetrical thrust, but is more expensive and heavier; the *actual* V_{MCA} is lower though. A small tail is cheaper and lighter, but increases the required airspeed for maintaining an equilibrium of forces and moments after engine failure. The fin may not be designed that small, that $V_{MC(A)}$ exceeds 1.13 times the stall speed V_S (FAR/CS 25.149 (c)).

This condition applies to straight flight only, while maintaining the small favorable bank angle and with maximum thrust. The *actual* V_{MCA} that a pilot will encounter when not maintaining straight flight will be much higher than 1.13 V_S, as will be explained below.

3.1.19. The vertical tail has to be, and is indeed sized only to maintain straight flight when the airspeed is decreased to or is as low as the published V_{MCA}, and the asymmetrical thrust is maximum, while a small bank angle of maximum 5° is being maintained away from the failed engine(s). The manufacturer determines the magnitude of the bank angle for minimum sideslip, hence minimum drag, and maximum rate of climb. When banking away from the small favorable 5° bank angle to either side, side force W·sin ϕ increases, increasing the sideslip. The minimum airspeed required to maintain equilibrium needs to be increased considerable when full rudder and/or aileron are required, to be able to maintain the equilibrium, or to prevent the fin from stalling. The *actual* V_{MCA} increases with bank angle above the AFM-published $V_{MC(A)}$. Further details follow below.

3.2. Flight-testing V_{MCA}

3.2.1. The (experimental) flight test techniques used to determine the Minimum Control speeds V_{MC} and to evaluate engine-out flying qualities are prescribed in Flight Test Guides: FAA Advisory Circular (AC) 25-7D (ref. 11), and EASA CS 23 (ref. 12). These test methods and conditions are also described in paper *Airplane Control and Analysis of Accidents after Engine Failure* by Avio*Consult* (ref. 13), for flight instructors and accident investigators (for free). The real value of V_{MCA} might be best understood by briefly explaining how V_{MCA} is determined during experimental flight-testing, in compliance with these Flight Test Guides.

3.2.2. ***Static V_{MCA} Tests.*** The airplane is in the test configuration, which includes low weight (worst-case weight for the to be published V_{MCA}), and a center of gravity aft (for shortest rudder moment arm) and maximum laterally into the good engine(s), both worst-case for V_{MCA} (smallest moment arms), but in the approved cg envelope.
At a safe altitude and an airspeed well above the predicted and/or anticipated V_{MCA}, the critical (outboard) engine is shut down and the thrust of the engine opposite of the shut-down engine is increased to maximum. Then the airspeed is slowly decreased while the wings are kept level (bank angle zero) until the heading can no longer be maintained with full rudder or 150 lb (667 N) of pedal force, or until zero bank angle cannot be maintained. If the rudder is at its maximum first, the airspeed is also called the directional V_{MCA}, if the ailerons are first, the airspeed is the lateral V_{MCA}. The highest airspeed at which either occurs is the **wings-level V_{MCA}**.
Lateral V_{MCA} will be higher on airplanes with powered lift, such as large propellers or lift augmentation, or after failures of roll control devices or a damaged or asymmetrical loaded wing (such as the subject Boeing 747 in this report).

3.2.3. Then the test continues by gradually increasing the bank angle away from the failed engine until the sideslip is zero or to the maximum approved 5° (by FAR/CS 25.149), while decreasing the airspeed until again the heading or bank angle can no longer be maintained. This airspeed is the **static V_{MCA}** of the airplane and is between 6 (small twins) to 30 kt (large transports) lower than the *wings-level* V_{MCA} (see Figure 6 below, top left).
If, during the test at this airspeed, the pilot would level the wings to bank angle zero, the heading or bank angle can obviously not be maintained; control will be lost. The *actual* V_{MCA} increases with decreasing bank angle to the wings-level V_{MCA}, which is higher than the V_{MCA} when the small favorable bank angle is being maintained.
In some cases, also the (larger) bank angle for zero rudder force is determined, and the rudder and aileron control forces at bank angle less than 5° into the inoperative engine. The effects of larger bank angles to either side is discussed in § 3.3 below.

3.2.4. ***Dynamic V_{MCA} Tests*** (sudden engine failure) are conducted at several airspeeds, down to the **dynamic V_{MCA},** at which speed the heading change after a sudden outboard engine failure is 20° and an average pilot will be able to recover. This V_{MCA} is usually a bit lower – safer than the static V_{MCA}.

3.2.5. ***AFM-Published V_{MCA}***. The highest of the static and dynamic V_{MCA} that are determined under the standardized conditions prescribed in FAR/CS 25.149 and mentioned above will, after extrapolation from the safe test altitude to sea level, be published as the *standardized* V_{MCA} in the limitations section of the AFM of the airplane, but remember that the in-flight tested and AFM-published V_{MCA} is measured during ***straight flight*** while maintaining ***a small bank angle*** into the good engine, while the remaining engines are set to provide maximum thrust. There is no requirement to determine the V_{MCA} during turns, or with a forward cg, at high weight, with partial rudder or ailerons, with fuel imbalance, other in failure modes such as damaged wings, deployed thrust reversers, or at several asymmetrical thrust settings because, as mentioned before in § 3.1.12, this would be very costly and lead to a very large table with V_{MCA} data, the use of which by pilots would be impracticable and prone to errors. Regulations simply assume that pilots maintain straight flight when maximum asymmetrical thrust is set, while also maintaining the small favorable bank angle as opted by the manufacturer. For these conditions the published V_{MCA} is the worst-case V_{MCA}. Nevertheless, the bank angle for which the published V_{MCA} is valid should be published with V_{MCA} data, and the conditions for which this V_{MCA} is valid (straight flight while banking a small bank angle away from the failed engine) should be emphasized, also in engine emergency procedures, as a life-saving reminder.
Refer to the documentation referenced in footnotes, or to the papers by Avio*Consult* (ref. 14) for further explanation of V_{MCA} and other V_{MC} flight-tests, amongst which a qualitative evaluation while engine(s) are inoperative in the traffic pattern.
The effect of bank angle and weight on V_{MCA} is not well known to pilots and accident investigators and will therefore briefly be explained below.

3.3. Effect of Bank Angle and Weight on V_{MCA}

3.3.1. Every graduate of a test pilot school knows that the V_{MCA} of an airplane, when the bank angle is 5° away from the inoperative engine, is lower than V_{MCA} when the wings are kept level because, as described in § 3.2 above, these two V_{MCA}'s are recorded during flight-testing.
This leaves the question whether the *actual* V_{MCA}, i.e. the V_{MCA} that the pilot will encounter in-flight, will decrease further when banking more than 5° into the good engine(s), and increase further when banking to the other side, into the inoperative engine(s), and how much? The answer can be found using the same equations of motion and stability derivatives of the airplane as design engineers use to size the control surfaces, and experimental test pilots use for predicting V_{MCA} prior to flight testing a prototype multi-engine airplane. An airplane has six degrees of freedom, three of which are of interest for analyzing the lateral and directional controllability: the sideward motions, caused by side forces, and the rotations about the longitudinal and vertical axes, caused by lateral resp. the directional moments. The applicable three simplified equations of motions are presented in Figure 5 below.

These equations and the V_{MCA} calculations are explained in the paper *Effect of Bank Angle and Weight on V_{MCA}* (ref. 15). The results of these calculations using coefficients of a Boeing 707/DC-8 type airplane are also briefly presented in the paragraphs below, and were used for writing the V_{MCA} papers, and for several analyses of accidents after engine failure (ref. 16). Trim means the control trim plus the additional hand or foot pressure input.

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

$$C_{l_\beta}\beta_{trim} + C_{l_{\delta_a}}\delta_{a_{trim}} + C_{l_{\delta_r}}\delta_{r_{trim}} = \frac{-L_T}{\bar{q}Sb} - C_{l_0} \quad \text{(Lateral moments)}$$

$$C_{n_\beta}\beta_{trim} + C_{n_{\delta_a}}\delta_{a_{trim}} + C_{n_{\delta_r}}\delta_{r_{trim}} = \frac{-N_T}{\bar{q}Sb} - C_{n_0} \quad \text{(Directional moments)}$$

Figure 5. The three simplified linear simultaneous lateral-directional equations of motion.

3.3.2. The three simultaneous equations in Figure 5 were rearranged to show the effect of bank angle ϕ and weight W on V_{MCA}, and show the required rudder and aileron deflections, and the resulting angle of sideslip, when the asymmetrical thrust is maximum, in a way that is easier comprehensible for flight operations. The bank angle is controlled by the pilot, and is the most important entry variable for the calculations.
To this effect, the equations are solved for the lowest speed (dynamic pressure q) at which either the maximum available deflection of the rudder (δ_r) or the ailerons (δ_a) is reached, or the maximum allowable angle of sideslip (β) is reached to avoid the fin to stall (14°), in other words for the lowest speed at which control can just be maintained, for the range of bank angles ϕ between −15° and +15°, i.e. into resp. away from the inoperative engine(s).

The results (out of ref. 15) are presented in Figure 6 below, for One Engine Inoperative (OEI – #1), and for Two Engines Inoperative (TEI – #1 and #2), respectively. The effects of Weight on V_{MCA} are presented in Figure 8 below. For larger bank angles, the simplified equations might neither be adequate, nor accurate, and should not be used to calculate reliable values, although the trend is obvious. The graphs below are calculated for inoperative left-wing engine(s), and need to be mirrored about the vertical axis for the accident airplane of which the right-wing engines were inoperative.

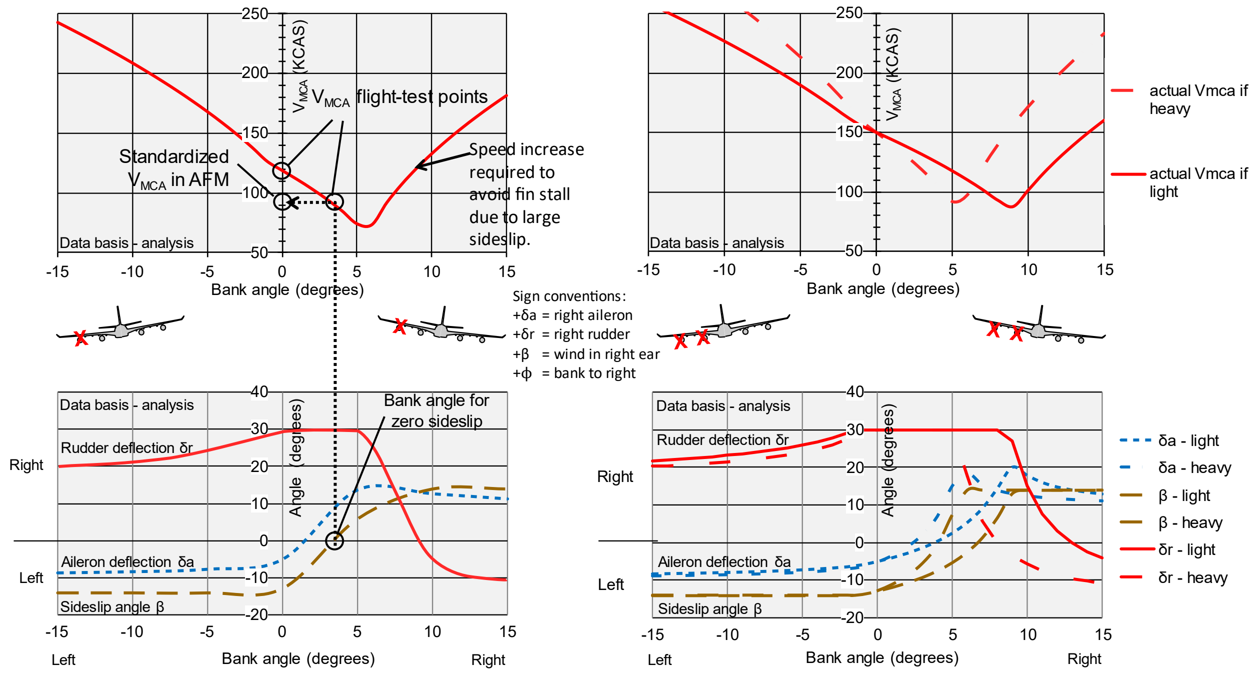


Figure 6. Effect of bank angle on V_{MCA} (top), and on the required control angle deflections and resulting sideslip (bottom) for OEI and TEI on left wing, other engines max. thrust.

3.3.3. ***The Effect of Bank Angle On V_{MCA}.*** The calculated graphs in the top of Figure 6 show the resulting minimum required airspeeds of a sample 4-engine airplane (like a Boeing 707) when OEI (the left engine #1) and when TEI (#1 and #2), and when maximum thrust is set on the engine(s) opposite of the inoperative engine(s). The graph on the right side also shows data for both high and low gross weights. The figures could not be recalculated for a Boeing 747-200, because its lateral-directional stability derivatives were not available. The airspeeds (q for dynamic pressure in Figure 5) shown in the top left and right graphs of Figure 6 are the ***actual*** **V_{MCA}'s** of the airplane for bank angles (ϕ) between −15° and +15° for the lowest gross weight (W, is mg in the side force equation in Figure 5).

3.3.4. ***Banking Into the Good Engine(s)***. The top left graph of Figure 6 shows the two V_{MCA} flight-test data points. For this airplane, which is in the test configuration as required by the FAA and EASA Flight Test Guides (lowest weight, aft cg, etc.), the sideslip angle β is zero when the bank angle is 3° away from the failed engine. At this bank angle, the drag is minimal, hence the remaining climb performance maximum. Therefore, the corresponding *actual* V_{MCA} (93 kt) will be published as the *standardized* V_{MCA} in the AFM (after extrapolating from the safe test altitude to sea level). The *actual* V_{MCA}, being the V_{MCA} that a pilot will experience in-flight, at bank angles other than the bank angle used for sizing the vertical tail and for measuring the standardized V_{MCA} during flight-testing (in this case +3°), is calculated with up to the maximum control surface deflections of either rudder (± 30°), aileron (± 20°) and for a sideslip angle less than or equal to ± 14°, being the horizontal angle of attack at which the fin with maximum rudder deflection (at maximum camber) stalls. The resulting speeds for bank angles in the calculated range of −15° to +15° are the lowest speeds at which an equilibrium of forces and moments can just be achieved and maintained, and hence, the loss of control can just be prevented when the asymmetrical thrust is maximum. The possible additional effects of a rudder ratio system, which reduces the rudder surface deflection with pedal input at higher airspeeds, are not included.

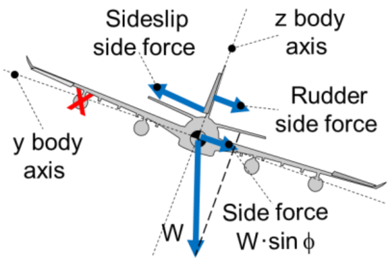


Figure 7. Bank angle larger than 8° into the good engine, with reversed required rudder.

The bottom left side of Figure 6 also shows that at bank angles larger than the favorable bank angle of 3° away from the failed engine, for this sample airplane, the increasing side force W·sin ϕ causes the sideslip angle to increase to 14°, being the maximum allowable (horizontal) angle of attack of the fin with deflected rudder before it stalls.

In addition, at ≈ 9° of bank into the good engines the rudder deflection needs to be zero for balancing the forces and moments; the sideslip side force alone, caused by side force W·sin ϕ, takes care of counteracting the asymmetrical thrust yawing moment (weathercock). Some test pilots will also determine this bank angle for zero rudder. At larger bank angles into the good engines, such as shown in Figure 7, the increasing sideslip side force due to the increased sideforce W·sin ϕ needs to be counteracted by an opposite side force: the rudder deflection needs to be reversed to avoid excessive yawing into the good engine(s). As the V-shaped lines in the top graphs of Figure 6 show, the *actual* V_{MCA}, being the airspeed required to keep the control deflections required for maintaining the equilibrium of forces and moments within their mechanical limits and the sideslip smaller than 14°, increases when the bank angle increases.

Noting the required reversal of the rudder to maintain control when turning into the good engine, the question can be raised whether pilots can be taught to do so. The answer is of course negative; there is no indication in the cockpit of an increasing sideslip. This might also have been the reason that FAR/CS 25.149 only require one V_{MCA} to be determined while a small bank angle of less than 5° away from the failed engine(s) is being maintained. This is safe and simple when the thrust is (increased to) maximum.

3.3.5. ***Banking Into Inoperative Engine(s)***. Keeping the wings level (bank angle zero), not only increases sideslip angle β (hence drag) as effect of the required rudder deflection to act against the asymmetrical thrust yawing moment, but also increases *actual* V_{MCA} to ≈ 119 kt, 26 kt higher than the AFM-published V_{MCA} for this type of airplane, in this configuration, as shown in Figure 6, top left. At larger bank angles into the inoperative engine(s) the actual V_{MCA} increases even more than when banking to the other side. A much higher airspeed is required to keep the rudder and/or aileron control surfaces within their available mechanical control travel for maintaining an equilibrium of forces and moments, in other words for being able to maintain controlled flight.

3.3.6. ***Safety Margins***. Often is said, even in the accident report (ref. 1), that a turn into the good engine(s) is preferable, has advantage, because the safety margin above V_{MCA} would be larger than when turning into the dead engine(s). As Figure 6 top left shows, the *actual* V_{MCA} between 0° and 6° bank into the good engines indeed decreases, but the AFM-published V_{MCA} is the V_{MCA} when the bank angle is, in this case 3° (as opted by the manufacturer, but ≤5°). If the bank angle is less than 6° away from the failed engine(s) or to the other side, the *actual* V_{MCA} only increases. If the bank angle increases above 6° to the good engine side, a higher airspeed is required for avoiding the fin to stall. Hence, a much higher airspeed is required to maintain control during turns to either side, although the speed increase when turning into the good engines needs not be as large as the increase needed when banking into the dead engines. But this large increase cannot be called a margin, isn't it?
But there is something else, more relevant, as was already explained in § 3.3.4 above. The data (Figure 6) shows that the rudder deflection needs to be decreased and reversed while banking more than 5° into the good engine, depending on the weight of the airplane (through side force $W \cdot \sin \phi$). The question was already raised above whether a pilot can be taught to do this (in Instrument Meteorological Conditions).
Hence, it is a myth that the margin of the indicated airspeed above V_{MCA} is larger when turning into the operating engine(s). By now it must be obvious to the reader that turns at high asymmetrical thrust settings to either side must be avoided, which is indeed the intention of the certification regulations in FAR/CS 25.149, but which is not adequately communicated to pilots and accident investigators in writing, neither in Airplane Flight manuals, nor in Training Manuals. Manufacturers are not required to publish the bank angle for which the AFM-published V_{MCA} is valid, and they do not publish this life-saving bank angle by themselves either, except for a very few. The increase of V_{MCA} with bank angle is not communicated either, but was indeed experienced by the 747 pilots, as will be explained below.

3.3.7. ***Controlling V_{MCA}*.** As explained above, the *actual* V_{MCA}, i.e. the V_{MCA} that a pilot will experience in-flight, can be lower than the standardized V_{MCA}, but only when the bank angle is between 3° and 6° away from the inoperative engine for this sample airplane, as shown in Figure 6 above top left. The *actual* V_{MCA} is much higher at other bank angles, i.e. during turns to either side. This applies to all multi-engine airplanes while OEI.
The AFM-published standardized V_{MCA} is determined with maximum asymmetrical thrust while maintaining a small (≤ 5°) bank angle away from the inoperative engine. Reducing the thrust of the engine opposite of the inoperative engine (just a bit – temporarily), decreases *actual* V_{MCA}, because the thrust asymmetry decreases, and the control requirement to counteract the thrust yawing moment decreases as well.
Hence, the pilot can contain the *actual* V_{MCA} with bank angle and, of course, also with a throttle, i.e. with the thrust level of the engine opposite of the inoperative engine.
This flight technique for keeping the *actual* V_{MCA} under control, and for allowing safe turns, when one or more engines are inoperative, was used by a competent Boeing 707 flight crew after both engines 3 and 4 separated off the right wing. During the turns for

the approach, the copilot reduced the thrust of outboard engine #1 a bit and increased the thrust of inboard engine #2, thus reducing the sum of the asymmetrical thrust yawing moments while maintaining the same performance. He in fact decreased the *actual* V_{MCA}. He also recommended a minimum speed of 200 kt to the captain, the pilot-flying, and selected the flaps to unlock the outboard ailerons, therewith increasing the lateral control power. They landed safely on Airbase Istres − Le Tubé in France. Knowledge saved lives.

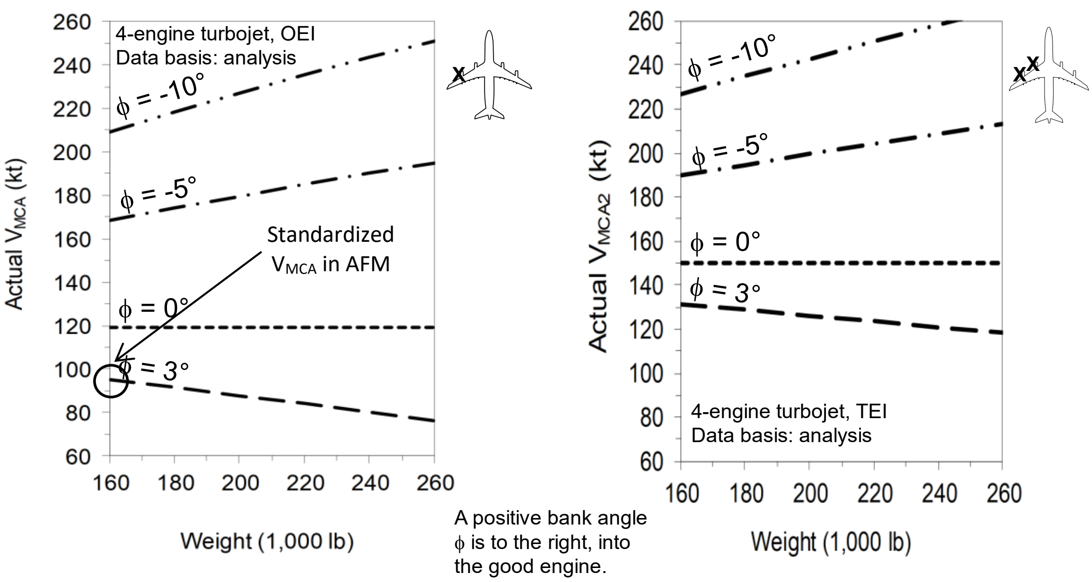


Figure 8. Effect of weight W on V_{MCA} of a sample 4-engine airplane for #1 (and #2) inoperative for several bank angles ϕ. Other engines max. thrust.

3.3.8. ***The Effect of Weight On V_{MCA}***. The graphs in Figure 8 show the effect of weight for several bank angles of the same sample airplane. The airspeeds at the intersection of the bank angles with the ordinate, the vertical *actual* V_{MCA} axis, are the same as in Figure 6 above. Figure 8 is similar to the figure that Lockheed presents in the C-130 Performance Manual SMP777, and will also be similar to Boeing 747 data, as for any multi-engine airplane when an engine is inoperative, and the thrust of the opposite engine is maximum; only the numbers will be different.

When the wings are level (bank angle ϕ = 0°), weight has no effect on the side forces, because sin ϕ in side force W·sin ϕ is zero. The asymmetrical thrust can only be counteracted by a side force due to rudder deflection, which results in a near −14° sideslip (wind in the left ear), which also causes much drag (see Figure 6 and Figure 3 above).

When banking into the inoperative engine (negative ϕ in this example in Figure 8), the *actual* V_{MCA} increases with weight. At the maximum weight of 260,000 lb, the *actual* V_{MCA} is ≈ 250 kt, 155 kt higher (!) than the standardized AFM-published V_{MCA} (see also Figure 6).

When the bank angle is 3° into the good engine (as used during flight-testing this airplane), the *actual* V_{MCA} decreases with increasing weight. At this bank angle, V_{MCA} is highest at low weight, hence, low weight is the worst-case weight for V_{MCA} and safest to publish for whatever the weight of the airplane. This is the reason that V_{MCA} is determined at the lowest possible weight during flight-tests.

Some publications for pilots state that V_{MCA} is determined with max. weight, which is wrong, as proven above. Sometimes, pilots indeed learn that low weight is most critical to V_{MCA}, but don't learn that V_{MCA} increases considerably with weight, when the small favorable bank angle is not being maintained as shown in Figure 8, except for Lockheed C-130 pilots, if they read their Performance Manual SMP777.

3.3.9. The effect of bank angle and weight as presented above was also duplicated for another airplane type by the late Dr. Ir. R. Slingerland of TU Delft in the Netherlands and his students. Prof. Dr. Ing. Bernd Hamacher of the University of Osnabrück in Germany complimented the writer of this report, and wrote: "*You are absolutely right that Vmca2 designates a very important configuration and the El Al accident is a proof for this*".

3.4. V_{MCA} Definition in Regulations

3.4.1. ***Regulatory Requirements***. Engine-out control requirements for the certification of transport category airplanes are prescribed in § 25.149 of both FAA Federal Aviation Regulations (FAR, ref. 17), EASA Certification Specifications (CS, ref. 18), and equivalent. FAR and CS 25.1513 require only one $V_{MC(A)}$ to be published as an operating limitation, the *standardized* V_{MCA}, which is determined under FAR/CS 25.149. This requires some explanation.

3.4.2. The definition of the *standardized V_{MC}* (is V_{MCA}) of a multi-engine airplane, as stated in FAR/CS 23.149 (b) and 25.149 (b), (refs. 17 and 18 and equivalent), which are for the certification of airplanes, is:

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

Regulations call this speed V_{MC}, but this definition is for a V_{MC} in the Air, for V_{MCA}, because there are also other V_{MC}'s, see below. V_{MC}, i.e. V_{MCA}, in other words, is the lowest airspeed at which *straight flight* can be maintained while the asymmetrical thrust is maximum and a small bank angle, though ≤ 5°, is being maintained away from the inoperative engine. More conditions apply, besides maintaining straight flight with the small bank angle, such as maximum rudder and/or aileron deflections or up to the maximum approved control force, the most aft center of gravity (cg) and the lowest possible aircraft weight, all of which result in the highest V_{MCA}, which is safest for publishing as a (worst-case) limitation for pilots in the AFM.
This definition is to be applied by airplane design engineers for sizing the vertical tail (fin) with rudder, and also the ailerons. The vertical tail must generate a large enough side force and hence yawing moment to be able to counteract the asymmetrical thrust yawing moment after engine failure. By sizing the vertical tail, the design engineer already defines the magnitude of V_{MCA}, hence V_{MCA} is a design parameter.
Most airplane manufacturers copy this $V_{MC(A)}$ definition unchanged into the FAA and EASA approved sections in their AFM's, and in lectures/textbooks for use by (airline) pilots, which is regrettably approved by Authorities, as will be explained below. Once the airplane is designed, built, tested, and certificated, the selected tail size imposes limitations on, i.e. flight-restrictions to be applied by pilots (§ 3.2.5). A few remarks on the use of this "design and certification" $V_{MC(A)}$ definition for and by pilots are presented next.

3.4.3. ***V_{MC} Definition Explained**. "V_{MC}" in* the FAR/CS definition is considered being the minimum control speed when takeoff flaps are selected, but a V_{MC}, higher or lower than the standardized V_{MC}, applies during the whole flight, from takeoff to landing, with flaps selected down or up, and for other configurations, in anticipation of, and after an engine failure. This is why today often V_{MCA} is used for V_{MC} in the Air.
In addition to V_{MCA}, other V_{MC}'s defined in the Regulations are: V_{MCG}, V_{MCL} and V_{MCL2}. V_{MCA2}, the V_{MC} in the Air when two engines are inoperative on the same wing, still applies to a 4- or more engine airplanes but was deleted from the Regulations many years ago, while

V_{MCL2} still exists; incomprehensible. V_{MCA2} is the minimum control speed that applies in anticipation of and after a second engine failure. This V_{MCA2} would have applied to this flight after separation of the two right-wing engines, if it still had existed.

3.4.4. *“Calibrated Airspeed”*. The calibrated airspeed (CAS) is the airspeed measured by a calibrated pitot-static system. Often Indicated airspeed (IAS) is used in Flight Manuals, but that is not correct. The indicated airspeed cannot be known at the time the Flight Manual is written, because the instrument errors of the installed Airspeed Indicator (ASI) are not known, and might change if the ASI is replaced in the future. The approved instrument errors might be 4 kt or more, meaning that the IAS of pilot and copilot might differ up to 8 kt. CAS is the same for any day, while IAS might differ. The pilot must use the supplied correction table to calculate CAS from the IAS. It could be that modern flight management systems show CAS on the display.
In Factual FDR data reports, IAS is often used as well. This FDR airspeed data can only be accurate if the airspeed indicators in the cockpit were recorded on video, which is definitely not the case. The airspeed in the factual FDR report is CAS.

3.4.5. The *“critical engine”*, usually an outboard engine, is included in the definition for use by design engineers only during tail design, and for test pilots for determining the highest, the worst-case V_{MCA} because failure of the critical engine results in the highest V_{MCA}, which is the safest single V_{MCA} to be published in the AFM for use by pilots. Failure of the critical engine does not lead to a higher V_{MCA} as often mentioned in pilot manuals; the published V_{MCA} is already the highest V_{MCA} after failure of either engine (during straight flight while banking 3° – 5°). The *actual* V_{MCA} after failure of any other engine is a few knots lower. In addition, an AFM contains only one engine emergency procedure that applies after failure of either engine, critical or non. Therefore, pilots do not have to know about the criticality of an engine; it should not be mentioned in a V_{MCA} definition for pilots. Pilots do not have to analyze whether the failing of failed engine is the critical engine. If critical engine is mentioned, then why not the much more relevant and large increase of V_{MCA} with bank angle?

3.4.6. *"Suddenly made inoperative"* is also only for engineers and test pilots; the vertical tail must be large enough, and the selected and published V_{MCA} needs to be high enough to limit the heading change following a sudden engine failure to maximum 20° for an average pilot. An airline pilot never “*suddenly makes*” an engine inoperative, only experimental test pilots should do, to verify compliance with the Regulations. Hence this statement does not belong in a pilot manual, either.

3.4.7. *"Possible to maintain control".* Control can be maintained at airspeeds as low as V_{MCA}, but only during straight flight, while also banking 3 – 5° (as opted by the manufacturer) away from the inoperative engine, when the asymmetrical thrust is set to maximum. V_{MCA} when keeping the wings level can be 6 to more than 30 kt higher than the published V_{MCA}, depending on the type of the airplane. V_{MCA} when banking with moderate bank angles to either side will increase up to 150 kt above the published V_{MCA}, as will be explained below. It is indeed *possible to maintain control*, but only during straight flight. The equilibrium of forces and moments that act on the airplane will definitely be lost if the indicated airspeed is not higher than the increased *actual* V_{MCA}. The more than 400 pilots (×2) who experienced this loss of control in the past 25 years do not live anymore to tell us about their final experience.

3.4.8. *"Maintain straight flight at the same speed with an angle of bank of not more than 5 degrees".* The V_{MC} definition is for airplane design engineers for sizing the control surfaces, as already described above, and for test pilots, who must maintain straight flight with an angle of bank of not more than 5 degrees when determining V_{MCA}. This line is out of FAR/CS 25.149 which is for design and certification of the airplane, not for airline pilots.

Airline pilots should indeed maintain straight flight, to keep the *actual* V_{MC} low, but accelerate to the takeoff safety speed V_2, while attaining and maintaining the same bank angle that the manufacturer used to size the vertical tail with rudder (3 – 5° away from the inoperative engine) for minimum drag and lowest *actual* V_{MC}, and climb (straight ahead) to a safe altitude before turning at a bit lower asymmetrical thrust setting (which reduces *actual* V_{MC}). The angle of bank can be a bit smaller when maintaining V_2 or V_{YSE} on small (Part 23) twins. Piper included the required bank angle in the legend of the Engine Inoperative climb performance data of the PA-44; other manufacturers don't (yet).

3.4.9. *"An angle of bank of not more than 5°"*. FAR/CS 25.149 allow the manufacturer to use a bank angle of maximum 5° away from the inoperative engine(s) for sizing the vertical tail and determining the minimum control speed. As mentioned before, the flight is not a coordinated flight when an engine is inoperative.
Due to the banking, a side force develops in the center of gravity that 'replaces' the side force due to sideslip (Figure 4 on page 16). Then the rudder does not have to overcome the sideslip side force anymore but only the asymmetrical thrust and its deflection can be smaller, or the airspeed be decreased until again the rudder is maximum deflected; hence, V_{MCA} is lower, as is the drag.
This is the reason why airplane design engineers use this lower V_{MCA} for sizing the vertical tail with rudder and ailerons; they save weight, aluminum, and construction cost. The up to 5° of bank away from the failed engine(s) does not result in a turn, but only in a lower V_{MCA} and less drag, hence larger remaining climb performance.
The reason why the angle of bank is *not more than 5°* is that, as shown in Figure 6 on page 19, the rudder deflection needs to be reversed from into the good engine to into the inoperative engine to avoid the fin to stall, and therewith to avoid the loss of control, at larger bank angles into the good engines.

3.4.10. *"V_{MC} may not exceed 1.13 V_S with aft cg, trimmed for takeoff and maximum takeoff weight",* and a few more conditions. This is not in the definition above, but is another certification requirement in FAR/CS 25.149 (c) that is often inappropriately used by pilots and their flight instructors. These restrictions are only intended to be used by airplane design engineers to prevent them from designing a too small vertical tail (which results in a higher V_{MCA}). A small tail is less heavy and hence cheaper to build and therefore preferred by manufacturers. But a small tail requires a higher airspeed to generate the forces and moments to counteract the maximum asymmetrical thrust yawing moment. V_{MCA} will be higher and results in higher takeoff speeds; the runways need to be longer or the payload less, which operators don't like. As shown in Figure 8 above, the worst case V_{MCA} is low weight, not maximum takeoff weight. This must also be an error in the Regulations.
Hence, there are publications which teach pilots inappropriately not to worry about V_{MCA} because this limit suggests that V_{MCA} is always lower than 1.13 V_S, but this only applies to the AFM-published standardized V_{MCA}, not to the *actual* V_{MCA} that pilots encounter inflight while not maintaining straight flight with a small favorable 3° – 5° bank angle away from the inoperative engine(s), as shown in Figure 6 above.
Therefore, this FAR/CS requirement is not at all for pilots. On the contrary, pilots should learn that V_{MCA} increases considerable when the bank angle is away from the small (≤ 5°) favorable bank angle to either side, when the asymmetrical thrust is high, and when straight flight is not being maintained, as was explained above.

3.4.11. ***Validity of the AFM-published V_{MCA}***. V_{MCA} is to be considered the minimum airspeed to be observed both in anticipation of, and after an engine failure when the thrust is asymmetric. But most important is to realize that the *actual* V_{MCA} which the pilot will experience in-flight is only equal to the published V_{MCA} under the conditions used during sizing the vertical tail with rudder, and during V_{MCA} flight-testing for the certification of airworthiness of the airplane, which are: straight flight while banking the small favorable bank angle (≤ 5°) away from the inoperative engine, maximum asymmetrical thrust, and either rudder or aileron maximum deflected. When maneuvering, the *actual*, the real V_{MCA} that a pilot will encounter in-flight, will be much higher (Figure 6 and Figure 8 above). As shown above, every bank angle has its own V_{MCA}, as does every asymmetrical thrust setting, every location of the cg, every (partial) rudder and or aileron input, in fact every parameter that affects the lateral and directional forces and moments that act on the airplane, even an accidental deployed thrust reverser in-flight, or a camera mounted on a wing tip. Regulations assume that when maximum thrust is selected, a pilot will fly only straight ahead while maintaining the small favorable bank angle, for lowest *actual* V_{MCA} and minimum drag. Regulations require only one $V_{MC(A)}$ to be published, the standardized $V_{MC(A)}$.

3.4.12. ***Missing in V_{MCA} Definition***. FAR and CS 25.1513 do require the V_{MCA} to be published in the Airplane Flight Manual, but do regrettably not require the manufacturer to publish the bank angle for which the AFM-published V_{MCA} is valid, and do not require a warning to maintain straight flight either, while attaining a small bank angle away from the inoperative engine(s) when the asymmetrical thrust is maximum. The much higher airspeed required before initiating and during turns should be mentioned as well (in engine emergency procedures) to prevent accidents due to the loss of control.
All multi-engine rated pilots know that the stall speed of an airplane increases with weight, and also during turns. They should also learn and never forget that the (*actual*) $V_{MC(A)}$ of an airplane increases with weight and bank angle, i.e. during turns to either side. A $V_{MC(A)}$ does not only apply to the takeoff configuration, but during the whole flight.

3.4.13. ***Improved V_{MCA} Definition for Pilots*.** With the facts and figures on V_{MCA} presented above, the reader will agree that the $V_{MC(A)}$ definition of FAR and CS 25.149 in § 3.4.2 above is not at all appropriate for use by pilots, and should not have been approved by aviation authorities for use in Airplane Flight Manuals. Accident and/or air safety investigators did regrettably never comment on the definition either.
Improved definitions of V_{MCA} for pilots could be:

> *$V_{MC(A)}$ is the lowest speed at which control can be recovered and only straight flight can be maintained when an engine fails or is inoperative and the thrust of the corresponding opposite engine is at the maximum level that the pilot can set from the cockpit, provided a bank angle is being maintained of 3 – 5 degrees [exact number for minimum drag to be provided by the manufacturer] away from the inoperative engine. $V_{MC(A)}$ increases considerable above the published value with increasing bank angles to either side; or*

> *V_{MCA} is the calibrated airspeed at which, when an engine fails or is inoperative, it is possible to maintain straight flight only, provided a small bank angle of [x]° is maintained away from the failed engine(s) when the thrust is maximum. The actual V_{MCA} increases considerable above the published V_{MCA} during banking to either side.*

3.4.14. **V_{MCA} *Incorrectly Described in Pilot Manuals.*** Reports of accidents after engine failure issued by Transportation Safety Boards all across the globe prove that pilots after engine failure neither maneuver their airplane in a way that complies with the flight restrictions that airplane design engineers were allowed to apply for sizing both the vertical tail with rudder and the ailerons, nor are (made) aware of the consequences this has for maintaining control during maneuvering. Accident investigators were regrettably never made aware either.
Most Airplane Flight Manuals (AFM) do not present these restrictions adequately and unmistakably, and do not present the correct definitions of the Minimum Control speeds in the Air (V_{MCA} or V_{MC}), and of takeoff speeds (V_R and V_2) that are calculated using $V_{MC(A)}$. The

consequence is that pilots do not hesitate to turn their airplane while the asymmetrical thrust is, or is increased to maximum, during which the *actual* V_{MCA} increases above the current airspeed and they lose control of their airplane and crash. Accident investigators did neither correctly analyze what happened, nor draft the correct conclusions and recommendations. A dead engine turned into a killing engine, because the pilots were not made aware of the (simple) defenses.
V_{MCA2}, the minimum control speed that applies after the loss of thrust of two engines on the same wing (n-2), seems even totally forgotten since Regulations FAR/CS 25.149 do not require this V_{MCA2} to be determined anymore, while this is a very important limitation for 4- or more engine airplanes, because V_{MCA2} not only needs to be observed when two engines (on the same wing) are inoperative, but also in anticipation of a second engine (on the same wing) to fail.
The one-engine inoperative and published standardized V_{MCA} applies not only when one engine is inoperative, but is also used to calculate the takeoff rotation speed V_R ($\geq$ 1.05 V_{MCA}) and takeoff safety speed V_2 ($\geq$ 1.1 V_{MCA}). The takeoff speeds would be safer, the margin above V_{MCA} would be higher, if the higher V_{MCA} with wings-level would be used, rather than the published standardized V_{MCA} to improve the takeoff safety in anticipation of one (outboard) engine to fail.
In the engine emergency procedures in the AFM, the applicable flight restrictions (straight flight only, no turns) when one or more engine(s) fail or are inoperative and max. thrust is set, are usually not briefly repeated as a life-saving safety reminder, or as a warning, to pilots.

3.4.15. ***Other Sources of V_{MCA} Knowledge***. So far, the theory of V_{MCA} as required for analyzing the Boeing 747 accident. Refer to the paper *Airplane Control and Analysis of Accidents after Engine Failure* (ref. 13) for more details and for other V_{MC}'s, such as V_{MCG} and V_{MCL}, and for the restrictions that come with V_{MCA}, and that also apply to the takeoff (safety) speeds V_R and V_2.

3.4.16. Other sources of V_{MCA} knowledge are presented in references. One quite interesting source is worth mentioning as well. The ***University of North Dakota*** published an online *Engine-out Interactive Simulation Trainer* (ref. 20) on its website. The simulated airplane is a small twin-engine Piper PA-44 Seminole. The difference of V_{MCA} with wings-level and with 5° into the good engine is not as large as for 4-engines turbojet airplanes. Nevertheless, the basics of the change of V_{MCA} with the small bank angle and many other variables are explained and demonstrated quite well, though only for straight flight.

3.4.17. With the theory of engine-out flight as presented above, it should now be possible to understand the analysis of the controllability of the mishap Boeing 747 that is presented in the next paragraphs.

4. Factual information Boeing 747 accident

4.1. The accident, in short

About six minutes after takeoff from runway 01L of Schiphol Airport, Amsterdam, during the Pampus standard instrument departure to the East, both engines on the right wing (#3 and #4) of the Boeing 747 freighter separated from the wing due to a fuse pin failure in pylon #3, while climbing through an altitude of ≈ 6,500 ft. The pilots decided within 28 seconds, while at a distance of ≈ 15 nm from the airport, to return to the airport immediately and initiated a right-hand turn. The aircraft continued to be controllable; the asymmetrical loss of thrust, the loss of weight of both right-wing engines and pylons, and the loss of lift due to the damaged right-wing could obviously be compensated for by the rudder, ailerons, and a high enough airspeed, with the current thrust setting (≈ MCT). During the continued wide descending right turn (25° right bank, over the lost engines), which was required because the airplane was too close to the airport, too high, and not able to establish and stabilize correctly on the glide slope of the pilot-requested runway 27, the throttles were advanced increasing the asymmetrical thrust level after which control of the airplane was lost and the airplane crashed into a residential area in Amsterdam-East.

4.2. Aircraft Information

4.2.1. Relevant airplane data for the analysis of lateral and directional controllability and performance were retrieved from the NASB report (ref. 1). Since the Airplane Flight and the Weight and Balance Manuals of the accident airplane were not available, some systems information was retrieved from a British Caledonian Operations Manual of the same type Boeing 747-200 that could be downloaded from the Internet (ref. 7).

4.2.2. ***Data of the mishap airplane***. The Maximum Takeoff Weight (MTOW) was 792,121 lb (359.300 kg), the actual Takeoff Gross Weight (TOGW) 745,823 lb (338,300 kg), and the center of gravity (cg) at 23.1% Mean Aerodynamic Chord (MAC). The Maximum Landing Weight (MLW) was 630,000 lb (285,763 kg). Fuel on-board at engine start was 158,733 lb (72,000 kg). Weight and cg were within approved limits (ref. 1).
Important limitations, such as the AFM-published minimum control speeds V_{MCA} and V_{MCA2}, being the minimum airspeeds at which control can be maintained during straight flight when one or two engines are inoperative, respectively, and the wing fuel-weight imbalance limits, were not presented in the accident report (ref. 1). These data were retrieved from other sources.

4.2.3. ***Engine data***. One JT9D-7J engine generates maximum 48,651 lb (216,410 N) thrust, the Maximum Continuous Thrust (MCT) is 40,200 lb (178,819 N), shown as 1.35 on the Engine Pressure Ratio[7] (EPR) instruments. The dry weight of one engine is 8,470 lb (3,842 kg), its pylon weight is unknown. Since the exact engine operating weights are not presented in ref. 1, it is estimated that the weight of one engine with its pylon attached is 11,000 lb (≈ 5,000 kg). The maximum approved EPR is not presented in the accident report either but is 1.62, according to the NLR (ref. 3).

4.3. Meteorological Information

4.3.1. At the time of takeoff from runway 01L, the sea level air pressure (QNH) was 1012 hPa (29.88 inHg). Surface wind was 040°/23 – 33 kt, temperature 13°C. The forecast at 5,000 ft was: wind 070°/30 – 35 kt, temperature 8° C. Just before the accident, at

[7] Engine Pressure Ratio (EPR) is the total engine and fan outlet pressure divided by the compressor inlet pressure, a measure of the generated thrust by the engine.

17:29:58 UTC, Air Traffic Control (ATC) reported QNH 1012 hPa, surface wind 050° at 22 kt. The crew asked 10 seconds later to repeat the wind: 050° at 22 (ref. 1, App 4.1). The weather at the time of the accident (17:36 UTC, 18:36 local time - dusk) was: light to moderate turbulence, clear and dry, visibility up to 2,000 ft 15 km, 1/8 alto cumulus at 13,000 ft (ref. 1).

4.4. Flight Recorders

4.4.1. FDR data were not included in the accident report, although ICAO requires that "the writer should assume that the reader is intelligent but uninformed and will analyse the facts presented in order to test the conclusions of the Final Report" (ref. 8). Objective FDR data are needed for such an independent analysis but were still not accessible at the time of conducting this analysis, because they were locked up in the Dutch National Archives for 75 years, which nobody understands except the investigators or the Board Members who might want to conceal their short falling investigation and prevent from being criticized by intelligent and knowledgeable readers. Some reworked FDR data was retrieved from public sources, ref. 2 and 3, but still should be verified using the original NTSB FDR factual report.

4.4.2. The Cockpit Voice Recorder was never retrieved from the accident site. The only voice recordings available were the radio communication of ATC with the crew, of which a transcript is included in the final report, ref. 1, Appendix 4.1.

4.5. Other Related Accidents

4.5.1. In the accident report, ref. 1, § 1.17.1, a number of accidents and incidents are listed that occurred due to pylon problems and the separation of engines. One (no. 3) is of particular interest; a Boeing 707 that also lost two engines about 6 months prior to this Boeing 747 accident. The pilots managed to continue the flight safely and land the airplane, because they were aware of how to maintain control of the airplane while the thrust is asymmetrical. In § 3.3.7 above, their flight technique was briefly explained.

4.5.2. As mentioned in the introduction (§ 2.1), more than 400 accidents with large and small transport, and commuter class multi-engine training airplanes occurred after a propulsion system malfunction during the past 25 years, because the pilots, unlike the Boeing 707 pilots, were neither (made) aware of the controllability of their airplanes after engine failure, nor about the do’s and don’ts when they have a dead engine on a wing. Accident investigators were not aware either, and did not draft accident-preventing recommendations. A number of supplemental analyses of engine-failure related accidents are presented on the Accidents Page of the website of Avio*Consult*[8].

5. Analysis of the Controllability After Separation of Two Engines

5.1. Introduction

5.1.1. Using the knowledge of experimental flight-testing airplanes with inoperative engines gained at the USAF Test Pilot School and from aeronautical university college books, which is briefly presented in § 3 above, the directional and lateral controllability of the Boeing 747 airplane following the separation of both engines off the right wing will be analyzed below.

[8] https://www.avioconsult.com/accidents.htm.

5.1.2. As mentioned above, no FDR data, except for a few graphs out of ref. 2 and 3, were available (yet).
The NLR, in ref. 2, used a different time line and very small graphs which makes these FDR data more difficult to use. Ref. 3 presents only limited control data that is used below. The NTSB Factual Report with original FDR data should be retrieved form the National Archives and reviewed to further improve this analysis.

5.2. Takeoff and Initial Climb

5.2.1. ***Introduction***. An FDR does not record the exact position of the airplane during flight, but logs altitude, heading and airspeed and much more data of the airplane, over time. Therefore, only ATC-radar data could be used for positioning. The departure and approach ground track of the airplane is presented in ref. 1, and will be discussed below.

5.2.2. ***Takeoff performance***. Witnesses, including an air traffic controller, testified that the airplane, shortly after liftoff, did not climb very well. They believed the climb performance was less than normal, and less than similar airplanes.

5.2.3. A pilot is allowed to takeoff using a reduced thrust setting of the engines, being a lower than maximum available thrust setting, which is calculated using the available runway length, the takeoff weight of the airplane, the outside air temperature, the air density, etc. A lower thrust setting saves fuel and preserves engine life. Another reason might be noise abatement. Most larger airplanes use this technique, because it saves money, but also results in a smaller Rate of Climb (ROC) after liftoff.

5.2.4. During takeoff, the initial thrust setting (Engine Pressure Ratio – EPR) was between 1.44 and 1.46 (Figure 9 below), which is lower than the maximum approved 1.72. Engine thrust during takeoff may be larger than Maximum Continuous Thrust (MCT - EPR 1.32) for an approved period, usually during a few minutes. Thereafter, the engine thrust must be reduced to MCT. This is what the Boeing 747 pilot factually did (Figure 9).

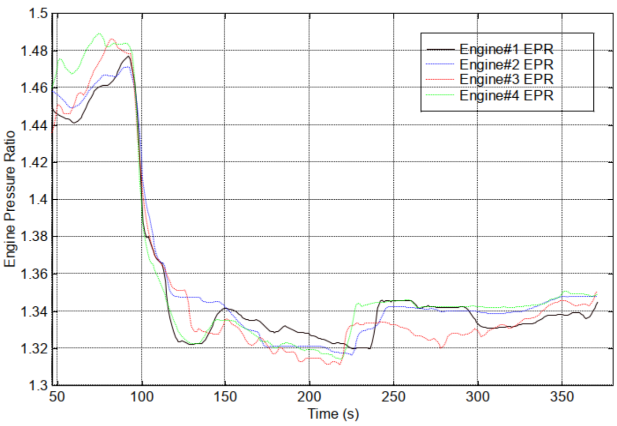


Figure 9. FDR Engine Pressure Ratio (EPR) data (NLR, ref. 2, Fig. 34.)

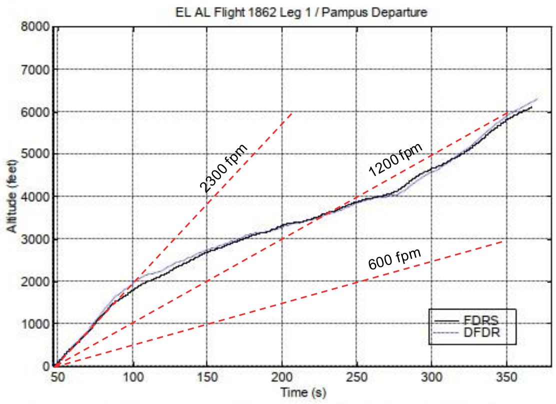


Figure 10. FDR altitude data and climb performance (NLR, ref. 2, Fig. 23).

5.2.5. The FDR-recorded altitude is presented in Figure 10, including a few lines showing the ROC in feet per minute (fpm). As shown, the ROC after liftoff from the runway was initially 2300 fpm, and from 100 seconds an average of 800 fpm until ≈ 225 seconds after liftoff.

5.2.6. When the thrust was reduced to approximately MCT, here a bit early at 100 s, the ROC, of course, decreased as well (Figure 10). The airplane was approved for a Pampus departure (to the East), which requires the Pampus VOR beacon to be passed at or above 3,000 ft, which the Boeing 747 did; the altitude was already ≈ 6,000 ft. Hence, the climb performance was adequate, and according to the rules.

5.3. The Flight Path

5.3.1. The flight path, i.e. the plot of the ground radar track of the airplane from takeoff to the crash was included in the accident report (ref. 1, Appendix 3.1) and is copied in Figure 11 below. The circled numbers refer to events in the FDR bank angle data of the flight in Figure 15 below, that show the turns before and after the engine separation, and are used in the analysis from § 5.5 below as well. The plot was however not the original plot.

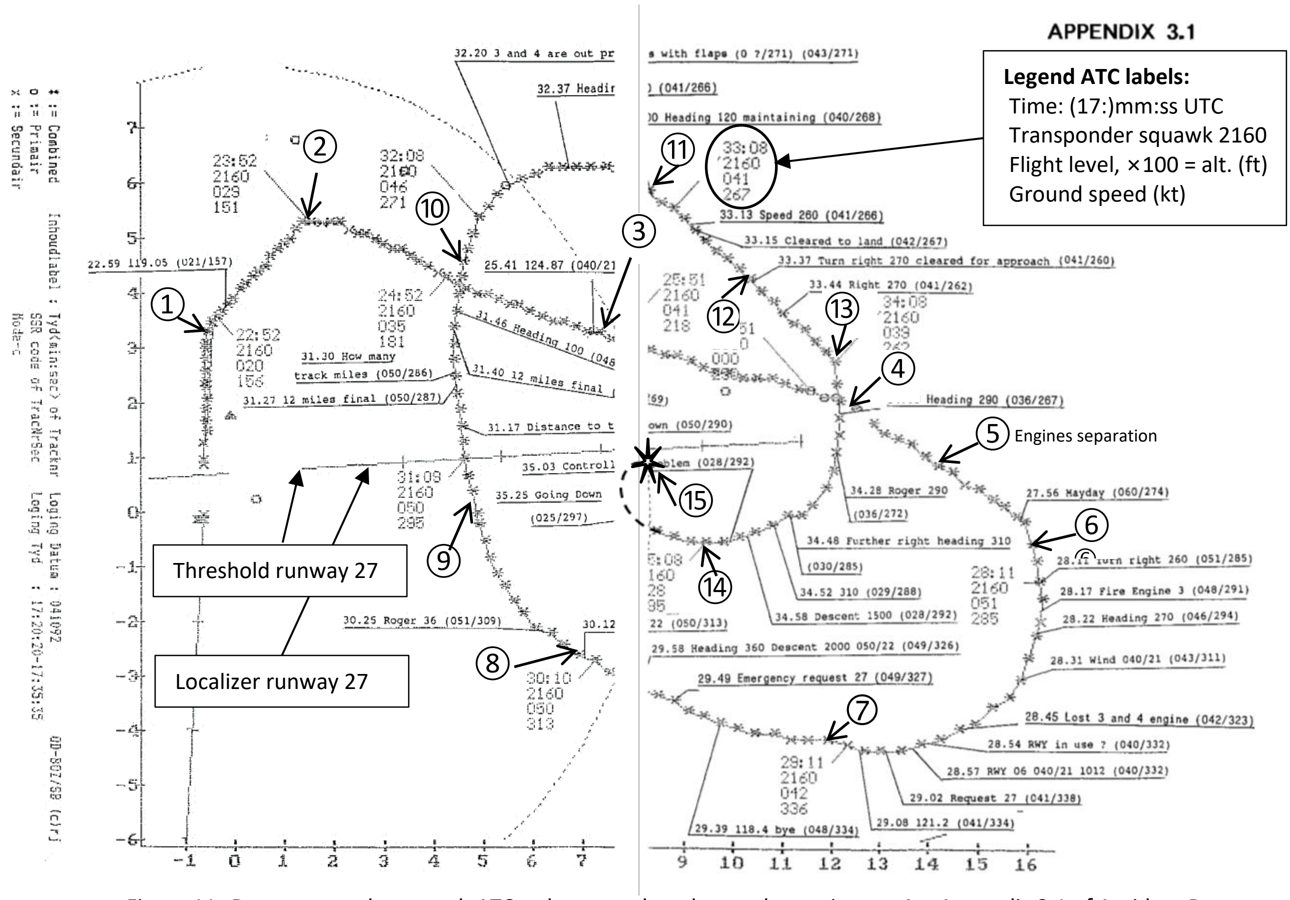


Figure 11. Departure and approach ATC radar ground track, one data point per 4 s, Appendix 3.1 of Accident Report.

5.3.2. A board member testified[9] that changes were made in the first part of the route, and the lead investigator testified[10] that the track was calculated by using both the FDR heading data and the wind. However, the FDR-recorded heading of an airplane of which two engines are inoperative cannot be used to calculate the true course of the airplane, because this heading includes a large sideslip angle, unless straight flight is being maintained while also maintaining a small bank angle between 0 and 5° into the good engines, when sideslip is zero (Figure 6, bottom right). The angle of sideslip is not measured in an airliner and hence, is not recorded on the FDR, but can be up to 14°, as shown in Figure 6 above for bank angles between −15° and +15°. Hence, the FDR-recorded heading cannot be used with the drift angle due to the wind to calculate the ground course/track. As was mentioned a few times before, a flight is not coordinated, when the thrust is asymmetrical. The lead investigator was obviously unaware of the difference between sideslip and drift angles. The exact ground track is not of importance for the analysis below, which is aimed at the controllability after engine failure; therefore, it is assumed that this figure presents the correct ground track, just for reference purposes.

[9] Parliamentary enquiry, hearing 26, Mr. M., 1998–1999, 26 241, nr. 11, page 296.
[10] Parliamentary enquiry, hearing 25, Mr. W., 1998–1999, 26 241, nr. 11, page 277.

5.3.3. The final seconds of flight are shown with an estimating dashed line to the well-known impact point, Figure 11 event ⑮, because either the inner margins of the pages in the report were not copied, or the distant ground radar might not have received radar returns from the airplane and/or of the transponder at low altitude. The direction of impact with the apartment building was to the East (ref. 1, Appendix 2.2).

5.4. Engines Separation and the Consequences for Controllability

5.4.1. At 17:27:30 UTC (event ⑤ in Figure 11), while the airspeed was 270 knots Calibrated Air Speed (KCAS, ref. 2) and the airplane climbed through 6,500 ft, at a distance of approximately 18 nm from the airport, a fuse pin failure in pylon 3 caused engine 3 and its pylon to separate from the wing and knock off engine 4 including its pylon as well (ref. 1). The cause of the separation, the failure of the fuse pin in pylon 3, was analyzed in detail in ref. 1; it is not the subject of this controllability analysis. The separation caused damage to the right wing. Below, the consequences of the loss of two engines, and of the damage of the right wing will be explained and analyzed.

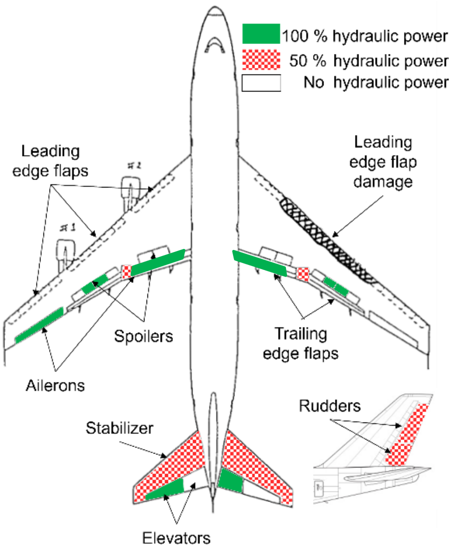


Figure 12. Remaining aerodynamic control surfaces after separation #3 and #4.

5.4.2. ***Remaining Control Surfaces***. After the loss of engines 3 and 4, the remaining hydraulically actuated aerodynamic control surfaces by hydraulic pumps on engines 1 and/or 2 were: left outboard aileron, left outboard elevator, right inboard elevator, spoilers 2, 3, 10, 11, and the inboard trailing edge flaps (ref. 1, page 15), as shown in the adjacent Figure 12. Actuated with 50% hydraulic power, from only engines 1 and/or 2 were: left and right inboard ailerons, upper and lower rudders, and stabilizer trim.

5.4.3. The effects of the loss of directional and lateral (hydraulic) control power after the separation of both right-wing engines, of the unbalanced weight of the wings, and of the loss of lift of the right wing due to leading edge damage on the lateral and directional controllability of the airplane will be analyzed in greater detail below.

5.4.4. ***Lateral Controllability After Engine Separation.*** Lateral controllability, i.e. the control of the airplane about the longitudinal x axis, is not only achieved by the ailerons and the roll-assisting spoilers, of which only 2 of 6 were available each on the left and right wings, but is also affected by the rudder deflection, the sideslip (Figure 5), and the weight imbalance and damage of the wings. The effects of leading-edge flaps, flap position, wing weight imbalance and damage of the right wing will be discussed briefly first.

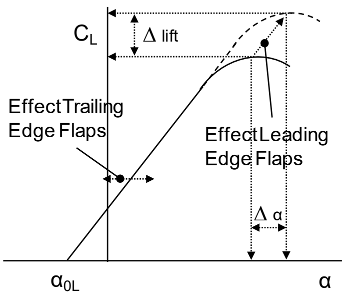


Figure 13. Lift versus angle of attack α and effect of Flaps.

5.4.5. ***Effect of Leading-Edge Flaps on Wing Lift.*** Parts of the leading edge of the wings are provided with the Leading-Edge Flaps, in two pairs. These flaps, sometimes also called slats, provide lift augmentation (increase of lift coefficient C_L with Δ lift) at higher Angles of Attack (AOA or α), which is the case when the airspeed is low, and also increase the stall angle of attack to a higher value (Δα), as shown in Figure 13. Therefore, these flaps are used during takeoff and landing, when the airspeed is low and hence, the angle of attack of the wings is large.

However, at the flap selection altitude of ≈ 4,800 ft, the airspeed was 260 kt or higher, after the separation of the engines, which is not a low airspeed. Hence, the angle of attack of the wings was not even near maximum, and the wings did not stall because of a low speed, or a high angle of attack. The difference between the leading-edge flap extension on the left and on the damaged right wing had effect on the lift distribution between both wings, because of the disturbed airflow on the right wing. FDR data at flap selection (17:31:40 UTC) show a decrease of bank angle, rather than an increase to the right (Figure 15 below, prior to ⑩).

5.4.6. ***Ailerons, Flaps and Spoilers for Lateral Control***. Lateral/roll control is provided by out- and inboard ailerons, and by flight spoilers on both wings. When the flap handle is set to position *Flaps one* (as the pilot did at 17:31:40 UTC, 12 seconds prior to event ⑩ in Figure 11), not only half of the Leading-Edge flaps (one pair) on each wing extend, but the outboard ailerons are also unlocked. Outboard ailerons provide a larger rolling moment than the inboard ailerons, because the moment arm to the cg is longer. Larger aileron control power is required during takeoff and approach to land when the airspeed is low. In addition to the ailerons, roll assisting flight spoilers on the top of the down going wing deploy when the control wheel is rotated beyond 8° to that side reducing the aerodynamic lift of that wing. After the separation of engines #3 and #4 with their hydraulic pumps, the right outboard aileron was inoperable, the inboard ailerons were actuated by only 50% hydraulic power, and 4 of 6 spoilers on each of the wings were also inoperable, as consequence of the loss of hydraulic power. The limited available aerodynamic control surfaces after the separation of the engines are shown in Figure 12 above.

5.4.7. The need to increase the roll control power could have been the reason why the captain selected *Flaps one*. Although the control wheel data in Figure 15 is a bit erratic, it seems that the average wheel deflection is a bit smaller after the selection of *Flaps one*, at event ⑩, than before. The limit speed for *Flaps one* for prolonged or holding flight is for a British Caledonian Boeing 747-200: 235 kt, and for a KLM 747-200/300: 275 kt. *Flaps one* was selected when the airspeed was still higher than 270 kt.

5.4.8. ***Wing Weight Imbalance After the Separation of Two Engines.*** The loss of thrust alone of engines does not cause the center of gravity of the airplane to shift laterally. Only when the fuel balance between both wings during prolonged engine-out flight is not adequately maintained, the center of gravity might shift outside of the approved lateral limits. To avoid imbalance, AFM's always present maximum approved fuel imbalance limits of the inboard and outboard tanks in both the left- and right-wings, the main reason being to ensure adequate aerodynamic roll or lateral control power of the airplane, as provided by ailerons and roll-assisting spoilers, when the airspeed decreases to the lower approach and landing speeds. Some airplanes also generate visible and audible fuel imbalance warnings, for the pilots to start cross feeding engines or transferring fuel between tanks.

5.4.9. The accident report (ref. 1) does not present the maximum approved (fuel) imbalance, and the AFM of the airplane was not available for review. A possible maximum could be found in the AFM of another 747-200 version (ref. 7): an alarm is issued when the imbalance of the outboard fuel tanks reaches 3,000 lb (1,360 kg), and of the inboard tanks 6,000 lb (2,720 kg).
The weight imbalance between the left and right wings after the separation of two engines and pylons (22,000 lb or 10,000 kg; § 4.2.3 above) is much larger than the maximum approved fuel imbalance. A large required aileron input to control the weight imbalance, and a much higher approach and landing speed should therefore be expected for approach and landing.

5.4.10. After the loss of engines #3 and #4, the center of gravity of the mishap airplane shifted approximately 1.74 ft (53 cm) laterally to the left. As the combined lift vector of both wings would not shift after loss of the weight of two engines alone, this lift vector would cause a rolling moment to the left about the shifted cg, which would require right aileron input to counteract. But unofficial available FDR data in Figure 15 below show otherwise; an aileron input to the left of an average of 35° was required after the separation of the engines, during the remainder of the flight.

5.4.11. ***Wing Lift Imbalance After the Separation of Two Engines.*** When a wing is damaged and its generated aerodynamic lift decreases, the vector representing the sum of the lift vectors of both individual wings together, which normally acts in the aerodynamic center on the centerline, would then displace laterally too, and generate a rolling moment. If the displacement is large, outside of the displaced cg, the displaced combined lift vector of both wings generates a rolling moment to the right, as is shown in adjacent Figure 14. The rolling moments generated by the rudder and sideslip side forces, which act above the cg, are not shown here; forces are not to scale.

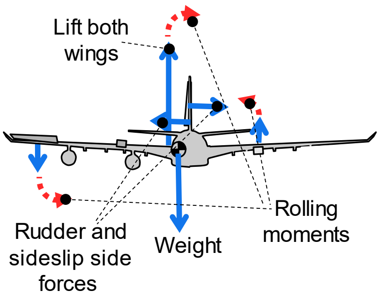


Figure 14. Shift cg and lift vector both wings, reduced roll control.

FDR data (Figure 15 below) shows, that the pilots obviously needed a rolling moment to the left; the aileron control wheel was rotated to the left for the remainder of the flight. This in fact means that the aerodynamic lift vector of both wings must have shifted into the good engines' side, even outboard of the also displaced cg due to the loss of the weight of two engines, causing a rolling moment to the right that needed to be counteracted by control wheel to the left, as shown in Figure 14. This large lateral shift of the lift vector might have been caused by the large loss of lift of the right wing due to structural damage caused by the separation of both engines, as shown in Figure 12 above. The extent of the damage of the Leading-Edge flaps and of the wing section behind the damaged flaps could not be determined in detail (ref. 1), but must have been considerable given the large required aileron control input to the left after the separation of the engines and during the remainder of the flight; the loss of lift of the right wing might have been larger than the loss of weight of two engines with their pylons.
To put this loss of weight in perspective, it is necessary to recap the airplane weight from § 4.2.2 above. The actual Takeoff Gross Weight (TOGW (= mass)) of the airplane was 745,823 lb (338,300 kg). Each wing generated little more than half of this weight as lift, i.e. more than 372,912 lb or 169,150 kg. The loss of two engines and pylons (≈ 22,000 lb or 10,000 kg) in fact means that only 6% of the lift generated by one wing was lost; not that much. As mentioned in § 5.4.10 above, the cg shifted only 1.74 ft (53 cm) to the left due to the loss of two engines with pylons.

5.4.12. The unexpected direction of the aileron control wheel input to the left in the FDR data in ref. 3 (Figure 15 below) was verified by analyzing the direction during the first turns after takeoff when all engines were still operating. The right turns indeed show a positive (right) bank angle following a positive right control wheel input (Figure 15, occurrences ① and ②). However, after the separation of the engines, things seem different. For instance, at 17:33:45 UTC, Figure 15, the control wheel is rotated from −20° to −75° (to the left) while the airplane rolls to the right (event ⑬) 15 seconds later. Because of this discontinuity, more and original FDR data of other parameters in the Factual NTSB report should be accurately reviewed before drawing final conclusions.

5.4.13. ***Lateral Controllability Flight 1862***. After the separation of the right-wing engines (Figure 15 below, event ⑤), the asymmetrical thrust yawing moments generated by engines #1 and #2 on the left wing yaw the airplane to the right about the cg, as was already mentioned above. The resulting sideslip (β – wind from the left) increases instantaneously, as does the drag. The rudder and sideslip side forces also contribute to the lateral moments (L), because they act on the fin with rudder above the cg (Figure 14). These lateral or rolling moments need to be counteracted with the ailerons (δ_a) and with the rudder (δ_r) as well, as shown in the equation of lateral moments in Figure 5.

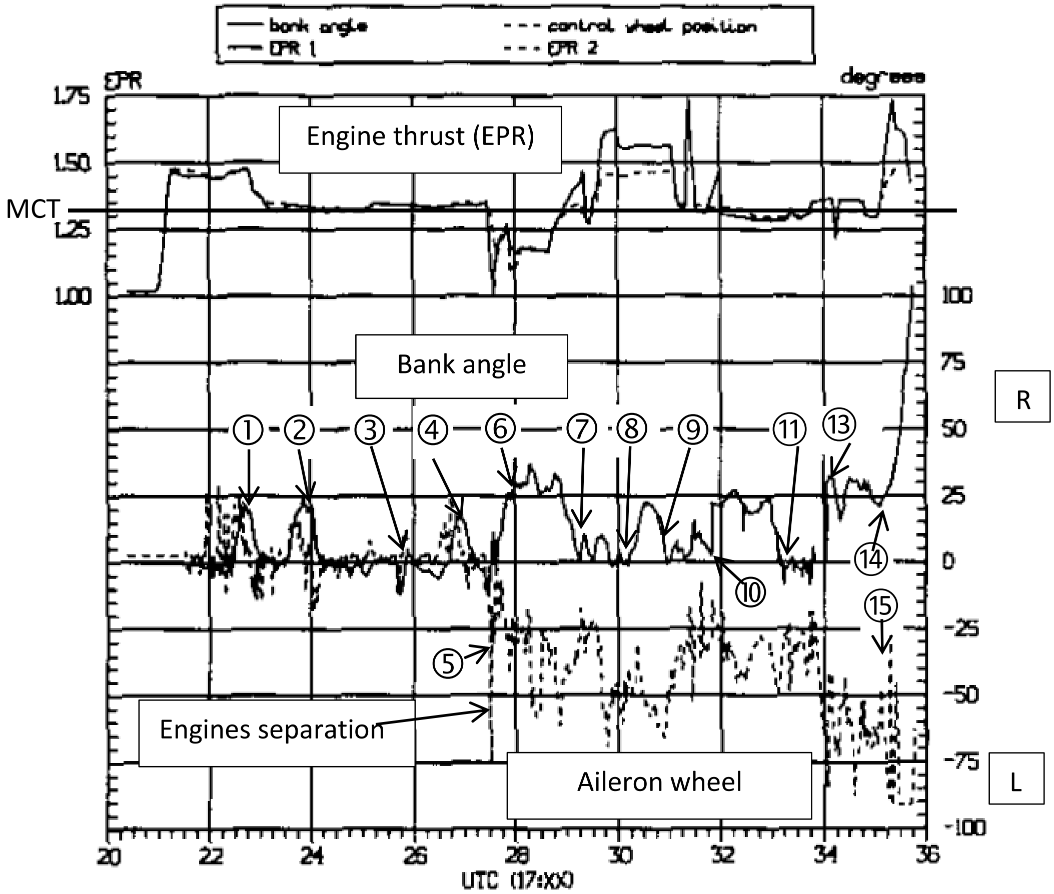


Figure 15. Bank angle, aileron wheel and EPR (FDR data, ref. 3). The circled numbers correspond with events in Figure 11.

5.4.14. An average of 35° of aileron control wheel input to the left was required during the remainder of the flight for maintaining lateral control at the average airspeed of 270 kt and an average EPR of 1.30. At this airspeed and this thrust setting, that was less than maximum EPR 1.72, the equilibrium of lateral forces and moments could obviously be maintained, because the airplane remained controllable.
But, as stated before, the equilibrium of forces and moments changes considerably with airspeed, asymmetrical thrust level, and bank angle.

5.4.15. If, when the ailerons are already (near) maximum deflected, the airspeed is reduced or the asymmetrical thrust is increased, an even larger aileron deflection would be required to maintain the balance of lateral forces and moments, but is not available due to the mechanical – design – stop. Then lateral control can only be maintained, i.e. the loss of control can only be prevented, by increasing the airspeed immediately.
Large aileron and/ or rudder deflections required during flight is a strong warning signal to pilots to not reduce the speed any further or to not increase the thrust (the yawing moments), or control will be lost. Then the ailerons and/or rudder obviously need a higher airspeed to generate the required control forces and moments for maintaining an equilibrium of forces and moments. Large control deflections in fact show that the *actual* V_{MCA}, being the lowest airspeed which can be obtained with full lateral control deflection at the

current level of asymmetrical thrust, increased to a value nearly as high as the current airspeed.

5.4.16. The consequence of the shift of both the cg (and hence the weight vector) due to the loss of two engines and pylons, and of the shift of the wing lift vector due to damage of the right wing, is that the approach speed (V_{APP}) and the landing speed (V_{REF}) cannot be as low as normal (V_{APP} = V_{REF} + speed additives for wind and turbulence; V_{REF} is the larger of V_{MCL2} and 1.23 V_S, or higher). These data were not provided in ref. 1, so could not be verified. A high-speed, in this case, tail wind landing on the crew-requested runway 27 (ref. 1) with near maximum aileron and rudder deflections (depending on the required asymmetrical thrust level) would be required.

5.4.17. Normally, trims can be used to reduce the aileron and rudder control forces on the control wheel and pedals. The authority of the trims of this Boeing 747 version is not known; the pilots must have had to use additional muscle force to balance the lateral and directional forces and moments, which they did achieve after the engine separation until the last seconds of flight.

5.4.18. ***Forces and Moments at a Larger Bank Angle***. During the final turn from event ⑬ in Figure 11 and in Figure 15, an average bank angle of 25° to the right was attained. As was discussed in § 3.1.8 above, when an airplane is banked, a component of the weight acts as side force W·sin ϕ in the center of gravity (in the body axes system) and hence, does not generate a yawing moment (moment arm = zero). The yawing moment to counteract the thrust yawing moment (about the z axis), still needs to be provided by the rudder though (Figure 16).

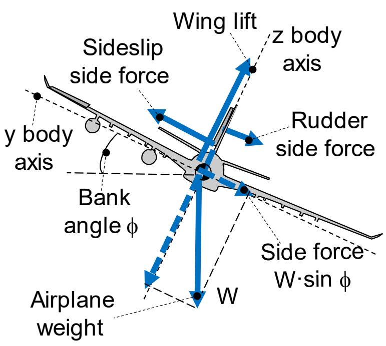


Figure 16. Side forces during banking 25° into the lost engines, damaged right wing. Forces not to scale.

The rudder side force and side force W·sin ϕ increase the sideward acceleration, therewith increasing the sideslip, until the increasing opposite side force due to sideslip balances the sum of the rudder and the bank angle (W·sin ϕ) side forces. Such an equilibrium is possible if the airspeed is not too low for the fin with rudder to generate an adequate side force and a yawing moment to act against the thrust- and other yawing moments, and the ailerons generate an adequate rolling moment to maintain the bank angle, but the resulting sideslip is large, as shown in Figure 6 (bottom right – mirrored). This figure also shows that the rudder requirement at increasing bank angles into the inoperative engines is less than maximum because of the large sideslip. The airplane, after the separation of the engines, remained controllable during the 25° banked turns so far, i.e. while the thrust setting, i.e. the thrust yawing moment, was not maximum (Figure 15). The required aileron and rudder deflections to balance the forces and moments were quite large though (Figure 15 resp. Figure 18). The pitch attitude and the airspeed could be maintained using the elevator during the slow, controlled descent. However, the equilibrium of lateral forces and moments was about to change dramatically.

5.4.19. ***Directional Control After Engine Separation.*** The vertical tail (fin) with rudder provides directional control. It provides weathercock stability, and side forces/yawing moments when the rudder is deflected by the pilot, when required, for instance after an engine failure, or during a crosswind takeoff or landing. Directional moments (Figure 5 on page 19) are generated by the rudder deflection (δ_r), the aileron deflection (δ_a), the sideslip angle (β) and by the asymmetrical thrust yawing moment (N_T) and airspeed (q).

5.4.20. ***Rudder Ratio Changers*** of the Boeing 747 reduce the deflection of the upper and lower rudders with increasing airspeed to keep the air loads on the fin with rudders within structural (design) limits. The (asymmetrical) engine thrust does not change with increasing airspeed, so the side force that the fin with rudder must be able to generate for counteracting an asymmetrical thrust condition, does not have to change with airspeed either. Since this force (horizontal lift) is proportional to the square of the airspeed ($\equiv V^2$), the rudder deflection should decrease with airspeed as a quadratic function as well ($\equiv 1/V^2$). This is achieved by the rudder ratio changers, as shown in Figure 17. The maximum available rudder yawing moment, required to counteract the thrust yawing moment, remains approximately equal to the maximum asymmetrical engine thrust yawing moment at all airspeeds. A pilot might not notice differences in directional control when using the rudder pedals at low and high speeds, and will not have to worry about overloading the fin at high speeds, not even with full rudder pedal input, although the AFM might still warn to avoid abrupt inputs.

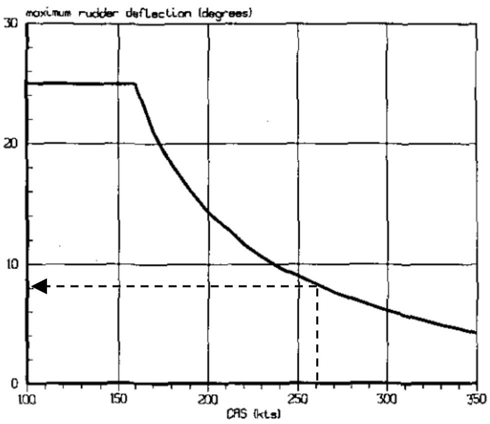


Figure 17. Rudder deflection as a function of airspeed with full rudder pedal.

Small differences might occur between the deflection of the upper and lower rudders because they are controlled by two separate ratio systems, which are cross-connected to the left and right upper and lower pitot tubes and static pressure sources. This effect can be seen in the FDR data in Figure 18 when the rudder pedal input increases and hence the

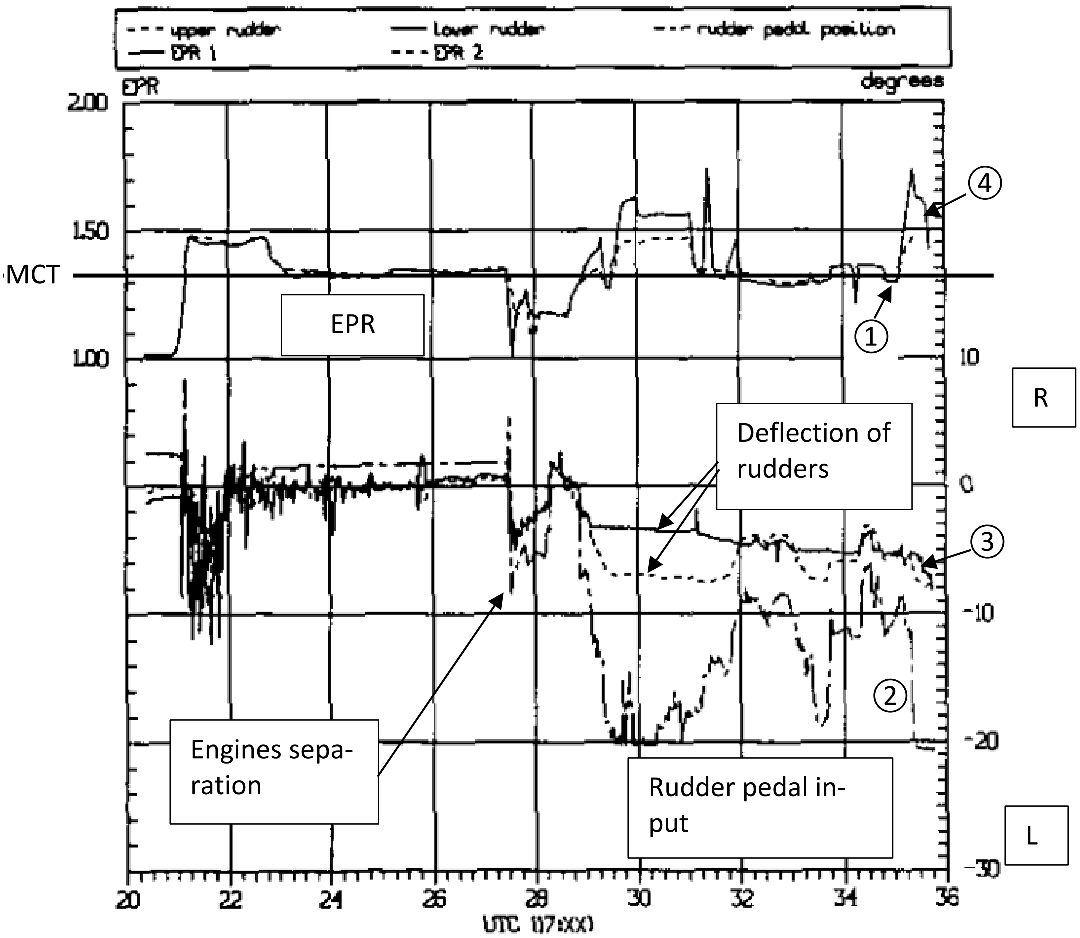


Figure 18. Rudder deflection, rudder pedal position and EPR (FDR data ref. 3).

sideslip, which increases the static pressure on one side of the fuselage. Also obvious is the limitation of the rudder deflection by the rudder ratio changers to the maximum 8° (Figure 18 above) at larger pedal inputs at an airspeed of 260 kt.

5.4.21. ***Directional Controllability Flight 1862***. After the separation of the right-wing engines, the asymmetrical thrust yawing moment generated by the engines on the left wing yaws the airplane to the right about the cg. The sideslip angle increases instantaneously (wind from the left), as does the drag.
The pilot must counteract this yawing moment using the rudder, and the lateral side effects/moments using the ailerons to re-establish straight flight. The rudder side force not only generates a yawing moment to counteract the thrust yawing moment, but also accelerates the airplane sideways, reversing and increasing the sideslip angle, in this case to the right. The sideslip angle increases until the increasing opposite side force due to this sideslip, generated by the fin and airplane fuselage, equals the rudder side force. The side force due to sideslip however, also generates a sideslip yawing moment that enhances the thrust yawing moment (Figure 19). The rudder deflection needs to be increased to overcome this as well; the sideslip increases. Both the resulting sum of the side forces, generated by the vertical tail by rudder and sideslip, and the resulting sum of the yawing moments, generated by the thrust and the vertical tail by rudder and sideslip, must be zero to achieve an equilibrium of forces and moments, which is required to be able to maintain equilibrium flight. The large sideslip and the control deflections for bank angle zero are shown in Figure 6 bottom right.

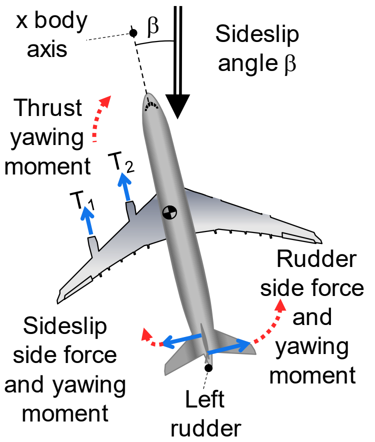


Figure 19. Most important directional forces and yawing moments during straight, engine-out flight, wings level.

At a high enough airspeed this equilibrium will not be a problem, but at too low a speed or at a high asymmetrical thrust setting, the fin- and rudder-generated forces and moments might not be adequate anymore to counteract the thrust yawing moments. The minimum speed required to maintain the equilibrium of directional forces and moments, in other words to maintain directional control, is highest when the level of asymmetrical thrust is maximum.
After the separation of the engines, the directional equilibrium of forces and moments could obviously be re-established and maintained at the current airspeed and the (less than maximum) asymmetrical thrust setting of engines 1 and 2; the airplane remained controllable, but a sideslip angle remained, as shown in Figure 19 and in Figure 6 for straight wings-level flight. Hence, the drag was not minimal, which in this case was not bad; the airplane had to descend for the return to the airport anyway.

5.4.22. Figure 18 above shows the deflection of the upper and lower rudders, the rudder pedal position, and the EPR, and is copied as FDR data from ref. 3. This is not an image out of the original NTSB Factual Report with FDR data either, but a collection of FDR data relevant for reviewing directional control, that might have been composed by the investigation committee.

5.4.23. ***Pitch Controllability***. The altitude is controlled with the elevator, operated by moving the control column forward and aft; control forces are reduced with the trim wheel or buttons which changes the angle of attack of the stabilizer.
There was no pitch controllability problem, despite the limited elevator control power after the loss of hydraulics. As mentioned in § 5.4.5 above, the wings did not stall at the

high airspeed, until the last seconds of flight when the wings were near vertical. FDR data should be reviewed to draw final conclusions on pitch control limitations, if any.

5.5. The Return for Landing

5.5.1. An all-engines operating final approach normally begins at 2,000 ft altitude, 6 nm from the runway threshold and established on the localizer, the lateral guidance component of the Instrument Landing System, which is the extended runway centerline. Then the landing gear is already down, landing flaps are selected and the remainder of the approach is a straight, descending flight, at a flight path angle of 3° and a stabilized airspeed. The approach procedure in case two engines are inoperative (n-2) should be presented in the El Al Boeing 747 AFM, but this was not available for review. British Caledonian recommends for a Boeing 747-200, when two engines are inoperative, a straight-in approach from 12 nm of which the first 6 nm are for deceleration to the final approach speed. A long straight-in approach avoids a final turn at the low final approach speed, during which the *actual* V_{MCA2} might increase too much (§ 3), and hence, prevents the loss of control.

5.5.2. When the engines separated from the wing (at 17:27:30 UTC), the altitude was approximately 6,500 ft, and the distance from the runway approximately 15 nm, just following crossing the extended runway centerline of runway 27, as shown in Figure 11 event ⑤. Accurate FDR data are required to evaluate heading, sideslip, and crab angles. At 17:27:56, the pilot reported to ATC: “*El Al 1862, mayday, mayday, we have an emergency*” (ATC radio transcript, ref. 1, Appendix 4.1), and started a right turn 2 seconds later (event ⑥).
The bank angle increased to an average of 30° to the right during 90 seconds for an approximate 160° right turn to return to the airport (Figure 11 event ⑥ to ⑦). Most airlines have procedures in place to first assess the emergency, the damage, etc., and then plan the engine-out approach and landing, which would take more than the 28 seconds from the engine separation to the turn. The El Al Boeing 747 was still too close to the runway, too high and too heavy for an immediate approach, which made descending turns necessary during which also fuel could be jettisoned to reduce the weight of the airplane to below the Maximum Landing Weight. Nevertheless, the pilots decided to return to the airport as soon as possible.

5.5.3. During the turn, ATC first directed the airplane to prepare for landing on runway 06 because of the ground wind 040° at 21 kt, but the pilot requested runway 27, just prior to event ⑦. He would have had to continue the turn in the direction of the initial point of this runway (at 6 nm), but the turn was not continued (⑦). The airplane flew for about 80 seconds in the direction of the airport. At 17:30:14 ⑧, the pilot asked “*what heading for runway 27*”. ATC responded with: “*Heading 360, heading 360, and then give you a right turn on, to cross the localizer first and you’ve got only 7 miles to go from present position*”. The airplane was too close to the airport and too high to be able to conduct a stabilized approach from that point. Another descending turn was necessary; ATC directed the airplane in direction 360°, to the North, towards the city center.

5.5.4. At 17:31:17 UTC (halfway between ⑨ and ⑩ in Figure 11), ATC asked "*what is the distance you need to touchdown*". The pilot responded "*12 miles we need for landing*". Then ATC asked "*Yeah, how many miles final .. eh correction .. how many miles track miles you need?*". The pilot responded with "*we need .. a 12 miles final for landing*". Then ATC said: "*Oké, right heading 100. Right heading 100*" which the pilot confirmed with "*heading 100*". ATC used the words "*track miles*", which the pilot did not understand, because it is not standard phraseology; “12 miles final” is, as the pilot used.

5.5.5. After establishing on heading 100, the pilot reported "*heading 100*" (halfway between events ⑩ and ⑪), which the ATC controller confirmed with "*Thank you 1862*".

Twenty one seconds later however, the pilot reported "*Okay, heading ..eh .. 120 .. and turning eh .. maintaining*". The pilot had maintained heading 100 for ≈ 20 seconds, then turned right to 120° (Figure 11, ⑪). He obviously wanted to stay close to the airport, rather than fly to the 12 nm final initial point and continue the descent to 2,000 ft. ATC did not comment on this (not directed) increased heading, but responded with "*Roger 1862, your speed is?*" which the pilot answered with "*260 kt*". This 120° heading would make it impossible to position the airplane on the extended runway centerline of runway 27 at a distance of 12 nm, as the captain asked for, and his procedures required.

5.5.6. At 17:33:15 UTC, 16 seconds after event ⑪ in Figure 11, the airplane was cleared to land. At 17:33:37, event ⑫, ATC directed *"El Al 1862 a right right turn heading 270 adjust on the localizer, cleared for approach",* which was confirmed immediately with *"right right 270"*. The airspeed was ≈ 260 kt (ref. 2). ATC can, using radar images and knowing the airspeed, predict quite accurately when to start a turn that should end on the runway heading. Regrettably, the pilot did not start the turn immediately, but ≈ 30 seconds later, at 17:34:08 with a bank angle of 25° to the right at an airspeed of ≈ 272 kt initially (event ⑬ in Figure 11 above). This was the second time the pilot did not follow the heading instructions of the ATC controller. Because of this delayed turn, he would not be able to adjust and establish on the localizer, on the extended centerline, at the desired distance and altitude to guide him straight to the threshold of runway 27.

5.5.7. Despite the attained bank angle of 25° to the right, the radar ground course did not increase at the same rate as before (from event ⑬ in Figure 11). This might have been caused by the decrease of the rudder deflection to ≈ −10°, as shown in Figure 18 (event ②) from time 17:33:45 to 17:35:15; the pilot obviously accepted a larger sideslip. At 17:34:18, ATC reported: *"El Al 1862, you're about to cross the localizer due to your speed, continue the right turn heading 290, heading 290, 12 track miles to go"*. The crew responded right away *"Roger 290"*. Twenty seconds later, ATC directed "*El Al 1862 further right, heading 310, heading 310*", which was confirmed with *"310".* The ATC controller provided heading instructions to direct the airplane to intercept the localizer from the South as soon as possible and furthest away from the runway, following the delayed turn that started at event ⑬ in Figure 11, rather than at ⑫.
A continued turn towards the extended runway centerline from the South, followed by a left turn to establish on the localizer, on the extended runway centerline, might have been possible, but would have ended at less than 6 nm from the runway threshold.
ATC anticipated this shortcut given its message 10 seconds before 17:34:58 (before event ⑭) "*Continue descent 1500, 1500*". The pilot responded "*1500 and we have a controlling problem*" (at 17:35:03). ATC had approved to continue the descent to 1,500 ft (at 17:34:58, 10 seconds prior to event ⑭) to account for the shorter distance than 6 nm to the runway. The airplane would be able to descend from 2,800 ft to 1,500 ft when reaching the extended runway centerline at a distance of less than 6 nm, but have little time to stabilize the airspeed at the landing reference speed and descend on the 3° glideslope.

5.5.8. A final turn to the left from heading 310°, to establish on the localizer at 1,500 ft would not have been a safe turn; the required bank angle would have been too large. As explained above in § 3.3.4, a turn into the good engines increases the sideslip angle from that side. Rudder deflection into the good engines is initially required to counteract the asymmetrical thrust. The camber of fin with rudder is then maximum; the horizontal angle of attack of the fin with rudder might easily increase above the stall angle of attack of the fin with rudder, resulting in a fin stall. As explained and shown in the data of Figure 6 top right side on page 19, the pilot would need to maintain quite a high speed when the thrust is increased, and reverse the rudder deflection for bank angles > 5° for maintaining the equilibrium of forces and moments. The pilots were certainly not trained to know and do this. The airplane would have crashed during that turn.

5.6. The Loss of Control

5.6.1. Then, at 17:35:08 (⑭ in Figure 11 and Figure 15), while the airplane continued its final right turn with a bank angle of ≈ 25° at an airspeed of ≈ 260 kt (ground speed 280 kt due to wind 050°/ 22 kt), and despite his report to ATC that they had *"a controlling problem"*, the pilot increased the thrust of both left-wing engines from EPR 1.3 to peak at the maximum level of 1.73 (Figure 15), but decreased to 1.65 within 7 seconds. The reason for this increase is unclear; the airplane was descending to 1,500 ft and passing an altitude of 2,800 ft, so there was no need to level off and increase the thrust yet. The engines reached the maximum EPR 15 seconds later, the rudder deflection increased to −20° (Figure 18, ②), the aileron wheel to −90° (Figure 15, ⑮), indicating that a large counteracting rolling moment was required.

5.6.2. The large increase of asymmetrical thrust while the airplane was banking 25° (as shown in Figure 16), increased the lateral and directional forces and moments acting on the airplane considerably. The already large opposite aileron and rudder inputs could not be increased any further anymore to counteract the increasing aerodynamic forces and moments at the maintained airspeed of 260 kt and the large asymmetrical thrust level; a higher airspeed would be required. The bank angle continued to increase (Figure 15 from event ⑭), despite a large opposite aileron input; lateral control was lost.

5.6.3. As the EPR increased (① in Figure 18), so did the rudder pedal input (②) to counteract the thrust yawing moment. As shown, the rudder surface deflection did increase and reached the maximum 8° (③) as allowed by the rudder ratio system (Figure 17) during the final seconds of flight at an airspeed of 260 kt, although the EPR, and therewith the thrust yawing moment, had already decreased (④).
The more accurate FDR heading and other data should confirm whether directional control at the speed flown (260 kt) could be maintained or was lost as well.

5.6.4. The large required aileron input of average 60° to the left prior to increasing the thrust was an indication that the lowest airspeed which can be obtained with full lateral control deflection was not much lower than the current airspeed of 260 kt (§ 3.1.15). A higher airspeed would be required for generating larger counteracting forces and moments by ailerons and rudder to be able to maintain control when the thrust would be increased above EPR 1.3. In other words, the *actual* V_{MCA2} had already increased to a value just below the airspeed, before the thrust was increased.

5.6.5. The large increase of thrust, while banking 25° into the 'dead' engines, had increased the *actual* minimum control speed for two engines inoperative (V_{MCA2}) to a value higher than the airspeed of 260 kt of the airplane at that instant, as predicted in § 3.3. The consequence was unexpectedly devastating: the control of the airplane was lost because the control forces and moments generated by aileron and/or rudder at the current airspeed were not large enough to maintain the equilibrium of lateral and/or directional forces and moments that acted on the airplane.
The captain ordered flaps up at 17:35:25 while going down, but that would lock-out the only remaining left outboard aileron, decreasing the roll control power and hence, decrease the lateral controllability even more.

5.6.6. After advancing the thrust levers of engines 1 and 2, the bank angle increased with an average, not very high, rate of 1.8 degree per second from 22° to 105° (in 45 seconds time), despite the large opposite control wheel input (Figure 15, ⑮). Although the FDR heading data needs to be reviewed, the ground path of the airplane suggests that the heading obviously could not be maintained either with an increasingly large, but probably not maximum opposite rudder pedal input (21°, Figure 18, ②).

The turn with a large 25° bank angle into the dead engines, the high weight of the airplane, as well as the increasing thrust had increased the *actual* V_{MCA2} to a value above the current airspeed of 260 kt, rendering the airplane uncontrollable with the maximum rudder and aileron deflections (§ 3.3 above). Side force W·sin ϕ increased with the increasing bank angle to the maximum (sin 90° = 1), being as large as the weight W of the airplane (while the vertical wings did not provide any vertical lift component). The airplane accelerated sideward to the ground. The vertical speed at 800 ft altitude, just prior to the impact, was ≈ 6,643 fpm[11] (ref. 2, Fig. 51; ≈ 65.6 kt); the forward speed increased to ≈ 295 kt at the end of the recording (ref. 2, Fig. 58), hence the airspeed vector, i.e. the flight path (not the direction of the longitudinal axis) of the airplane at 800 ft, was at an angle of ≈ −12.5° to the horizon ($\tan^{-1}$ 65.6/295). These data need to be verified with original FDR data, if required. Gravity pulled the airplane down towards the earth; the bank angle had increased to a little further than vertical (105°, Figure 15), when the FDR-recording ended.

5.6.7. The airplane collided with an apartment building in an Easterly direction. For the consequences of this collision, the reader is referred to ref. 1.

5.7. Other Findings Control and Performance

5.7.1. ***Landing Weight*.** The crew started jettisoning (dumping) fuel shortly after the separation of the engines in an attempt to reduce the weight of the airplane before landing to below the Maximum Landing Weight (MLW). This MLW is included in § 4.2.2 above (630,000 lb or 285,763 kg), but should be verified with the AFM, that was not yet made available. The fuel jettison rate of a Boeing 747 is max. 2,000 kg/min., meaning that more than 30 minutes would have been required to reduce the weight of the airplane to MLW or below. As the pilots returned nearly immediately after the separation of the engines for landing, they might have considered an intentional overweight landing and hence a much higher landing speed, which would have reduced their survivability. The fuel jettisoning might have continued until the airplane crashed; witnesses testified that kerosine landed in their yard. The minimum altitude for jettisoning fuel is 6,000 ft, except in emergencies.

5.7.2. *Wind for Landing*. The maximum approved tailwind (component) during landing for a Boeing 747 is 10 kt. The ATC reported wind at 17:29:58 UTC was 050°/ 22 kt, hence a tail wind component in the direction of runway 27 of 17 kt, which is too high a tailwind component for a landing. Such a tailwind increases the ground speed, which would already be higher due to the loss of two engines ($>V_{MCA2}$ + (wind) additives). The required runway length to bring the airplane to a stop, when it would survive the high weight high-speed touchdown, would be much longer. The AFM was not available to calculate the landing distance.

5.7.3. ***Demo Wing Weight Imbalance in a Boeing 747 Simulator*.** Capt. Rinsema, a retired KLM flight instructor, told that within a week after the accident, he and his crew evaluated the effects of the loss of two engines in a Boeing 747-200/300 flight simulator by maintaining a wing fuel imbalance of 22,000 lb (10,000 kg), equivalent to the weight of two engines plus pylons, and a simulated damaged right-wing leading edge. It is not known whether inoperative control surfaces were also simulated. They experienced that the simulated airplane, in this configuration, became uncontrollable when the airspeed decreased below 238 kt. The *actual* minimum control speed in this simulator had obviously increased to a value of 238 kt. The rudder and/or aileron deflections were maximum; no additional rudder and/or aileron deflections would be available at lower speeds

[11] The altitude decreased in 14 seconds time from 2,400 ft to 850 ft. Then the Rate of Descent was 110.7 fps, which is 6642.8 fpm or 65.6 kt.

to counteract increasing adverse forces and moments acting on the airplane due to the asymmetrical thrust, unbalanced weight of the wings, and the wing damage. This, in fact, is also a definition of the minimum control speed, but in other words.

5.7.4. ***Demo Controllability TEI in a Boeing 747 Simulator*.** After the presentation of a paper on the controllability after engine failure of a Lockheed C-130 for the Netherlands Association of Aeronautical Engineers (NVvL), Avio*Consult* was invited by the Netherlands Airline Pilots Association (VNV) to also present the paper to their Flight Safety Committee on 19 Sep. 2000. The paper was amended to be more suitable for the Boeing 747 audience. During a visit to the training center to collect relevant 747 AFM engine-out data, a 747-300 simulator ride was made possible that was used to demonstrate the increase of V_{MCA} during turns. The flight instructor was convinced that the airplane was capable of turning at an airspeed as low as V_{MCA2} while two engines on one wing were inoperative and the other two at maximum thrust, but when asked to initiate the turn in the direction of the dead engines, he could not maintain control of the airplane and crashed (in the simulator). His only word was "damn" in a murmur when it happened. A lesson was learned, but most probably not passed on. During the VNV-presentation that was attended by many airline captains, most were not impressed – no relevant questions were asked.

5.7.5. ***ATR-72 Simulator***. A few years ago, I was asked by two ATR-72 Flight Instructors in different countries to review their AFM and Performance Guide on engine-out control and performance, because they were concerned that the recommended takeoff and other airspeeds were less safe than should be expected. They were right, the manuals were not written with care. I sent a copy of my review to ATR, but received no response. The review is available for download (ref. 25). One of the instructors showed me in a simulator of a well-known manufacturer that the rudder control input required after failure of engine 1 and 2 was the same, rather than opposite. This simulator was obviously not evaluated with care and knowledge either.

5.8. Findings of Review of Several Boeing 747 Pilot Manuals

5.8.1. ***Introduction***. Part of any accident investigation should also be the review of the AFM of the mishap airplane and of other manuals that are in-use for operating the airplane, such as the company Aircraft or Airplane Operating Manual.
The FAA approved manuals that are required for operating the Boeing 747 airplane are listed by document numbers in the Type Certificate Data Sheet (TCDS). This data sheet, which is a part of the Type Certificate, prescribes conditions and limitations under which the product for which the Type Certificate was issued meets the airworthiness standards of the Federal Aviation Regulations. The TCDS of the El Al Boeing 747-258F (ref. 21) refers on page 4 to the FAA Approved Weight and Balance Control and Loading Manual (WBCLM): D6-13700, and to the FAA Approved Airplane Flight Manuals: D6-13703, D6-33747, D6-35747, D6-34747. The airplane cannot be considered airworthy if any of these approved manuals were not in use by the operator.

5.8.2. Neither of these manuals were referenced in the accident report (ref. 1). The inventory of this accident in the NASB archives do not include these either. Rather than these El Al Boeing 747-200 manuals, a copy of the KLM Aircraft Operations Manual (AOM) 747-206B/306 resides in the accident archives, and is referenced in ref. 1, so this manual might have been used (inappropriately) by the accident investigators. A company AOM is not approved by authorities to be used for operations with an airplane. In addition, the KLM Boeing 747 is equipped with engines that have a different thrust level output, and there might be other differences that have effect on lateral and directional controllability as well, meaning that the minimum control and other safety speeds are different from the

El Al Boeing 747. In the KLM AOM, neither the definitions of minimum controls speeds, nor the values of V_{MCA} and V_{MCA2} are included.

5.8.3. Many airlines and other operators write and use their own Aircraft/Airplane or Flight Crew Operating Manuals, or Pilot Operating Handbooks which might not be subject to review by Approving Authorities either. Such manuals describe, in detail, the characteristics and operation of the company airplane and its systems. When these manuals do not comply with the formally reviewed and approved parts of the flight and loading manuals, which are defined in the TCDS of the airplane, and with certification requirements and limitations, operations with the airplane cannot be considered airworthy either. Writing and reviewing piloting manuals requires high-level multi-disciplinary knowledge, ref. 31.

5.8.4. ***British Caledonian Boeing 747-200 Operations Manual.*** As the AFM of the El Al Boeing 747 was not available for review, this Boeing 747-200 Operations Manual (ref. 7) could be retrieved from the Internet, although differences for control and performance and for safety speeds could exist (because the engines are of a different type, with different thrust output). The El Al Boeing 747 manuals should still be reviewed when made available.

5.8.5. A definition of V_{MC} or V_{MCA} was not found, these were not included in the List of Abbreviations (00.10.05), either. Only V_R and V_2, that are calculated using $V_{MC(A)}$, were included. V_{MCA} was used in two-engine-inoperative procedures though (pages 02.10.05, 02.20.07, and 02.30.01), but was not called V_{MCA2}.

5.8.6. The crosswind limit during landing this airplane is 20 kt, the maximum approved takeoff and landing tailwind is 10 kt; Flaps 1 limit speed is 235 KIAS (page 01.10.01).

5.8.7. The condition 'severe damage or *separation* of engines' is recognized by the fire warning bell ringing and an engine fire warning light illuminated and/or airframe vibration with abnormal and/or inconsistent engine instrument indications with yaw (02.20.01). The engine emergency checklist for engine fire, *severe damage or separation* requires the flaps up, and a minimum airspeed of 280 KIAS (02-10-2).

5.8.8. The V_{MCA2} (straight flight, 5° bank) is 143 kt resp. 157 kt (for -7A respectively CF6-50 engines) to commit height (02.10.05). V_{MCA2} was obviously still presented, which is good, although FAR/CS 25.149 do regrettably not require manufacturers to publish a V_{MCA2} for two inoperative engines (n-2) anymore, as was mentioned before, while failure of two engines on the same wing obviously still occurs. V_{MCA2} already applies when one engine is inoperative, in anticipation of a second failure.

5.8.9. The Two Engines Inoperative emergency checklist (02.20.06) includes: 'Fuel Jettison (if required) – Complete', to reduce the landing weight to minimum possible.

5.8.10. On page 02.30.01, a CAUTION: 'On any Two Engine Inoperative Approach do not reduce speed below V_{MCA} before the commit point of 500 ft AAL'.

5.8.11. On a sample landing data card for two engines inoperative, for a weight of 227,000 kg, the maneuver speed with flaps up is 243 kt, with flaps one 203 kt (04.32.04A). Maneuver speed is the maximum speed at which large and abrupt control inputs may be applied by the pilot. At higher speeds, structural limits may be exceeded during such control inputs.

5.8.12. ***Relevant Findings***. V_{MCA} and V_{MCA2} were not appropriately defined and explained in this manual. The landing tail wind on runway 27 would be too high. The flaps were selected at a speed (285 kt) above the limit of this manual (235 kt). The minimum required airspeed of 280 kt was not maintained during the critical phases of the return flight. Jettisoning fuel to reduce the weight to below the Maximum Landing Weight was not com-

pleted, as required in the checklist. The pilots used large, up to the maximum control input travel at a speed higher than the maneuver speed (203 kt) of the airplane.
It is obvious that the El Al pilots exceeded limits of this manual, which might differ from the manual of their airplane, and did not follow all items of their (emergency) checklist that must have been similar to the checklist described above.

5.8.13. ***KLM Aircraft Operations Manual 747-206B/306.*** This manual was briefly reviewed because it was obviously used by the accident investigators.

5.8.14. *§ 2.8.1 Max. wind components*. When hydraulic systems 3 and 4 are inoperative, the crosswind limit is 20 kt, the tailwind limit is 10 kt, both further affected by runway- or weather conditions.

5.8.15. *§ 2.8.2 Speed limitations*. In this AOM chapter, neither V_{MCA} nor V_{MCA2} are listed as airspeed limitation, while Regulations require V_{MCA} to be published in the AFM, obviously for pilots to be made aware of. If pilots don't use the AFM, but only their company AOM, the AFM-required limitations should be included in the AOM. V_{MC}'s are used to calculate rotation speed V_R and takeoff safety speed V_2, which are published in the AOM, but not the limitations and conditions for which the used V_{MCA}'s are valid (straight flight, bank angle 3° to 5° away from the inoperative engine(s) when maximum thrust), and consequently for which the listed V_R and V_2 are valid as well, because these are only 5% resp. 10% higher than V_{MC} (more conditions apply). AOMs should be reviewed as well for critical content, not only after an accident, but also to be approved for use by pilots.

5.8.16. The maximum speed for extending flaps to position 1 is 275 kt, to position 5 is 255 kt. The max. speed for gear extension is 270 kt. These flap speed limitations are higher than for the British Caledonian Boeing 747.

5.8.17. § 6.4.17, Sub § 1.2, Control when two engines inoperative. "With two engines inoperative on one side, the combination of low speed and high thrust should be avoided. V_{MCA} is established at sea level under standard day conditions using full take-off thrust on two engines on one side. Full rudder is used and a 5° bank towards the operative engines. The certified value is 157 kt. Since a go-around will not be executed at a speed below mid bug, V_{MCA} will not be a problem".

This paragraph is basically correct; V_{MCA2} is indeed established using full takeoff thrust on one side, but at a safe altitude and then extrapolated to sea level, ISA. Missing here is the utmost important condition for pilots that the certificated value of $V_{MCA(2)}$ is valid only during straight flight, while maintaining 5° bank away from the inoperative engines (for lowest $V_{MCA(2)}$ and minimum sideslip, hence drag). As mentioned before, a V_{MCA} applies always, during takeoff, climb, cruise, approach, go-around, and landing, not only during go-around. Both V_{MCA}, after failure of one engine, and V_{MCA2} will indeed be a problem when straight flight is not being maintained while the thrust is maximum. V_{MCA2} (for a bank angle of 5°) is obviously 157 kt. The increase of $V_{MCA(2)}$ with bank angle is not mentioned in this AOM either.

5.8.18. § 6.4.17, Sub § 1.3, Go-around. "Apply thrust and simultaneously apply up to full rudder to ensure directional control, assisted if necessary by a slight bank towards the operative engines. Stop the power lever advance just prior to full rudder travel. When airspeed increases and excess rudder becomes available, advance the power levers to GA setting".

Also correct, except that a slight bank angle towards the operative engines does not assist directional control, but reduces the rudder requirement and decreases the *actual* $V_{MCA(2)}$, and decreases the drag, increasing performance, as shown in § 3.3 above. The small bank angle results in a small side force in the center of gravity that, when equal to the rudder side force required to counteract the asymmetrical thrust, results in a balance of lateral

forces; the sideslip, hence drag, will then be minimal, climb performance maximal. The rudder deflection is then solely for counteracting the thrust yawing moments.
Stopping the power lever advance just prior to full rudder during a go-around is a very good point, but also important is that when during flight the rudder is already (near) maximum, the asymmetrical thrust lever should not be advanced any further, or control will be lost. This not only applies to the rudder, but also to the ailerons. When a go-around becomes necessary, accelerate down the glideslope to a higher airspeed while increasing the thrust and the rudder for maintaining the heading, until the rudder pedal deflection is maximum, and then initiate the climb. Decrease the asymmetrical thrust (outboard engine) if the heading cannot be maintained with maximum rudder.

5.8.19. ***Relevant Findings***. V_{MCA} and V_{MCA2} are not published as limitation is this manual, neither is the maneuvering speed. The pilot selected Flaps 1 at a TAS of 285 kt, 10 kt above the limit of this Boeing 747 version. The tail wind limit in this manual would also be exceeded when landing on runway 27.

5.8.20. Pilots are not informed of the increase of $V_{MCA(2)}$ with bank angle, although the pilots are advised to *"stop power lever advance just prior to full rudder travel"*, during a go-around procedure, which prevents the *actual* V_{MCA} from increasing above the current airspeed for which full rudder is required, and therewith prevents the loss of directional control. The pilots of El Al 1862 should have known this advice; they advanced the power levers when the aileron and rudder controls were already near maximum.

5.8.21. **KLM Plane Facts Boeing 747, No. 352.** On page 2, maintaining an acceptable flight path "may require use of unusual techniques such as the application of full aileron or rudder or in an asymmetrical thrust situation, reduction of power on the operating engine(s) to regain lateral control. This may also require trading altitude for airspeed or vice versa. The objective is to take whatever action is necessary to control the airplane and maintain a safe flight path. Even in a worst-case condition where it is not possible to keep the airplane flying and ground contact is imminent, a ’controlled crash’ is a far better alternative than uncontrolled flight into terrain". Good text, regrettably not all pilots and accident investigators read and understand this.

5.8.22. Page 3, Procedures. "After flight path control has been established, accomplish the recall steps of appropriate non-normal procedures. The emphasis at this point should be on containment of the problem and not on configuring the airplane for an immediate landing. Examples of this type of checklist include 'Engine Fire, Severe Damage or Separation', 'Multiple Engine Flameout or Stall', or 'Rapid Depressurization'". Good as well.

5.8.23. There are many more good advices on maintaining the controllability in this copy of Plane facts.

5.8.24. On page 2 of 4, in § 5: "Stall speed increases with angle of bank and Increasing load factors. Therefore, it is prudent to limit bank to 15° in the event maneuvering capability is in question".
The increase of the stall speed is only 2 – 3 kt with 15° of bank. However, the increase of V_{MCA} with bank angle is much larger, can be 90 kt per 15° of bank, and is not mentioned. The El Al pilots experienced such an increase. This increase was also demonstrated in a KLM 747 simulator, see § 5.7.4 above.

Bank angle	V_{MCA}	
	one engine out	two engines out
5°	114	155
0°	146	191

Table 1. V_{MCA} in KLM DC-8-50 Flight Crew Reference Guide, 1988, bank angle zero and 5° away from the inoperative engine.

5.8.25. ***KLM Flight Crew Reference Guide***. The V_{MCA}'s of a DC-8-50, also a 4-engine turbofan airplane, were published in § 1.3.2 of the KLM Flight Crew Reference Guide (FCRG – ref. 22) of 1988, as shown in Table 1 above.
This table confirms that the effect of bank angle is indeed large for this swept-wing airplane; V_{MCA} with one engine inoperative when the wings are kept level is 32 kt higher than published V_{MCA} (which is determined with a 5° bank angle into the good engines for smallest sideslip, hence lowest drag, and max. climb performance). The published V_{MCA} when two engines are inoperative (V_{MCA2}), which is also determined with 5° of bank into the good engines, is 155 kt and increases to an *actual* value of 191 kt when the wings are kept level. The *actual* V_{MCA2} at other bank angles into or away from the inoperative engines will be much higher than 191 kt for a DC-8, as might have become clear in the analysis presented in § 3.3.3 above and shown in the adjacent Figure 20 for a turn into the good engines. This figure confirms what is shown in the calculated Figure 6 on page 19 above, for engine #1 inoperative.
This (quite good) KLM manual also states: "*Bank towards the operating engine (s) must not be exaggerated. On aircraft with wing-mounted engines V_{MCA} decreases 6 to 7 kt/degree of bank up to a bank angle of 5°. Above 5° bank the reduction in V_{MCA}/degree of bank is smaller and at 8-10° bank, V_{MCA} starts to increase rapidly due to the start of flow separation at the vertical tail caused stall and consequently loss of control. A bank towards the wrong side, i.e. towards the dead engine(s) will increase V_{MCA} by a similar and even higher rate; 5° bank towards the wrong side can increase V_{MCA} as much as 60 to 80 kt above the certified V_{MCA}*". This manual confirms the effect of bank angle on V_{MCA} presented in § 3.3 of this analysis. Regrettably, the accident investigators and board members (many of them were airline pilot) did obviously not know, understand, and review this manual.
Although not mentioned, it will be obvious that the airspeed for maintaining control during banking requires to be increased to an airspeed higher than $V_{MCA(2)}$ plus its increase due to banking, i.e. higher than the *actual* $V_{MCA(2)}$.

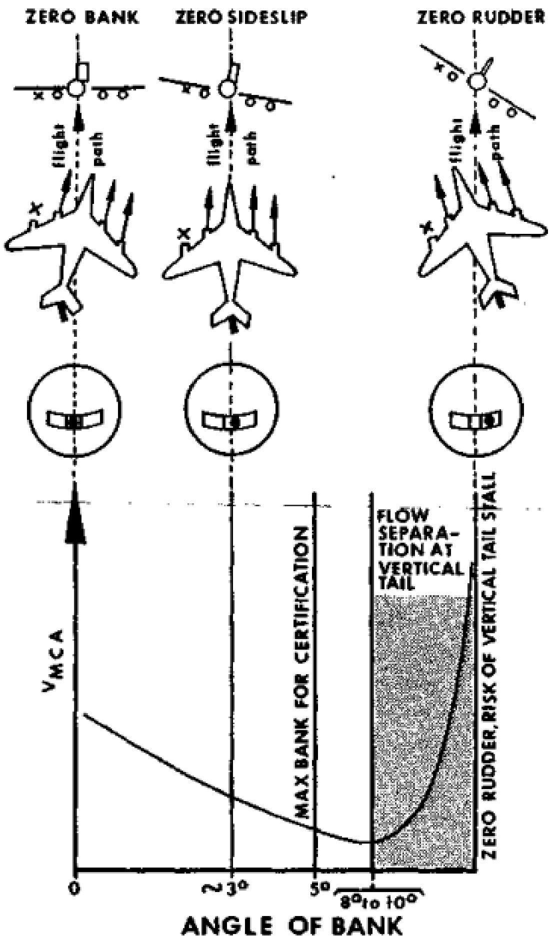


Figure 20. V_{MCA} versus Angle of Bank, Engine #1 inoperative, KLM DC-8-50 Flight Crew Reference Guide, 1988.

5.8.26. ***Relevant Findings***. This KLM publication proves that in 1988, KLM pilots were still made aware of the increase of the AFM-published V_{MCA} to a much higher *actual* value when banked away from the favorable bank angle of 3° for this airplane. The huge effect of weight was regrettably not adequately included as Lockheed did for the C-130 (§ 3.3.8). This contributed to the challenge of the author of this analysis to calculate not only the *actual* V_{MCA} at other bank angles than 0° and 5° into and away from the good engines, but also the effect of weight, as presented in § 3.3 above.

6. Conclusions Boeing 747 accident

6.1. Conclusions

6.1.1. The findings, causes and contributing factors established in this report, which are limited to controllability, handling, and performance, are listed below and include both the immediate and the deeper systemic causes. Please refer to the accident report (ref. 1) for the other findings, conclusions, and recommendations.
The conclusions are written a bit longer than usual to ensure that readers who have no engineering background, or who quickly 'jump' to the conclusions, rather than reading the whole technical report, are still offered thorough explanation, and also because this report is about unknown, lost, and/or forgotten knowledge that caused this fatal accident and that resulted in many imperfect reports of accidents after engine failure which did not improve the safety of flight. Nobody wants to get killed or lose loved ones because the pilots were not made aware anymore on how to control an airplane after engine failure. Paragraph numbers between parenthesis refer to the analyses of the subjects above.

6.1.2. The takeoff from runway 01L and the climb performance of the Boeing 747 before the separation of the engines were adequate, and in accordance with the rules (§ 5.2).

6.1.3. During climb-out, at an altitude of approximately 6,500 ft, both engines with their pylons separated from the right wing due to a fuse pin failure in the pylon of engine 3 (§ 5.4.1). The crew started a turn back to the airport within 28 seconds, rather than analyzing the emergency and the condition of the airplane first, and plan and prepare for a safe return, which would take more than 28 seconds (§ 5.5.2). The pilots did not wait until the fuel jettison was complete for the airplane weight to decrease below the Maximum Landing Weight, which would take at least 30 minutes (§ 5.7.1).

6.1.4. When dispatched for the flight, the mass and center of gravity of the airplane were within the prescribed limits, but after the separation of both engines off the right wing, the center of gravity shifted ≈ 1.74 ft (≈ 53 cm) to the left, and the combined lift vector of both wings shifted to the left as well because of the loss of lift due to damage of the right wing (§ 5.4.10). The large required aileron input to the left, needed to counteract both the shift of the lift vector and the lateral forces and moments due to the asymmetrical thrust, reduced the remaining aileron control power (to the left) considerable during the remainder of the flight (§ 5.4.11), even while the airspeed was 260 kt or above.

6.1.5. Despite the loss of thrust and weight of two engines, the damaged right wing, and the limited hydraulic power for actuating the remaining control surfaces, the equilibrium of forces and moments (aka controlled flight) could be maintained using large aileron and rudder deflections though, while the thrust of the left-wing engines 1 and 2 was between EPR 1.30 and 1.55, though less than the maximum available EPR 1.72 (§ 5.4.14). Lateral control was seriously hampered, because only less than 50% of the lateral control surfaces remained available (§ 5.4.2). Nevertheless, the airplane continued to be controllable for 8 minutes and completed 1½ turn with this limited control power during which it descended controllable; the airspeed was obviously high enough for the aerodynamic control surfaces ailerons and rudder to generate the required forces and moments to counteract both the asymmetrical weight due to the loss of two engines, the loss of lift of the damaged wing, and the less than maximum asymmetrical thrust of engines 1 and 2. The equilibrium of forces and moments could be maintained (§ 5.4.17).

6.1.6. The maximum approved tailwind (component) during landing of a Boeing 747 is 10 kt. ATC reported a ground wind of 050°/ 22 kt. The runway in use for landing was runway 60. The crew however, requested runway 27 for landing which would result in a tailwind during landing of 17 kt, higher than the maximum approved 10 kt by the aviation authorities for a Boeing 747 (§ 5.7.2). They were too close to this runway and too high for an immediate landing on runway 27 and needed an additional descending approach pattern.

6.1.7. During the outbound track to the East in a pattern to descend to 2,000 ft and to position the airplane for the two-engine inoperative 12 nm final approach to runway 27, in compliance with the two-engine inoperative approach procedures in the Airplane Flight Manual, the pilots did not follow the heading instructions (the vectors) given by the ATC controller, twice (§ 5.5.5, § 5.5.6). Instead, the pilots turned from heading 100° to 120°, to the South-East, staying closer to the airport, and also delayed the ATC recommended final turn for 30 seconds, too long. As a consequence, this turn ended too far south of the extended runway centerline and at too short a distance from the runway (Figure 11, ⑭). The ATC controller continued to provide heading and altitude guidance for the pilot to still establish on the extended runway centerline and capture the 3° glideslope but now at a shorter distance of 4.5 nm from the runway threshold at an altitude of 1,500 ft (§ 5.5.7). Stabilizing on the glideslope immediately following a final turn to the left, into the operating engines, and decelerating to the final approach speed at this short distance would have been a challenge (§ 5.5.8). The crew selected the wrong runway for approach and landing, and did not conduct the approach in compliance with the emergency procedures.

6.1.8. During the continued descending right turn towards the extended runway centerline with a bank angle of 25°, away from the operating engines, while the airspeed was ≈ 260 kt, the aileron control wheel deflection required to maintain that bank angle was an average of 60° to the left, implying that the airspeed of the airplane was almost too low to maintain the equilibrium of lateral control forces and moments at this bank angle due to the current (less than maximum) asymmetrical thrust setting, the loss of weight of two engines, and the damage of the right wing. The lowest airspeed at which control can be maintained with maximum aileron and/or rudder deflections, in other words the *actual* minimum control speed when two engines are inoperative (V_{MCA2}), had obviously already increased to a value almost as high as the current airspeed of 260 kt (§ 5.6.4).

6.1.9. Then, during the continued 25° banked right turn, and despite the near maximum aileron and rudder control inputs, the pilot increased the thrust of both left-wing engines. Engine #1 reached maximum (EPR 1.72) while engine #2 lagged behind. The increase of asymmetrical thrust caused the bank angle to increase from 25° to 105° to the right in ≈ 12 seconds' time (⑭ in Figure 15). The increased opposite aileron control wheel deflection to −90°, to the left, and the rudder pedal input to −20° to the left as well, to counteract the increasing bank angle, came 15 seconds later, and could not prevent the bank angle from increasing any further. The airspeed was obviously too low for the ailerons and rudder to generate the larger forces and moments required to counteract the increased forces and moments due to the increased asymmetrical thrust of both left-wing engines, and the other adverse forces and moments acting on the airplane; lateral control of the airplane was lost.
The lowest airspeed required to maintain control with full lateral (and/or directional) control deflection at the maximum asymmetrical thrust setting was obviously higher than the current airspeed of 260 kt. In other words, the *actual* V_{MCA2} of the airplane had increased to a value higher than the current airspeed (§ 5.6.2). The power levers advance should have stopped prior to reaching full control travel while the airplane was banking (§ 5.8.18). If the pilots had known about the conditions for which the published minimum control speeds of their airplane are valid, i.e. straight flight while maintaining a small ≤5° bank angle into the good engines, they might not have increased the thrust during the turn. Increasing the thrust on the two left-wing engines during the turn sealed their fate.

6.1.10. Increasing the thrust during banking, while the control wheel was already rotated ≈ 60° to the left, proves that the pilot did not at all realize that the *actual* lateral V_{MCA2} had already increased to only a few knots below the current airspeed of the airplane, as caused by the bank angle (Figure 6 on page 19 above). Maybe he never heard of an increasing or of a lateral minimum control speed (§ 3.2.2).
The pilots were obviously never made aware of the huge effect of bank angle on $V_{MCA(2)}$ (§ 3.3). Their knowledge and understanding of the controllability of the airplane after engine failure was inadequate. Although the flight crew members were properly licensed and qualified for the flight in accordance with existing regulations, as stated in ref. 1, they obviously fell short on the knowledge of, and experience with flying safely while engines are inoperative. However, the pilots are not to blame, as will be concluded below.

6.1.11. It could not be determined whether the flight was conducted in accordance with the (emergency) procedures in the Flight Manual of the Airplane and/or Operations Manual of the company, because these manuals were not available. It is obvious though, that the standard operating procedure for handling the airplane after the loss of thrust of two engines on one wing was either not followed, or not effective in preventing the loss of control.
In the engine emergency procedure of a comparable Boeing 747-200 manual, the minimum airspeed to be maintained '*after engine fire, severe damage, or* ***separation of engines'*** needs to be 280 kt with flaps up (§ 5.8.7). The maximum flaps extend speed was 235 kt (§ 5.8.6). If these speed limits would also have applied to the El Al Boeing 747-258F, they were not observed by the pilots.

6.1.12. The operator, the pilots, their training organization, the investigators of the NASB, the participating accredited representatives of other Safety Boards, of manufacturers and of aviation authorities involved in the investigation were obviously neither aware of the flying qualities, of the limitations, and of the flight restrictions that apply after engine failure, nor of the real value of the published minimum control speeds of a multi-engine airplane.
The NASB did not include any words on, or the value of $V_{MCA(2)}$ in their final report, let alone conclude that the published V_{MCA2} of the airplane was valid only during straight flight, while maintaining a small bank angle ≤ 5°, as opted by the manufacturer, into the operating left-wing engines, and at maximum asymmetrical thrust level. Pilots consider V_{MCA} to be as low as the published value during the whole flight and hence, consider V_{MCA} of no importance, except during takeoff. They were not aware that V_{MCA} increases while banking, while this was still clearly explained in KLM manuals issued in 1988 (§ 5.8.25). They were not the only ones; nearly all involved in piloting, and in investigating the controllability of this and more than 400 other reviewed engine-failure accident reports across the globe (§ 2.1), 'suffered' from unknown, lost, or forgotten knowledge, which is to be considered a **very serious systemic error of global concern**.

6.1.13. If the operator supplied the flight crew with an Airplane Operating Manual (AOM), rather than with an Airplane Flight Manual (AFM), and did not copy V_{MCA} and V_{MCA2} data and their proper definitions and limitations that apply to pilots into this manual, then the consequence is that pilots might never be made aware or reminded of the real value of V_{MCA} (as defined in FAR/CS 25.149, § 3.4.2) and of V_{MCA2} (§ 5.8.17). The manuals and procedures used by the pilots were most probably not reviewed adequately by competent reviewers and inspectors before issue, and by investigators after the accident; this was not mentioned in the report (ref. 1). See also ref. 31.

6.1.14. There was no pitch control problem, despite the limited elevator control power after loss of hydraulic power of engines 3 and 4. FDR data should be reviewed to draw conclusions on probable pitch control limitations, if any (§ 5.4.23).

6.1.15. Neither the quality assurance system, nor the flight training organization of the operator had obviously identified the shortfall in engine-out procedures and training, which do not comply with airplane certification regulations and specifications (§ 3.4). The accountable civil aviation authority's safety oversight of the operator's procedures, operations, and flight training was obviously inadequate as well. However, this is not to be blamed to this operator, it is a shortfall of **global concern** as well.

6.1.16. The plot showing the ground track of the airplane in the accident report (ref. 1, appendix 3.1) was corrected and plotted using the FDR-recorded heading of the airplane and the wind data. With these data, the wind correction angle (the drift angle) and therewith the ground course of the airplane was calculated and the ground track reconstructed. The FDR-recorded heading however, includes the sideslip angle due to the asymmetrical thrust, which can be quite large. Hence, the ground course calculation was inappropriate and cannot be accurate. Sideslip angle and drift angle are definitely not the same (§ 5.3.2).

6.1.17. The analysis of the controllability of airplanes, and the drafting of accident-preventing conclusions and recommendations requires not only flight experience, but also high-level academic engineering knowledge which many pilots, accident or air safety investigators and rule makers regrettably seem not to have (anymore). Adequate knowledge seems forgotten or was not passed on to the younger generation of pilots and investigators, but is indeed required to make the right conclusions and determine the real cause of accidents. The engine-out training of multi-engine rated pilots and of accident investigators need to improved. The shortfall of knowledge is of **global concern** as well.

6.2. Contributing Factors of Global Concern

6.2.1. As mentioned in the introduction, this analysis was not only conducted to analyze the controllability of the Boeing 747-258 after the separation of both engines off the right wing, but also to draw renewed attention to the often-inappropriate crew response to propulsion system malfunctions, which was the real cause of more than 400 publicly reported accidents all across the globe during the past 25 years. The crew response was inappropriate because pilots were and still are not adequately made aware of the limitations and flight restrictions that are a consequence of the application of approved FAA and EASA certification regulations and specifications by manufacturers during designing multi-engine airplanes, small and large (Part 23 resp. Part 25, ref. 17 and 18).
To be more specific for an engine-failure case, regulations allow manufacturers to minimize the size of the directional and lateral control surfaces (rudder and ailerons), the consequence of which is that there is an airspeed below which the controls are no longer effective for maintaining the equilibrium of forces and moments acting on the airplane which is required to be able to maintain control when one or two engines fail, or is/are inoperative. This speed is called the Minimum Control speed in the Air, abbreviated V_{MC} or today more often V_{MCA}. As there are many factors that have influence on such an equilibrium, there are also many minimum control speeds (§ 3.1.10, etc.).

6.2.2. Regulations require only one V_{MC} to be published in the Airplane Flight Manual, which usually applies to the takeoff configuration, but in any case, only during straight flight while maintaining a small favorable bank angle, but less than 5° away from the inoperative engine, and while other variables than the bank angle that have influence on this speed are at their worst-case values, such as a low gross weight and a center of gravity longitudinal most aft and laterally into the dead engine, but within the approved envelope (§ 3.4.1). The small bank angle reduces both V_{MCA} and the sideslip angle to a minimum (§ 3.2.3 and Figure 6 on page 19). This is the standardized V_{MC} (§ 3.4.2), which is also used to calculate the takeoff rotation speed V_R and the takeoff safety speed V_2.

FAR and CS 25.1513 require that *"the minimum control speed V_{MC} determined under § 25.149 must be established as an operating limitation"*. But Regulations do not require manufacturers to include the small bank angle, for which this (standardized) V_{MC} is valid as an operating limitation. Pilots read in V_{MC} definitions that V_{MC} is determined during straight flight with maximum asymmetrical thrust, but are not made aware that the *actual* V_{MC} increases with bank angles to either side, and decreases when reducing thrust. They consider the published V_{MC} is always low and safe for maneuvering and do not hesitate to make turns when the asymmetrical thrust is or is increased to maximum, which turns a dead engine into a killing engine (§ 3.3.3).

6.2.3. Pilots are not adequately made aware to only maintain straight flight when the asymmetrical thrust is (increased to) maximum and to also attain the small favorable bank angle of 3° to 5° away from the inoperative engine(s). Maintaining wings level increases the *actual* V_{MC} already between 6 kt for a small commuter class airplane and 30 kt for a 4-engine transport above the published V_{MC}, if a small bank angle was indeed used by the manufacturer to determine V_{MC} (Figure 6). Neither pilots, nor accident investigators are made aware anymore of this huge increase in their Flight and Training Manuals, and during in-flight or simulator training (§ 3.3.3).
This often-unknown increase also affects the safety of takeoff speeds V_R and V_2 (with the wings level) that are calculated using the published V_{MC} (determined with a small bank angle). Keeping the wings level might increase the actual V_{MC} above the calculated V_R and/or V_2.
Regulations also suggest that V_{MC} is for the takeoff configuration and after a sudden failure of the critical engine only, while (an *actual*) V_{MCA} applies during the whole flight, both in anticipation of and after failure of any of the engines, as this accident and many other engine failure related accidents also prove (§ 3.4).

6.2.4. Most writers of Airplane Flight Manuals and Aircraft Operating Manuals and their reviewers/inspectors did not interpret FAR/CS 25.149 and 23.149 correctly (§ 3.4.2), and do not realize how V_{MC} is determined during flight-testing (§ 3.2). They wrote and approved inappropriate definitions of V_{MC} and/or V_{MCA} for pilots, without including its bank angle limitations and thrust effects which are of life-saving importance for pilots to be made aware of. See also ref. 31.

6.2.5. This also leads to the contributing factor that the approval of Flight Manuals by authorities falls short, also because the inspectors of FAA, EASA and equivalent organizations might not have the required high-level aeronautical engineering knowledge to conduct the reviews. Accident and/or air safety investigators do usually not review manuals adequately either, during an accident or incident investigation, which they should.

6.2.6. Thirty years ago, there were still pilot and training manuals with correct content about the characteristics of $V_{MC(A)}$, including the limitations that inoperative engine(s) impose on controllability (§ 5.8.25 above), but somehow this knowledge faded away, or was deleted by unaware flight instructors or other pilots lacking any engineering background, given this Boeing 747 and many more fatal accidents with small and large multi-engine airplanes after engine failure during the past 25 years. Errors in, or shortfall of manuals for pilots should be considered **deeper systemic errors that are of global concern**. Improvement is necessary for aviation to become safer. Therefore, closer attention was given to the inappropriate content of Airplane Flight and other pilot manuals. Avio*Consult* reviewed several flight, training, and other pilot manuals, including manuals of contemporary twin-engine airplanes used for multi-engine-rating training, and published the reviews on its website (ref. 23). The conclusion can be drawn inappropriate manuals contribute to fatal accidents.

6.2.7. FAR and CS 25.149 (ref. 17 and 18) do not require the minimum control speed when two engines on the same wing are inoperative (V_{MCA2}) to be determined and published in Airplane Flight Manuals (anymore). This requirement was deleted from these civil Regulations many years ago, but still exists in military regulations. A V_{MCA2} does not only apply after failure or separation of two engines off the same wing of a 4 or more-engine airplane, as was the case for this accident, but also when one engine is inoperative in anticipation of a second engine to fail on the same wing (§ 3.1.13). Deleting and/or excluding V_{MCA2} was and still is incomprehensible; V_{MCA2} was definitely required during the flight, descent, and approach of this Boeing 747.
The minimum control speed during approach and landing, V_{MCL2}, did not apply (if it existed in 1992), because the airplane was not yet in the landing configuration. However, during an approach when two engines are already inoperative and the required thrust is less than maximum, the *actual* V_{MCL2} will be very low. When a go-around becomes necessary, the thrust is increased to maximum and the flaps are selected up, after which V_{MCA2} applies, not V_{MCL2} anymore. The reason for determining and publishing a $V_{MCL(2)}$ is unclear.

6.2.8. Regulations FAR and CS 25 (and 23) which are intended for the certification of airplanes are also used by writers of airplane flight and other pilot manuals and by flight instructors. They then notice that the minimum control speed V_{MC} of their airplane may not exceed 1.13 times the stall speed (V_S), and teach this limit. However, this limit is for preventing the vertical tail from being sized too small, which is the reason why it is in FAR/CS 25.149, being the regulation for the certification of airplanes, not for their operational use. The V_{MC} as meant in FAR and CS is the V_{MC} during straight flight. When making turns while an engine is inoperative and the thrust is increased to, or is maximum, pilots will experience that the *actual* V_{MCA} will increase far above 1.13 V_S (but pilots who did, regrettably don't live anymore to testify) (§ 3.4.10).

6.2.9. Flight Instructors and pilots do not have to read and know these FAA/EASA Aviation Regulations, Certification Specifications, and Flight Test Guides to learn what the real value is of V_{MCA}, how V_{MCA} is determined, and what the flight limitations and restrictions are by design and flight-test. Regulations should require these limitations and restrictions, such as maintaining straight flight when the thrust is maximum, to be published appropriately with $V_{MC(A)}$ in flight and training manuals for pilots. More than 400 pilots who experienced an engine failure in the past 25 years did not hesitate to turn their airplane as soon as possible to return to the airport for landing, including the pilots of this Boeing 747, after which they not only lost control, but also their own lives and that of their passengers. They were not made aware to maintain only straight flight as long as the asymmetrical thrust is or needs to be maximum, and did not learn that they can control the magnitude of (the *actual*) V_{MCA} with bank angle and asymmetrical thrust level (§ 3.3.7).
This shortfall in Regulations and in Pilot Manuals is the real cause of most engine-failure related accidents.

6.2.10. As mentioned above, airline companies often issue their own Airplane Operating Manuals (AOM) in which V_{MC}'s and their definitions are not copied from the AFM, because the manual writers (and their reviewers) might not consider this of importance, despite the FAR/CS requirement mentioned in § 6.2.1 above that does apply to an AOM as well, if this AOM replaces the airplane AFM for use by pilots. An AOM is not subject to approval by authorities. Pilots using only an AOM might never get to see the V_{MC} data of their airplane, and do not read the real definition of V_{MC}'s (§ 3.4.13).
The airplane can in fact not be considered airworthy if the TCDS approved Airplane Flight Manual is not being used (§ 5.8.1). It could not be determined whether V_{MC}'s are properly addressed in the El Al Boeing 747 AFM and/or AOM, because these manuals were not available for review. If Airplane Operating Manuals are used, these should be subject to authoritative approval just like Airplane Flight Manuals.

6.2.11. The many engine failure accidents across the globe prove that multi-engine training seems not appropriate anymore, neither in training manuals, nor in simulators and in-flight. A pilot learns to respond to engine failures in small two-engines airplanes for the multi-engine rating. When this basic engine-out training is not appropriate, a pilot will not respond adequately to engine failures during the remainder of his or her career. If the training manuals and the flight manual of the training airplane are not appropriate either, the controllability of an airplane after engine failure might not be understood.
The simulators used for engine-out training should be capable of properly simulating the increase of V_{MCA} with bank angle in either direction; not all of them do (§ 5.7.5).

6.2.12. The definition of V_{MC} for the certification of airplanes in FAR/CS 25.149 or 23.149 (§ 3.4.2), which is for airplane design engineers and test pilots, is usually copied by manufacturers and flight schools/instructors straight into pilot manuals and training syllabi, while it should be amended for use by pilots (§ 3.4.13). The increase of (*actual*) V_{MCA} with bank angle (and thrust) is usually not mentioned in Airplane Flight and Training Manuals, except in Lockheed manuals (§ 3.3.8), and in an old KLM Flight Crew Reference Guide (§ 5.8.25), and perhaps in more manuals I am not aware of.
The guidance in pilot manuals on engine-out flight is inadequate. The review and approval of pilot manuals at a high aeronautical engineering level obviously fell short, because there might not be a requirement for manuals that are used by pilots for operating an airplane to be reviewed and approved by a team of competent aeronautical engineers and pilots.

6.2.13. Pilots believe they know all about airplanes (and the public believes they know it all), but many of them regrettably do not know (anymore) how to handle an engine-out airplane, and do not realize the large effects of asymmetrical forces and moments acting on the airplane when one or more engines is/are inoperative. Pilots are trained, qualified, and licensed to operate airplanes and follow airplane and air navigation procedures, and do that well, but might not be educated and qualified at a high enough level of aeronautical engineering to evaluate the controllability of airplanes, and to write and review flight training syllabi, flight manuals, and even to conduct accident investigations on the subject of airplane control after engine failure.
This was already more than 80 years ago the reason that test pilot schools were founded by the larger airplane manufacturing nations (UK, USA, FR) because too many expensive prototype airplanes and their crews were lost during flight-testing by incompetent flight crews. Test pilot schools teach performance, flying qualities, airborne systems, and flight test techniques at MSc level in a classroom and in-flight to highly experienced pilots and engineers, to be both able and qualified to flight-test and evaluate small and large, slow and fast airplanes, and to determine flight limitations, including during engine-out flight. Pilots without proper engineering education should not be considered qualified for writing flight critical definitions and procedures in Airplane Flight Manuals, and to contribute to accident investigations on the subjects of performance and flying qualities. Several experienced airline captains participated in the investigation of this and many more accidents, but did not draw the conclusions that a test pilot school graduate would do, and which are presented in this report.
Pilots do not need to be an engineer, but should be open to and consult engineering knowledge and expertise and not exclude engineers. There also is a reason why aspirant pilots need to have basic knowledge of forces and moments acting on a body prior to entering pilot training.

6.2.14. The NASB report of this accident (ref. 1) did not draw conclusions on the real cause of the loss of control, but only that "*current standard industry training requirements and procedures do not cover complex emergencies like encountered by El Al 1862*". The emergency was not that complex, because there even was an emergency procedure on the *separation of engines*. Nevertheless, as shown above in this report, the engine-out training and procedures indeed fell short, but the basics to cover complex emergencies are there, although these are not understood and correctly applied because flight instructors, authoritative inspectors and accident investigators do not have adequate engineering knowledge and understanding of engine-out flight. Of the 400 reviewed accident investigation reports, not a single one concluded the loss of controllability correctly, i.e. in compliance with the certification and flight-test requirements of the airplanes, nor recommended the appropriate measures to be taken to prevent such accidents. It requires high-level engineering knowledge to do so, not only flight experience. Pilots and investigators should realize:

Prerequisite for controlling an airplane is a high school diploma, for analyzing the controllability an engineering degree.

6.2.15. Many flight instructors and pilots publish papers and videos on the Internet, which are not complying with FAR and EASA Regulations and Flight Test Guides, and therefore is alarming. These people contribute to accidents rather than prevent them because they teach both improper knowledge and in-flight engine-out training. When Regulations and pilot manuals would be perfect, and provide a true and understandable explanation of engine-out flight, pilots would not refer to incompetent amateurs on the Internet.

6.2.16. Pilot training syllabi are often not in compliance with the real capabilities and limitations of airplanes during engine-out flight, and with the flight restrictions that come with V_{MCA}, which remained obviously unnoticed during formal inspections or reviews, otherwise accidents would not occur. In addition, there still are flight simulators out there that do not simulate engine failures in accordance with the behavior of an engine-out airplane, most probably because the simulators were not built and evaluated using adequate aeronautical engineering knowledge on the subject of flying qualities. The faulty training material, the lack of proper guidance in formally approved flight and training manuals, failing inspections and reviews, and imperfect simulators are contributing factors to engine failure accidents, of which most are fatal. Above, these are already called systemic errors of global concern.

6.3. Causes Of This Boeing 747 Accident

6.3.1. When the fuse pin in pylon 3 would not have failed, the accident would not have occurred. But a failure does not have to lead to a catastrophe. Airplanes are designed and flight-tested to be able to continue to fly safely when a failure occurs, such as in this case, when two engines are inoperative or are separated from the wing. Limitations are determined during flight-testing, and (emergency) procedures and (airspeed) limitations, necessary to achieve an adequate level of safety during failures modes, are published in the Airplane Flight Manual of the airplane for the pilots to use and observe. The Boeing 747 Airplane Flight Manual even presents an engine emergency procedure which includes engine separation. But when these procedures and limitations are not clearly described, explained, trained, and understood by flight instructors, and are not taught to and used by pilots as intended, then safety is at stake. This was obviously the case for this, and many more, if not all, engine-failure related accidents.

6.3.2. ***The cause*** of the accident was that the pilots were not made aware that increasing the asymmetrical thrust on the remaining engines 1 and 2 on the left wing to maximum, while the airplane was in a turn with a bank angle of 25° to the right, increased the lowest speed at which control can be maintained with full lateral and/or directional con-

trol deflections, being the *actual* minimum control speed V_{MCA2}, to a level above the current airspeed of the airplane, after which control was lost.
The airspeed of the airplane was not high enough for the ailerons and rudder to be able to generate adequate forces and moments to counteract the forces and moments due to the maximum asymmetrical thrust and other forces during the turn, including the gravitational attraction by mother Earth. Aviation Regulations FAR and CS 25.149 do not require the control surfaces of an airplane to be sized large enough to be capable of turning at maximum asymmetrical thrust levels, but only to maintain straight flight (§ 3.4.2). The pilots obviously did not know; their airplane and training manuals did not write adequately about this subject, and their flight instructors never told them. A case of unknown, lost, or forgotten knowledge that led to a catastrophe.

6.3.3. Not only the pilots were obviously never made aware of the increase of the minimum control speed with bank angle. Flight instructors, accident investigators, and monitoring aviation authorities were not either. They all obviously suffer from the loss or lack of appropriate knowledge of flight with inoperative engine(s), which is still taught though at aeronautical universities and test pilot schools (§ 3), and still can be found in older Flight Crew Reference Guides (§ 5.8.25) and in Performance Manuals of certain manufacturers (§ 3.3.8), but regrettably not anymore in contemporary flight training manuals and syllabi, Airplane Flight Manuals, and Airplane Operating Manuals. There must have been people who inappropriately decided to delete this from manuals because they did not understand this either, and thought this knowledge was not correct or not necessary. They regrettably did not consult aeronautical engineers before taking this step, which leads to the root cause of most, if not all engine failure related accidents:

6.3.4. The cause of this and most other engine-failure related accidents is also that the Regulations do not require the flight limitations and restrictions, that are a consequence of the approved airplane design method, to be included effectively in the airplane flight and training manuals. Accidents occur, because pilots are not adequately made aware anymore of the hazards of flight while an engine is inoperative. If the imperfect Regulations are not improved, accidents will continue to occur.

6.3.5. ***The root cause*** of the accident is the growing gap between flight operations and aeronautical engineering, that needs to be bridged (again). Pilots believe they know all about airplanes and don't need aeronautical engineers, but pilots, except for a few, have only little knowledge of engineering, at high school level. Pilots are trained to operate and navigate an airplane across the globe and do that well, but they are not 'equipped' with higher level engineering knowledge to be able to explain or investigate the controllability of an airplane after a propulsion system malfunction and other complex topics.
The required guidance for pilots to be able to continue a flight safely when one or more engines fail, or is/are inoperative, was regrettably deleted from flight, operating, and training manuals and from in-flight training syllabi, and even from Federal Aviation Regulations and EASA Certification Specifications by people who are obviously not educated at a high enough engineering level to be able to thoroughly understand the controllability of a multi-engine airplane after engine failure. Furthermore, a lot more mistakes are made in pilot manuals which a competent aeronautical or flight test engineer would not accept. Manual writers, manual reviewers, flight instructors, inspecting and approving authorities, and finally also accident investigators are obviously not required to be educated at a high enough level anymore. Fortunately, aeronautical universities and test pilot schools continue to teach this and other subjects at MSc level.

7. Safety Recommendations

7.1. Recommendations on controllability by the NASB

7.1.1. Ref. 1, § 4.6: “Evaluate and where necessary improve the training and knowledge of flight crews concerning factors affecting aircraft control when flying in asymmetrical conditions such as with one or more engines inoperative including:

- advantages and disadvantages of direction of turn;
- limitation of bank;
- use of thrust in order to maintain controllability.”

7.1.2. The first sentence and the last bullet present good recommendations and are also discussed throughout in this report, and in § 3.3.7, resp. The first bullet is discussed in § 3.3.6 in this report, and the second bullet in § 3.3 (turns at high asymmetrical thrust should never be made, not even with limited bank).

7.1.3. More recommendations are to be made, and are presented below.

7.2. Recommendations To Aviation Authorities and Transportation Safety Boards

7.2.1. These recommendations on the subject control and performance are of global concern, for airplane manufacturers, for Certified Flight Instructors of multi-engine airplanes, for Transportation Safety Boards and for Aviation Authorities across the globe.

7.2.2. It would improve aviation safety and prevent accidents if airplane flight and training manuals for pilots, more specifically the airspeed limitations for engine-out flight and engine emergency procedures, are written and reviewed not only by pilots, but by a multi-disciplinary team that includes the aeronautical engineering knowledge that was needed to design and flight-test airplanes, human factor and other expertise, including knowledge on how the limitations in-flight were determined, and under which conditions these limitations are valid. This also applies to the inspecting and approving authorities for reviewing pilot manuals and flight and simulator training syllabi, to avoid lifesaving knowledge from getting lost or forgotten (ref. 31).

7.2.3. It would improve safety and prevent accidents if US Federal Aviation Regulations, EASA Certification Specifications, and equivalent Regulations across the globe (§ 25.1513 and § 23.1513), would be amended to require manufacturers to publish not only the standardized minimum control speed of an airplane in their Airplane Flight, Operating and Training Manuals, but also the bank angle for which the published V_{MCA} is valid, which usually is the bank angle for minimum sideslip (≤ 5° away from the inoperative engine), because the *actual* V_{MCA} that a pilot will experience in-flight varies considerable with bank angles to either side.
Manufacturers should also be required to not only publish the (standardized) V_{MCA} for minimum drag (maximum rate of climb), but also the higher V_{MCA} for wings-level which is to be used for calculating rotation speed V_R and takeoff safety speeds V_2, because these safety speeds are only 5% resp. 10% higher than V_{MCA}; this safety margin is most often smaller than the difference between standardized V_{MCA} and V_{MCA} with wings level (more conditions apply), implying that an airplane may rotate at an airspeed below the actual V_{MCA}, if the other factors that have effect on V_{MCA} are at their worst-case values.

7.2.4. Pilots must be made aware as soon as possible that the $V_{MC(A)}$ that is published in the Limitations Section of Airplane Flight Manuals is valid for straight flight only while maintaining a small bank angle of 5° or less away from the inoperative engine for minimum drag, which was used by the manufacturer for sizing the control surfaces and for determining V_{MCA}. When an engine is inoperative, turns to either side can only be made safely after climbing straight to a safe altitude, and after the asymmetrical thrust is decreased a bit, temporarily. The pilot-definition of V_{MCA} should be changed to reflect this.

7.2.5. Engine Emergency procedures should include a warning that turns should not be made when the asymmetrical thrust is or is increased to maximum, or control will be lost. If possible, also a chart, a graph with the effect of bank angle on V_{MCA}, similar to Figure 6, should be included. Most manufacturers already present the less increasing stall speed V_S with bank angle (and weight) in charts or tables in their Airplane Flight Manuals, so why not a chart with the much more increasing V_{MCA} with bank angle? FAR and CS 25 (and 23) should be amended to this effect.

7.2.6. The minimum control speed when two engines are inoperative on the same wing of 4 or more engine airplanes (V_{MCA2}) was deleted from the Regulations many years ago, but should again be included, because V_{MCA2} also applies when one of the engines is inoperative, in anticipation of a second engine to fail, and during a go-around when two engines are inoperative. In the future, e-powered airplanes might have more than 4 engines, some of them near the wingtips, the failure of which can have considerable consequences for controllability. V_{MCL} and V_{MCL2} were introduced in the past, but should be reconsidered; are these really required?

7.2.7. Airlines often write their own Airplane Operating Manuals for use by their pilots, rather than supply their flight crews with an FAA or EASA approved Airplane Flight Manual. However, an FAA or EASA approved Airplane Flight Manual, as defined in the Type Certificate Data Sheet, is required to be in use for the airplane to be considered airworthy. Airplane Flight and Weight and Balance Manuals are subject to approval by Aviation Authorities, while an Aircraft Operating Manual is not. If only an Airplane Operating Manual is in use during flight operations, the airplane cannot be considered airworthy; an Airplane Flight Manual has to be on-board and its limitations and procedures must be observed, for a purpose. An Airplane Operations Manual, if in use, should also be subject to approval by authorities, or at least parts thereof.

7.2.8. The knowledge on engine-out flight, and the in-flight or in-simulators conducted engine-out training need to be improved. A pilot must be made aware that he/she controls the magnitude of the minimum control speed with bank angle and the level of asymmetrical thrust. This must be included in training syllabi for increasing flight safety. The simulators used for engine-out training should be capable of properly simulating the increase of V_{MCA} with bank angle in either direction.

7.2.9. Pilots were obviously not made aware that large uncommon aileron and/or rudder deflections are a strong warning signal that the current airspeed is barely high enough to maintain control, and that the loss of control might be imminent if bank angle, thrust or any other factor that affects the lateral and directional equilibrium of forces and moments is changed.

7.2.10. The Airplane Flight and the Operating Manuals as well as the Training Manuals and syllabi that the pilots of the El Al Boeing 747 might have used, need to be reviewed to determine whether V_{MCA} and V_{MCA2} data, the conditions for which these speeds are valid, and engine-out performance data, were adequately included in these manuals, including the flight- and control limitations and restrictions that apply. Manuals of all other multi-engine airplanes should also be reviewed on these subjects to avoid accidents when an engine fails.

7.2.11. Currently there is obviously no higher knowledge-level guidance and review requirement for ascertaining that the rules and regulations are in accordance with aeronautical engineering principles and practices. In some cases, rules do not even comply with other regulations and (flight-test) guides (advisory circulars) published by the same authorities. The left hand of aviation authorities doesn't know what the right hand is doing.

7.2.12. This also applies to Transportation Safety Boards who are assigned to investigate airplane accidents. The fact that hundreds of investigations of controllability of airplanes after a propulsion system malfunction did not (yet) result in accident preventing recommendations, should lead to the recommendation that accident and air safety investigators definitely need a higher level of engineering education on this subject. An investigator (just like all of us) *only sees what he looks for, and only looks for what he knows*.

7.2.13. On the Internet, many pilots and flight instructors publish their own opinion on controllability of airplanes after engine failure. Controllability is about forces, not only lift forces, but also gravitational forces and components thereof, and about moments that are acting on airplanes; it's physics, not an opinion; the equilibrium of forces and moments for an airplane to remain controllable after failures is not negotiable.

7.2.14. Authorities should ensure that a high level of engineering expertise is being available and applied during pilot training, and monitor whether expertise is indeed in place where it is essential, for instance for the review of training manuals and syllabi.

7.2.15. Quality systems and safety audits (like LOSA) should be improved to include the recommendations presented above.

7.2.16. *The bottom line*: the knowledge gap between aeronautical engineering and flight operations needs to be bridged before safety can be advanced, and before aviation drifts further into failure.

7.3. Safety Recommendations of Global Concern to ICAO

7.3.1. As described above, several State civil aviation authorities and organizations across the globe seem not open and willing to improve safety, as they should. Therefore, the safety recommendations in this report are herewith also made to ICAO because ICAO might consider the reported safety recommendations regarding systemic deficiencies, having a high probability of recurrence with the potential for significant consequences and requiring timely action to improve safety, as Safety Recommendations of Global Concern (ref. 30).
Therefore ICAO, as principal world organization in aviation, is recommended to take the lead in improving regulations, pilot training and accident investigation, and take up the fight against incompetence at safety critical positions. Many authorities hesitate, didn't act after being informed, because amending regulations and flight and training manuals might raise questions of the public, and might lead to law suits. But ICAO must enhance aviation safety, whatever it takes.

7.3.2. ICAO is also strongly recommended to include in the Manual of Aircraft Accident and Incident Investigation, Doc 9756 Part III Investigation, a chapter on the investigation of the controllability after a propulsion system malfunction for which § 3 out of this report could be used, or the more complete report *Airplane Control and Analysis of Accidents after Engine Failure* (ref. 13), which includes propeller airplanes and examples of accident analyses with and without FDR data.

7.3.3. As concluded in this report, crucial safety guidance for use after the separation of two engines was missing in the Airplane Flight Manuals, Airplane Operating Manual and most probable also in Training Manuals. Currently, the manuals used during flight training and during flight operations are not investigated during accident investigations, but it is recommended to do so. ICAO is recommended to include a chapter on the investigation of manuals used by pilots (and/or maintenance) in the *Manual of Aircraft Accident and Incident Investigation* (ref. 8). Suggestions can be found in ref. 13, § 7.

7.3.4. In the recent past, many amendments were initiated by TSB's to change the protection of investigation data, such as in Annex 13, § 5.12, and prevent these data from being publicized. The investigators who are behind these change requests might want to conceal their less good reports, and their short-falling analyses of accidents. Fortunately, ICAO requires for writing reports that "*the writer should assume that the reader is intelligent but uninformed and will analyse the facts presented in order to test the conclusions of the Final Report"* (ref. 8, Appendix 2 to Chapter 1, § 1).
Although *"the sole objective of the investigation of an accident or incident shall be the prevention of accidents and incidents" (Annex 13 § 3.1, ref. 5),* an accident investigator does not improve the safety of aviation, and prevent accidents, but readers of accident reports should do. An accident investigation report is not a closing verdict, but should be the launching document of activities to increase the safety by knowledgeable people across the globe who are responsible for the safety of flight. Readers of the reports should, but can only succeed if they understand and can reproduce what exactly happened. Hence facts, which objective FDR data indeed are, should not be withheld from the readers.
It is strongly recommended that ICAO refuses any change request which tries to withheld objective facts and figures of accidents and incidents from the public. Better experts out there than investigators should not be excluded from contributing to aviation safety, like I did with this report, and as was stimulated by ICAO.

7.4. Reported Safety Actions

7.4.1. After a tragic fatal accident with a Hercules C-130H accident on Eindhoven Airport in The Netherlands in 1996, I wondered why the pilots increased the engine thrust for a go-around just prior to touchdown (at low speed) while two engines on the same wing failed due to bird ingestion during final approach. Several other fatal engine failure accidents occurred in the nineties. I noticed that pilots did not operate their airplanes in compliance with design and flight-test techniques, and wanted to do something about it.
I started writing papers to explain engine-out flight, presented these in several countries and wrote many reviews of accident investigation reports and airplane and flight training manuals. Please refer to the Downloads and Accident pages of website Avio*Consult*[12]. On the Links page of this website, many links are provided to formal Regulations, relevant Advisory Circulars and course material of aeronautical universities and test pilot schools.

7.4.2. I also wrote many letters and emails to FAA, NTSB, ATSB, NASB, Flight Safety Foundation, Investigators in Charge, manufacturers, etc. during the past 20 years, but received no response. My letters must have fallen in the hands of people who never heard of what I wrote about. My safety actions were most probably moved to the eternal archives prematurely because they were obviously not understood due to the lack or loss of knowledge.
Many accidents would not have occurred if the recommendations made by Avio*Consult*, that are in-fact based on an academic level of knowledge, would have been used. A too low level of knowledge obviously has achieved decisive influence in the world of aviation; aviation is drifting into failure if such incompetence is not brought to a halt.

[12] https://www.avioconsult.com.

Human beings, who are almost unique in having ability to learn from the experience of others, are also remarkable for their apparent disinclination to do so

This quote is out of a video of NTSB Board Member Dr. Earl F. Weener, titled *Loss of Control During Takeoff and Landing* (ref. 24). Dr. Weener did not respond to my personal letter to him about this subject either, and obviously disinclined to learn from a Test Pilot School graduate and the Aeronautical Universities in his own country, while he is an engineer himself. However, his staff might have withheld the letter from him, showing that the NTSB might, like other TSB's, not be equipped with the high-level knowledge required to analyze the controllability of airplanes before and after an engine failure, which is also confirmed in the next paragraph.

7.4.3. On 30 June 2019, a Beech 300 crashed on airport KADS, Texas USA, killing all 10 on-board after engine #1 lost power. I was asked to write a post on the BeechTalk Forum, which I did (ref. 26). I also started reviewing the increasing number of documents in the NTSB docket of this accident. Well before the final report was issued, I notified the Investigator-in-Charge, a PhD of the Denver office, of mistakes made in the Performance Study and in the Sideslip, Thrust and Rudder Study (ref. 27). My input was, regrettably, neglected by an obvious non-engineering PhD. In the Probable Cause in the NTSB report the pilot was blamed, but the real reason for the loss of control was that the Pilot Operating Handbook of the airplane does not provide guidance to keep V_{MCA} low after engine failure. FAR 23 does not require to provide this guidance. This was obviously not taught to the pilot either; his multi-engine training was inadequate as well, because Certified Flight Instructors do not (need to) know, and hence, cannot teach this.
The *actual* V_{MCA} was higher than the published V_{MCA} because straight flight (runway heading) was not maintained using up to maximum rudder, a bank angle of 5° into the good engine was not attained, and propeller #1 was not feathered; all ingredients that led to an unavoidable Loss of Control, and regrettably also to the 10 unnecessary fatalities. It's just physics; pilots should be educated to understand this. The large sideslip (drag) also prevented the airplane from accelerating to V_2. The NTSB report does not lead to the prevention of similar accidents. A missed chance, because investigators were obviously not educated at a high enough level to conduct such investigations. People will continue to die, unless adequate measures are taken to increase knowledge and improve the investigations.

7.4.4. On 22 Feb. 2023, a DA-42 two-engine airplane, used by many flight schools for multi-engine training, crashed during an engine-out training flight in Slovakia. I became curious whether its Airplane Flight Manual would be correct on the subject of engine-out operations and complies with EASA Flight Test Guides. A limited review was conducted after which the conclusion is: regrettably it's not. This review is loaded with explanations to learn from and to help improve the manual; it is not written to apportion blame or liability (ref. 28). Many remarks apply to flight manuals of other multi-engine airplane types as well. The review was emailed to the Investigator-in-charge, and to the airplane manufacturer. No response was received. A local flight school in The Netherlands, who operates this type of airplane as well, was also informed, but did not adequately respond either.

7.4.5. Already in 2005, changes were recommended for FAR and CS 23.149 and 25.149 in a paper *Imperfections and Deficiencies in FAA/ FAR and EASA/ CS 23 & 25 that might lead to Accidents after Engine Failure* (ref. 29), but this paper might also have fallen in the hands of people who did not understand; nothing was achieved. Many accidents continued to occur.

7.4.6. In June 2019, the paper *Safety-Critical Procedure Development Requires High Level Multi-Disciplinary Knowledge* was presented to the Safety Forum in Brussels, ref. 31.

7.4.7. Philosopher Arthur Schopenhauer once said:

Every man takes the limits of his own field of vision for the limits of the world

My papers and this report should have widened up the limits of the field of vision of pilots, of investigators, and of Regulators who bear responsibility for the safety of pilots and their passengers. Nevertheless, people who don't have the required wide field of vision, can't contribute to safety.

7.4.8. I am aware that the high self-esteem or stubbornness of many professional aviators make them laugh and forget about my accident analyses, or deny it, "never heard of, can't be true". They resist because of their own limited field of vision, and of their own incompetence on the subject. But one day they will accept, because the work is based on science and experience, not on opinion. They don't want to get killed either, because of ignorance, and leave their own next of kin behind in mourning.

7.5. Investigation Should Be Reopened

ICAO Annex 13 § 5.13 recommends: "If, after the investigation has been closed, new and significant evidence becomes available, the State which conducted the investigation shall reopen it". In this report, significant evidence is presented which is obviously also new to accident investigators and which is of global concern, reason why the Dutch Transportation Safety Board is requested to reopen the investigation, taking into account the new evidence, analysis, findings, conclusions, and recommendations in this report.
The objective of the original accident investigation, being the prevention of accidents, was not met. Within 4 years after this Boeing 747 accident, four more accidents after engine failure occurred in The Netherlands alone. Such accidents continue to occur all across the globe, with the main cause being the lack or loss of knowledge of flight with an asymmetrical powered airplane. The recommendation to include the flight limitations, that were allowed to be used for sizing the control surfaces during the design phase of the airplane, and their consequences for airplane control in pilot manuals was never included in TSB investigations, nowhere across the globe. The recommendation to improve the multi-engine rating pilot training, and the training of accident investigators on the subject of airplane control after engine failure was never included either.
Original FDR data was not available to AvioConsult at the time this report was written, but could further increase the value of this, or the reopened investigation. ■

List of References

1. NASB Aircraft Accident Report 92-11. *El Al Flight 1862 Boeing 747-258F, 4X-AXG*, Amsterdam, Oct. 4, *1992. https://asn.flightsafety.org/reports/1992/19921004_B742_4X-AXG.pdf*.
2. M.H. Smaili. *Flight data reconstruction and simulation of the 1992 Amsterdam Bijlmermeer airplane accident,* June 2003. NLR-TP-2003-392. https://reports.nlr.nl/server/api/core/bitstreams/6be04940-27fa-4775-b340-f4932022a446/content.
3. H. Tigchelaar. Yearbook Netherlands Association of Aeronautical Engineers (NVvL) 1995, page 9, *Aerodynamic, Flight Mechanical and Flight Technical Aspects of the EL AL 1862 Accident Investigation.* RLD (Dutch CAA).
4. Avio*Consult.* List of accidents after engine failure, 1996 – 2024. https://www.avioconsult.com/downloads/List of accidents after engine failure.pdf.
5. ICAO. Annex 13 to the Convention on International Civil Aviation, *Aircraft Accident and Incident Investigation.* International Civil Aviation Organization. ISBN 978-92-9258-937-0.
6. Harry Horlings. Video lecture on YouTube, *Airplane Accidents after Engine Failure, the Real Value of* $V_{MC(A)}$, Subtitle: *How to prevent a dead engine from turning into a killing engine.* Two accidents are also briefly analyzed. Avio*Consult* 2014. https://youtu.be/Wbu6X0hSnBY.
7. *British Caledonian Model 747 Operations Manuals.* https://drive.google.com/drive/folders/1IPtLCxSB5GMRDNlxmCcQcf9_cg8yRa7d.
8. ICAO *Manual of Aircraft Accident and Incident Investigation, Doc 9756 Part IV, Reporting, Appendix 2 to Chapter 1 – Report Writing Conventions, § 1 General Guidelines.*
9. Dr Jan Roskam. *Airplane Design,* 8-part set of books. Kansas University (KU) and DAR Corporation. https://shop.darcorp.com/index.php?route=product/product&product_id=59.
10. *Flying Qualities Textbook,* USAF Test Pilot School. Part 1 *(ADA170959)* and Part 2 *(ADA170960).* US Archives.
11. *FAR 25 Flight Test Guide,* https://www.faa.gov/documentLibrary/media/Advisory_Circular/25-7D.pdf.
12. *EASA/CS Flight Test Guide* http://easa.europa.eu/agency-measures/docs/certification-specifications/CS-23/CS-23 Amdt 3.pdf#page=196, $V_{MC(A)}$ testing, from pdf page 257 (§ 23.149).
13. Harry Horlings. *Airplane Control and Analysis of Accidents after Engine Failure,* Avio*Consult*, 2005. https://www.avioconsult.com/downloads/Airplane Control and Analysis of Accidents after Engine Failure.pdf.
14. Harry Horlings. Several papers on the subject airplane control after engine failure. https://www.avioconsult.com/downloads.htm.
15. Harry Horlings. *Effect of Bank Angle and Weight on* V_{MCA}. Avio*Consult*. Download #6 on the Downloads Page. https://www.avioconsult.com/downloads/Effect of Bank Angle and Weight on Vmca.pdf.
16. Harry Horlings. Several supplemental analyses of accidents after engine failure, Avio*Consult.* https://www.avioconsult.com/accidents.htm.
17. Code of Federal Regulations, *Title 14, Part 23 and 25 Airworthiness Standards,* https://www.ecfr.gov/cgi-bin/text-idx?SID=a368e3764d61c98423b17629b48e8223&mc=true&tpl=/ecfrbrowse/Title14/14CIsubchapC.tpl.
18. EASA *CS 23 & 25 Certification Specifications,* https://www.easa.europa.eu/en/document-library/certification-specifications; V_{MCA} in § 25.149.

19. Dr. Jan Roskam. Airplane Design, Part VII, Chapter 5. *Lateral-Directional Stability and Control.* Kansas University (KU) and DAR Corporation. https://shop.darcorp.com/index.php?route=product/product&product_id=59.
20. *One Engine Inoperative Aerodynamics interactive simulations,* University of North Dakota, https://mediafiles.aero.und.edu/aero.und.edu/aviation/trainers/one-engine-inoperative-aero-dynamics/.
21. *Type Certificate Data Sheet A20WE, III – 747-200F, Model 747-258F,* Eligible Serial Number 21737, https://drs.faa.gov/browse/excelExternalWindow/DRSDO-CID110620563720230316163910.0001.
22. *KLM Flight Crew Reference Guide,* 1988, Issue no.: 2, § 1.3 Asymmetric Engine-out Operation.
23. Harry Horlings. Several reviews of pilot manuals, including of DA-42, PA-44, B737-200, and of pilot training manuals, on website https://www.avioconsult.com/downloads.htm, downloads 4 and 7 – 15.
24. Dr. Earl F. Weener. *Loss of Control During Takeoff And Landing.* NTSB. https://www.youtube.com/watch?v=f78kS4Xzbis&feature=youtu.be.
25. Harry Horlings. *Critical Review ATR-72 Airplane Flight and Performance Manuals,* Avio*Consult.* https://www.avioconsult.com/downloads/Review ATR-72 Pilot Manuals.pdf.
26. *Posts by* Avio*Consult on the BeechTalk Forum*. https://www.avioconsult.com/downloads/Posts on the BeechTalk Forum by AvioConsult.pdf.
27. Harry Horlings. *Review Beech 300 Accident Report, June 30, 2019, KADS*, including notes on the Performance study and POH, sent to the NTSB, 42 pages. https://www.avioconsult.com/downloads/Review Beech BE-300 2019-06-30 KADS final report, notes, perf. report.pdf.
28. Harry Horlings. *Limited Review Diamond DA-42 Airplane Flight Manual,* https://www.avioconsult.com/downloads/Review DA 42 Airplane Flight Manual.pdf.
29. *Harry Horlings. Imperfections in FAR and EASA 23 and 25,* AvioConsult, 2005, https://www.avioconsult.com/downloads/Imperfections FAR & EASA CS 23 & 25 by AvioConsult.pdf.
30. ICAO *Safety Recommendations of Global Concern*. https://www.icao.int/safety/airnavigation/AIG/Pages/Safety-Recommendations-of-Global-Concern-(SRGC).aspx.
31. Harry Horlings. *Safety Critical Procedure Development requires high level multi-disciplinary knowledge*, Safety Forum, Brussels, June 5, 2019. https://skybrary.aero/video/safety-critical-procedure-development-requires-high-level-multi-disciplinary-knowledge.
    The slides of this paper: https://skybrary.aero/bookshelf/books/4665.pdf.
    The paper: *https://www.avioconsult.com/downloads/Safety-critical%20Procedure%20Development.pdf.*

List of Abbreviations

Abbreviation	Meaning
AFM	Airplane Flight Manual
AOM	Aircraft Operating Manual
ATC	Air Traffic Control
ATR	Avions Transport Régionaux
BSc	Bachelor of Science degree
cg	Center of Gravity
CS	Certification Specification (EASA)
CVR	Cockpit Voice Recorder
EASA	European Aviation Safety Agency
EPR	Engine Pressure Ratio – measure of thrust of an engine (footnote 6)
FAA	Federal Aviation Administration (USA)
FAR	Federal Aviation Regulations (FAA)
FCRG	Flight Crew Reference Guide
FCTM	Flight Crew Training Manual
FDR	Flight Data Recorder
ft	foot or feet
g	Normal acceleration by gravity (32.2 ft/s^2, 9.81 m/s^2)
ICAO	International Civil Aviation Organization
KLM	Royal Dutch Airlines
kt	knot(s)
KU	Kansas University
lb	Pound or pounds
m	meter(s)
MCT	Maximum Continuous Thrust
MLW	Maximum Landing Weight
MSc	Master of Science degree
N	Newton (measure of force)
NASB	Netherlands Aviation Safety Board
NLR	National Aerospace Laboratory, Amsterdam
nm	Nautical Mile (1 nm = 1852 m)
NTSB	National Transportation Safety Board (USA)
OEI	One Engine Inoperative (n-1)
ROC	Rate of Climb
s	second(s)
TCDS	Type Certificate Data Sheet
TEI	Two Engines Inoperative (n-2)
TPS	Test Pilot School
TSB	Transportation Safety Board
USAF	United States Air Force
UTC	Universal Time Coordinated (Greenwich Mean Time)
V_{MC} or V_{MCA}	Minimum Control Speed Airborne (or in the Air), One Engine Inoperative
V_{MCA2}	Minimum Control Speed Airborne (or in the Air), Two Engines Inoperative
V_{MCL}	Minimum Control Speed during Approach and Landing
V_S	Stall speed
V_R, V_2	Rotation speed and takeoff safety speed
W	Weight (of the airplane)
W·sin ϕ	Weight times sine of bank angle ϕ; a side force acting in the cg when banking

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