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ANALYSIS
of the controllability of the crashed Saab SF-340B
at Schiphol Airport, 4 April 1994, during the final flight phase

References

A – Aircraft Accident Report 94-05, Netherlands Aviation Safety Board, October 1995.
B – Paper *Airplane Control and Accident Investigation after Engine Failure*, Avio*Consult*, June 2005. Download 3 on the Downloads Page of website www.avioconsult.com.
C – Paper *Control and Performance during Asymmetrical Powered Flight*, Avio*Consult*, 2012. Download 2 on the Downloads Page of website www.avioconsult.com.
D – Paper T*he Effect of Bank Angle and Weight on* V_{MCA}, Avio*Consult*, Sept. 2007. Download 6 on the Downloads Page of website www.avioconsult.com.

1. Introduction

1.1. On 4 April 1994, a catastrophic accident with a Saab SF-340B happened at Schiphol Airport, Amsterdam in the Netherlands, following a malfunction in the right engine. After reviewing the formal Aircraft Accident Report (ref. A), Avio*Consult* noticed that the air minimum control speed (V_{MC} or V_{MCA}) of the airplane was not discussed, not even mentioned in the analysis section of the Report, while just prior to the accident the asymmetrical thrust setting was high, the propeller of the affected engine was not feathered and the airspeed was low, which are all ingredients for the loss of control that can lead to a catastrophe. The V_{MCA} of all multi-engine airplane types is an important factor for sizing the vertical tail, for maintaining control (and performance) after engine failure and is determined during experimental flight-testing and subsequently listed in the limitations section of Airplane Flight Manuals (AFM), in order to prevent engine failure related accidents. V_{MCA} is to be observed by airline pilots at all times.

1.2. Harry Horlings of Avio*Consult*, a graduate Flight Test Engineer (class 1985A) of the USAF Test Pilot School (TPS), wrote this detailed Analysis of the controllability of the airplane, based on the formal experimental flight-test conditions and techniques for determining the V_{MCA} of multi-engine airplanes while one engine is inoperative, using the data out of the formal Aircraft Accident Report (ref. A).
The V_{MCA} flight-test conditions and techniques can be found in Test Pilot School (TPS) books and manuals, in FAA and EASA flight test guides and in college books of aviation faculties of Dutch and US (and more) universities and are also presented and explained in ref's B and C. Some of these documents, including a TPS chapter on Asymmetrical Power, can be downloaded via links under References on the Downloads page of website www.avioconsult.com.

1.3. This Analysis is limited to the data and crew response as recorded by the Flight Data Recorder (FDR) during final approach and go-around that were provided in graphs in the Aircraft Accident Report (ref. A).

1.4. Below, a brief summary of the theory of airplane control after engine failure (out of ref.'s B and C) is presented first, to provide the theoretical background to be able to understand this Analysis. Then the factual events of the final phase of the flight are analyzed and the flight-test based opinion of the cause of the accident is presented, including conclusions and recommendations. Finally, the question is asked and answered whether this accident could have been prevented.

2. Airplane control after engine failure

2.1. Following an engine failure, the yawing moment due to the asymmetrical thrust can be counteracted by using the rudder. The size of the vertical tail with rudder is determined during the design phase of the airplane. The tail design engineer is allowed by FAR and CS 23.149 and 25.149, to use a bank angle of maximum 5 degrees (away from the inoperative engine), because this small bank angle reduces the required size of the vertical tail (saving manufacturing cost), reduces the sideslip (increasing the engine-out rate of climb), and also decreases the minimum control speed V_{MCA}. The vertical tail is only large enough to maintain straight flight at airspeeds as low as V_{MCA}, while maintaining the small bank angle, but definitely not for maintaining control during turns at V_{MCA}! Please refer to Ref. B or C for a thorough explanation.

2.2. During the experimental flight-test phase of every multi-engine airplane type, engine-out testing is performed to verify/ determine V_{MCA}. This V_{MCA} is included in the limitations section of Airplane Flight Manuals (AFM) to be observed by the pilots.
The question can be asked that if the airplanes are thoroughly tested, then why do engine failures still lead to catastrophic accidents all around the globe so often? To answer this question, Avio*Consult* researched many investigation reports of engine failure related accidents and found many errors, deficiencies and misunderstandings about V_{MCA}, not only in the accident investigation reports, but also in Aviation Regulations, Airplane Flight Manuals, engine emergency procedures and student pilot textbooks. The V_{MCA} that is used by airline pilots is not the V_{MCA} that experimental test pilots have determined during flight-testing. Somewhere in the line between flight-testing and operational use of V_{MCA}, vitally important conditions and limitations for the use of V_{MCA} are left out. The results of the research were documented in a Paper (ref. B) in which almost all there is to know about airplane control while an engine is inoperative in presented and many ready-to-copy suggestions for improvement of Airplane Flight Manuals, engine emergency checklists, Aviation Regulations, student pilot textbooks, etc., are included. Ref. C presents the errors and deficiencies on V_{MCA} that still exist in AFM's today.

2.3. **Minimum control speed – V_{MCA}.** When an engine of a multi-engine airplane is inoperative and the thrust of the other engine(s) is high, a big yawing moment (= force x arm) in the direction of the inoperative engine is generated. In addition, on propeller airplanes, the reduced speed of the airflow over the wing section behind the propeller of the inoperative engine causes a rolling moment into the inoperative engine. These yawing and rolling moments can normally be controlled by deflecting the rudder and ailerons, but the forces generated by these aerodynamic control surfaces are highly dependent on the (square of the) airspeed. Consequently, there is a minimum airspeed below which the vertical fin with rudder and/ or the ailerons does not generate high enough aerodynamic forces anymore to counter the yawing and rolling moments caused by the asymmetrical thrust (and propeller drag); the motions of the airplane can no longer be controlled, the rudder and/ or ailerons seem not effective anymore. This airspeed is called minimum control speed in the air (abbreviated V_{MCA} or sometimes incompletely as V_{MC}).
The magnitude of V_{MCA} is dependent on many factors, a few of which will be mentioned below. In US Federal Aviation Regulations (FAR), EU Certification Specifications (CS) and equivalent regulations, it is agreed to standardize V_{MCA} and determine V_{MCA} only during straight equilibrium flight while the critical engine is inoperative, the opposite engine is set to produce maximum takeoff thrust, the cg is aft, the weight is as low as possible and the rudder and/ or ailerons are either fully deflected or up to reaching a predetermined rudder or aileron control force limit, whichever occurs first during the test, and finally with a small bank angle of maximum 5 de-

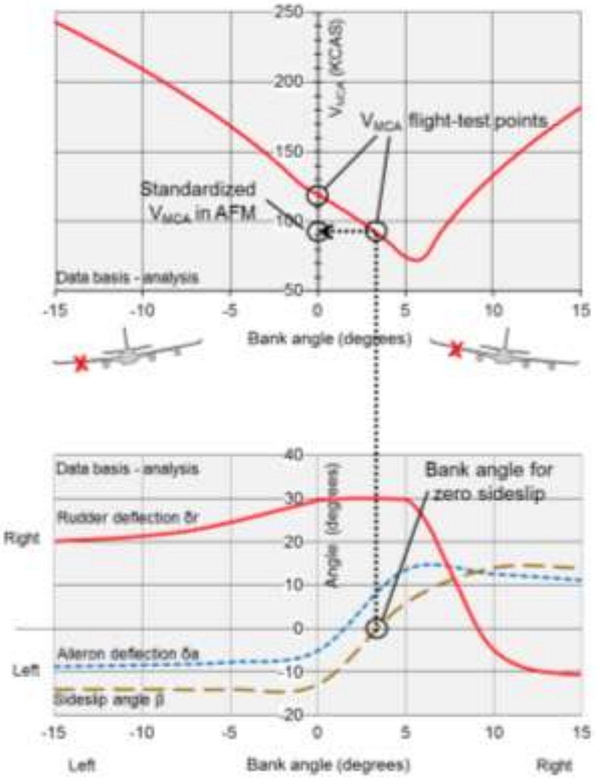
grees, as opted by the manufacturer. The vertical tail of the airplane might be designed to only enable straight, equilibrium flight when using this bank angle.
The V_{MCA} determined this way is included as an airspeed limitation in the limitations section of the AFM of all multi-engine airplanes, as a single number or in a table in which weight, altitude and temperature are the entry variables.
As mentioned above, the magnitude of V_{MCA} is, besides on other factors, dependent on control deflections, on propeller feathering and on bank angle. The effect of these three factors on V_{MCA} will be briefly discussed below because these played a significant role in this accident.

2.4. **Control deflection.** V_{MCA} of a multi-engine airplane is determined when the rudder and/ or ailerons are either fully deflected or after reaching a predetermined rudder or aileron control force limit, whichever occurs first during the test. If the rudder is not fully deflected (while the thrust is maximum) to maintain the straight flight equilibrium, then the *actual* airspeed for the vertical fin with rudder to generate a side force high enough to counter the – still same – high asymmetrical thrust will have to be higher than the airspeed that was measured during the flight-test to determine the FAR and CS based V_{MCA} for which fully deflected directional controls were used (provided the maximum approved control force is not exceeded). This *actual* airspeed for maintaining control is therefore higher than the AFM published V_{MCA} that was determined under FAR and CS. This higher *actual* airspeed can also be called *actual* V_{MCA}.
On military transport airplanes, only a maximum of ¾ (75%) of the available control power of rudder and ailerons may be used to determine V_{MCA}, to leave some control power margin for countering gusts; in addition, control forces may be higher. This in fact means that the V_{MCA}'s of airplane types that are used both as civilian and as military transports can differ from each other. Ref.'s B and C present more details on V_{MCA}.

2.5. **Propeller feathering.** V_{MCA} of propeller airplanes is determined while the propeller of the inoperative engine is feathered, if an auto-feather system is provided. When the propeller of an airplane is not (auto-)feathered because the engine is idling, as was the case during this accident, the drag of the not-feathered propeller increases the asymmetrical drag of the airplane which enhances the yawing moment induced by the operating engine. To counter this additional moment, the side force generated by the vertical fin and rudder needs to be higher. This can be achieved by either increasing the rudder deflection or, if the deflection is already maximum, by increasing the airspeed: the *actual* V_{MCA} is higher than the flight-test determined and AFM-listed V_{MCA}.

2.6. **Bank angle**. The manufacturer may, in accordance with FAR and CS, opt to use a bank angle of maximum 5 degrees during the flight-test to determine V_{MCA}, the effect of which will be briefly discussed here; ref.'s B, C and D present many more details. The test pilots of the manufacturer will normally use a bank angle of 3 to 5 degrees away from the inoperative engine, while the thrust is at the maximum takeoff setting and while maintaining straight, constant heading flight. While banking, the side force due to the small bank angle ($W \cdot \sin \phi$) is in the same direction as the side force due to sideslip when the wings are level, reducing the required rudder deflection for the balance of side-forces. This smaller rudder deflection leaves room for further reducing the airspeed, until maximum rudder or either one of the other limits is again reached. The small bank angle therefore decreases V_{MCA} and also decreases the sideslip and therewith the total drag of the airplane. The favorable effects of the small bank angle are that the airplane can maintain straight flight down to a lower airspeed and, in addition, that the engine inoperative climb performance is increased. The normally very small margin between the indicated airspeed and *actual* V_{MCA} is increased, which is favorable for safety. Flight testing showed that V_{MCA} with a 5 degree bank angle away from the inoperative engine is at least 8 knots (kt) lower than V_{MCA} with wings level on most airplanes. The difference in V_{MCA} of a DC-8 type airplane between wings level and 5 degrees away from the inoperative engine is even 32 kt (!) for only one (outboard) engine out, as is illustrated in the figure below, for bank angles into and away from the inoperative engine (source: DC-8-50 FCRM).

2.7. The manufacturer has, in accordance with FAR and CS, the option of choosing a bank angle of maximum 5 degrees to determine V_{MCA}, but the airline pilot definitely has no option for using bank angles up to maximum 5 degrees, unlike the definition of V_{MCA} in most AFM's might let believe. If the pilot, during any operational flight with an inoperative engine, does not maintain the same bank angle that the manufacturer used to determine V_{MCA} while the thrust setting is high, then the *actual* V_{MCA} is higher than the AFM-listed V_{MCA}, as is illustrated in the figure below. This increase of V_{MCA} is in itself not a problem, but if this *actual* V_{MCA} (red line) increases above the indicated airspeed, or if the airplane decelerates to an airspeed below the *actual* V_{MCA}, control of the airplane will be lost for sure. If the wings are kept level during takeoff or go-around, the *actual* V_{MCA} will most often already be higher than the takeoff speed if the other factors that have influence on the magnitude of V_{MCA} happen to be at their worst case value too. Hence, there definitely is a bank angle condition/ requirement for an airline pilot that always applies to the AFM-listed V_{MCA} (but that regrettably is almost never included, except in performance diagrams). This also means that making (procedural) turns at low speed and high asymmetrical thrust settings is very dangerous and should be avoided.
Engine emergency procedures in AFM's or Operating Manuals of most multi-engine airplanes allow pilots to keep the wings level to within ±5 degrees after engine failure, but this is a dangerous misinterpretation of the applicable FAR and CS paragraphs that are for the certification of airplanes, nor for their operational use. In AFM's, a specific bank angle should be prescribed with V_{MCA} for which the listed V_{MCA} is valid. This small bank angle is most often between 3 and 5 degrees away from the inoperative engine. V_{MCA} increases also as the bank angle increases above 6 degrees into the good engine, in this example, because of the increase of sideslip and hence, the risk of fin stall.



Effect of Bank Angle on V_{MCA}
as calculated in Ref. D

2.8. The controllability of an airplane with an inoperative engine is only tested during straight, constant heading flight and not during turns. The small bank angle is for maintaining engine-out equilibrium during straight constant heading flight only, not for turning. It might be possible to initiate a turn during a departure or approach at an airspeed as low as the listed V_{MCA}, but it can never be ascertained that turns at an airspeed at or below the listed V_{MCA} can be terminated in a controlled way if the thrust setting is high, simply because it is not required to test this; the vertical tail is not designed to do this either.
The subject SF-340B airplane of this Analysis proved that a turn could not be terminated despite full control surface deflections and at an airspeed that was still well above the AFM-listed V_{MCA} as well as above the stall speed.
The bank angle that the manufacturer used for determining the V_{MCA} of the SF-340B is unknown; there is currently not even a requirement in FAR and CS to publish this bank angle with the V_{MCA} data.

2.9. **Effect of other factors on V_{MCA}.** During experimental V_{MCA} flight-testing, the worst case weight (lowest), cg location (aft) and thrust level (high) are used to determine the worst case, the highest V_{MCA}. Additional factors that affect V_{MCA} may exist as well; therefore a pre-determined V_{MCA} test configuration is applied. This test method limits the amount of V_{MCA} test flights and

test data and also confines the amount of V_{MCA} data in the AFM, making it easier for airline pilots to look-up a safe V_{MCA} for the actual takeoff, go-around and landing weights, cg, etc. (and for calculating rotation speed V_R and takeoff safety speed V_2). Whatever the weight, cg location or thrust level is, the *actual* V_{MCA}[1] due to these factors will not be higher than the flight-test-determined worst case V_{MCA}, provided the same bank angle is applied that was used to determine V_{MCA} (§ 2.6). This worst case V_{MCA} is therefore published in the AFM, either as a single number (easy to use) and on Part 23 airplanes also indicated by a red radial line on the airspeed indicator or on a placard, or in a graph or table in which weight, altitude and/ or temperature are the entry variables for operations at higher weights, altitudes and/ or temperatures. The required bank angle is most often not published with V_{MCA} though, which is considered a deficiency.
The *actual* V_{MCA} can also be lower – safer – than the AFM published V_{MCA} though, for instance when the asymmetrical thrust is not as high as used during V_{MCA} testing or when the cg is forward. V_{MCA} can also be lower than stall speed V_S in which case the airplane is said to be controllable down to the stall, which however does not apply for all bank angles, as might have become clear after reading the previous paragraphs.

2.10. **Performance.** Flight-testing also proved that the total airplane drag is minimum and hence the remaining one-engine-inoperative climb performance is maximum, if the same small bank angle (of 3 – 5 degrees, as specified by the manufacturer) is maintained away from the inoperative engine, as was used to determine V_{MCA}, because then the sideslip and therewith the drag is minimum. This bank angle condition, including the exact bank angle and its direction, is most often indeed included in the header or legend of performance diagrams or tables in many AFM's, but for unknown reasons not in the controllability and airspeed limitation sections of the AFM's, while controllability is more vital to survival than performance.

2.11. **Summary of airplane control after engine failure.**

2.11.1. The V_{MCA} listed in Airplane Flight Manuals is valid only if either the rudder is or ailerons are fully deflected, or up to one of the control force limits, provided the bank angle is the same as used during determining V_{MCA} (3 to 5 degrees away from the inoperative engine) and the propeller of the inoperative engine is (auto) feathered. Any other bank angle, unfeathered propeller or less control deflection increases the V_{MCA} considerably to a higher actual value, a higher and more dangerous *actual* V_{MCA} that is not indicated on any of the instruments.
The definition of V_{MCA} in an AFM should never state 'maximum 5 degrees' for approved banking while an engine is inoperative, but should present the exact bank angle that was used to determine V_{MCA} and hence, for which the listed V_{MCA} is valid. Refer to ref. C for more deficiencies that usually exist in definitions of V_{MCA} in AFM's.
Main point is that there not only is a single V_{MCA} as listed in the AFM, but that there are many more (*actual*) V_{MCA}'s that are dependent on the actual setting of the asymmetrical thrust as well as on the degrees of deflection of the rudder and/or ailerons, on propeller feathering, on the bank angle and on other factors. Please refer to ref.'s B and C for more information on V_{MCA}.

2.11.2. The controllability of an airplane after engine failure down to an airspeed equal to the listed V_{MCA} is only guaranteed, as is confirmed by flight-testing, as long as:

- the airspeed is equal to or higher than the AFM-listed V_{MCA}, **and**
- a constant bank angle is maintained between 3 and 5 degrees, as opted and specified by the airplane manufacturer, away from the inoperative engine while the thrust setting is high, **and**
- the propeller of the inoperative engine is (auto-) feathered (if applicable), **and**
- the rudder and/ or aileron is fully deflected, or one of the FAR/ CS approved control force limits is reached, whichever comes first.

[1] *Actual* V_{MCA} means the V_{MCA} that a pilot will experience in-flight after engine failure with an actual thrust setting, actual bank angle, actual control input and actual values of the other variables that affect V_{MCA}.

Control will not be lost by definition if these conditions are not met. If, for instance, the actual cg is forward, the moment arm to the rudder is longer and hence the rudder-generated yawing moment is bigger than during determining V_{MCA}. The *actual* V_{MCA} will be lower – safer.

2.11.3. The listed conditions also guarantee the maximum remaining climb performance after engine failure, because then the sideslip is near zero and hence, the drag is as low as it can get under the given engine-inoperative condition.

3. Factual accident information

3.1. Ten minutes after takeoff, an oil pressure warning of the right hand engine made the captain decide to return to the airport. He left the affected right engine idling; its propeller was not feathered. On short final, the airplane got displaced to the right of the runway and at 45 ft Radar Altitude, the captain decided to go-around using the thrust of the left engine only; the right engine was kept idling. The airplane crashed 13 seconds later.

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

4. Analysis

4.1. Two of the Flight Data Recorder readout graphs that are included in the formal Aircraft Accident Report (ref. A) contain the data that were used to perform this analysis. To enable easier analysis of the relevant data, the indicated airspeed and the bank angle data were copied from one graph into the graph containing the rudder and aileron deflections, the engine torque and the heading. This new graph is included as Attachment 1 on page 11. The graph from which the bank angle and airspeed data were used is included in Attachment 2 for reference purposes. A small distortion in both graphs, due to printing and/ or scanning errors, could not be prevented; the accuracy is considered still adequate for this analysis, though.
In the text below, event markers (like ①) are being used to link the text to the events in the graph. The interesting flight phase for this analysis begins at 12:45:41, defined as event ①.

4.2. The right engine was kept idling throughout the final phase of the flight; the torque was approximately 10%. The propeller was not feathered, which resulted in propeller drag that enhanced the thrust asymmetry of the left engine and hence, increased the yawing moment to the right and increased the *actual* V_{MCA}. For maintaining straight flight in this condition at maximum thrust of the left engine engine #1, the side force generated by the vertical tail (and rudder) would have to be larger by either increasing the rudder deflection or, if the rudder deflection is already maximum, by increasing the airspeed. If the heading cannot be maintained while the rudder deflection is less than maximal, the *actual* V_{MCA} is obviously higher than the current airspeed for that limited rudder deflection. This *actual* V_{MCA} will be higher than the standardized V_{MCA} that is listed in the AFM. The standardized V_{MCA} was measured while the propeller was feathered, provided the feathering system was automatic, and with maximum rudder.

4.3. At 12:45:41 (①), at a radar altitude of 110 feet (ft) and an indicated airspeed of 115 knots (kt), 4 kt below the threshold speed for 20 degrees flaps (V_{TH20}), the torque of the left engine was increased from 40% to 65%. The increased propulsive lift of the blown wing section (plus flaps) behind the propeller of the left wing caused the airplane to bank from approximately wings level to 3 – 4 degrees to the right. As the bank angle started to increase to the right, the pilot increased the aileron deflection to the left, to approximately 20 degrees of max. 24 degrees, to counter the bank angle increase.
Since the aileron deflection was not maximum, the pilot obviously did not attempt to attain a safe bank angle of 3 – 5 degrees away from the inoperative engine to keep *actual* V_{MCA} as low as possible (§ 2.6). The exact required bank angle was not presented in the Aircraft Accident Report, most probably because the manufacturer did not provide this number in the AFM. Ra-

ther than attaining a safe bank angle away from the inoperative engine, a bank angle of 3 degrees was maintained to the wrong side, into the dead engine, for a few seconds, which definitely adversely affected (i.e. increased) the *actual* V_{MCA}.
At this time, the airplane was still controllable about the roll axis, though, as shown by the aileron deflection and bank angle plots.

4.4. The increased thrust of the left engine also increased the yawing moment to the right. This yawing moment was enhanced by the drag of the not-feathered propeller of the idling right engine (§ 2.5). Rudder deflection was increased by only 2 degrees to 14 degrees of the available 30^+ degrees to the left, which was obviously not enough to counter the yawing motion at the current airspeed, because the nose of the airplane started to move to the right while the torque reached (only) 65% (at 12:45:43, ②).
Because of the limited rudder deflection for the given asymmetrical thrust setting and bank angle, the heading could not be maintained, i.e. controlled. The air speed was too low for the vertical tail with only partial rudder to generate a high enough side force to counter the yawing motion. This in fact means that the *actual* V_{MCA} at that time must have been higher than 115 KIAS (knots indicated airspeed). The airplane was in fact already out of (directional) control at 12:45:43 (②), two seconds after increasing the thrust, while the IAS was 115 kt, still 12 kt above the flight manual listed – worst case / standardized – V_{MCA}.
The increase of the *actual* V_{MCA} to a value higher than the AFM listed V_{MCA} was caused by the adverse bank angle (into the idling engine), by the additional yawing moment caused by the drag of the not-feathered propeller and by the limited rudder deflection as well.

4.5. In addition, this yawing must have resulted in an increase of the sideslip (into the left ear), causing a side force to the right that started displacing the airplane to the right, away from the runway centerline. The tail wind (11 kt from 7 o'clock) will also have contributed to this displacement. The localizer deviation trace on the graph shows the total displacement (③). In addition, the sideslip increased the total drag of the airplane even more, therewith reducing the remaining one-engine-inoperative climb performance.

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

4.7. At 12:45:53 (⑥), the airplane had apparently drifted so much to the right of the runway centerline that the pilot decided to go-around. The airspeed at that time was 110 kt, 9 kt below V_{TH20} but still 7 kt above the Flight Manual-listed V_{MCA}. The torque of the left engine was increased from 40% to 98% in 7 seconds. The rudder deflection remained unchanged, approximately halfway, 15 degrees, to the left. Due to the increase of the propulsive lift of the blown wing section behind the left propeller, the aircraft started to bank to the right to which the pilot responded with full aileron deflection to the left (⑦). The bank angle however continuously increased slowly (3 degrees per second) to the right for the remainder of the flight while the aileron deflection remained full left, apart from a pulse to the right. This pulse is not visible in the right aileron graph and might be a data glitch. Due to the low airspeed, the ailerons were no longer effective enough to control the banking under the given thrust and drag asymmetry conditions; lateral control was lost. The *actual* V_{MCA} must have increased to a value higher than 107 KIAS (§ 2.6).

4.8. After the engine torque increased above 67% (⑧), the half rudder deflection to the left could not prevent the yawing motion from reversing to the right. The yaw rate increased to approximately 4 degrees per second to the right, also for the remainder of the flight. Directional control was now also lost (⑧). At event ⑨, about 7 seconds prior to the impact with the ground, the rudder deflection was finally increased, with some hesitation, to be fully deflected to the left at the moment of impact. The two-second discontinuity in the bank angle and airspeed data as shown in the graph may have been caused by the increased rudder deflection or the aileron pulse to the right (⑦). In any case, the full rudder deflection came way too late.

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

5. Conclusions and cause of the accident

5.1. The propeller of the idling right engine was not feathered and consequently caused high drag and a yawing moment that enhanced the yawing moment generated by the operative left engine. Because of this increased yawing moment, a higher airspeed than the Fight Manual-listed V_{MCA} was required for the vertical fin and rudder to be able to generate a high enough side force to counter the increased yawing moment and maintain control of the airplane during the final phase of the flight (§ 2.5). The rudder however, was not fully deflected. Therefore, the airspeed required for generating a high enough rudder yawing moment was also higher.

5.2. The standardized V_{MCA} that is listed in the Airplane Flight Manual was 103 KIAS and was determined while the rudder deflection was maximal and the propeller of the inoperative engine was feathered and hence, its drag was low. Some of the other factors used to determine the Flight Manual-listed – worst case – V_{MCA} were: a small bank angle (as opted by the manufacturer, but max. 5 degrees) away from the inoperative engine, an aft cg and lowest possible weight (smallest side force $W \cdot \sin \phi$). The *actual* V_{MCA} is usually lower, safer, when the small bank angle is being maintained. However, the *actual* V_{MCA} varies considerably with bank angle and rudder deflection. Therefore, the Flight Manual-listed V_{MCA} is valid only if the bank angle is the same as the bank angle that was used during flight-tests to determine V_{MCA}, usually a small 3 – 5 degree bank angle away from the inoperative engine, as opted by the manufacturer, and with maximum rudder deflection (for zero yaw). The small bank angle is most probably not prescribed in the SF-340B Flight Manual as a requirement for maintaining control while an engine is inoperative, the thrust setting of the operating engine is high and the airspeed is low. This is regrettably not required by Aviation Regulations (yet). The higher required airspeed for the rudder to develop a higher side force to overcome the drag of the not-feathered propeller for maintaining control of the airplane was in fact a higher *actual* V_{MCA} than the standardized V_{MCA} that was listed in the Flight Manual.

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

5.4. The second loss of control during the approach occurred following event ⑧ at 12:45:56 and resulted in a catastrophe. Control of the airplane was lost, because the *actual* V_{MCA} increased above the indicated airspeed of 107 KIAS at that time. The increase of *actual* V_{MCA} was caused by:

(1) not attaining a small bank angle of 3 – 5 degrees away from the inoperative engine, (just) before advancing the throttle. This small bank angle is required to keep the *actual* V_{MCA} to the lowest possible value for the given conditions and to minimize the sideslip, therewith minimizing the drag and maximizing the remaining single-engine climb performance (§ 2.10). Due to not maintaining the small bank angle away from the inoperative engine, the *actual* V_{MCA} was higher than the Flight Manual-listed standardized V_{MCA} and in this case also higher than the indicated airspeed, causing the loss of control. The Flight Manual-listed V_{MCA} (103 KIAS in this case) is valid only if the bank angle is the same as used to determine V_{MCA} (and to size the vertical tail), in most cases 5 degrees away from the inoperative engine (§ 2.6).

(2) not increasing the rudder deflection during the thrust increase to maintain the heading. The yawing moment generated by only 50% of the available rudder deflection, at the given airspeed, was not high enough to prevent the airplane from yawing into the dead engine following the thrust increase (§ 2.4).
Although the indicated airspeed was still higher than the AFM-listed V_{MCA}, the *actual* V_{MCA} for the given 50% rudder deflection must have increased to a value higher than the indicated airspeed, leading to the loss of control. The AFM-listed V_{MCA} is valid only if the rudder deflection is the same as used to determine V_{MCA}, which usually is full rudder, or a deflection for which the pedal force is 150 lb (or 180 lb for military airplanes).

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

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

6. Safety recommendations

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

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

6.3. Improve aviation Regulations (FAR and CS 23.149 and 25.149) by adding the requirement to list the bank angle that was used to design the vertical tail and determine V_{MCA} with the V_{MCA} data in the Airplane Flight Manual. Additional recommendations for improvement of Regulations are presented in ref. B.

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

7. Could this accident have been prevented?

7.1. This question can be answered by a straightforward 'Yes'. This accident, like most engine failure related accidents, could have been prevented by either reducing the thrust asymmetry a little, or by timely applying controls to minimize the adverse effects of the thrust asymmetry. Either of these actions is only required when the airspeed is low and the asymmetrical thrust is high, which is the case during takeoff, go-around and when increased thrust is required in the traffic pattern to maintain altitude, or on final approach to maintain glide slope.

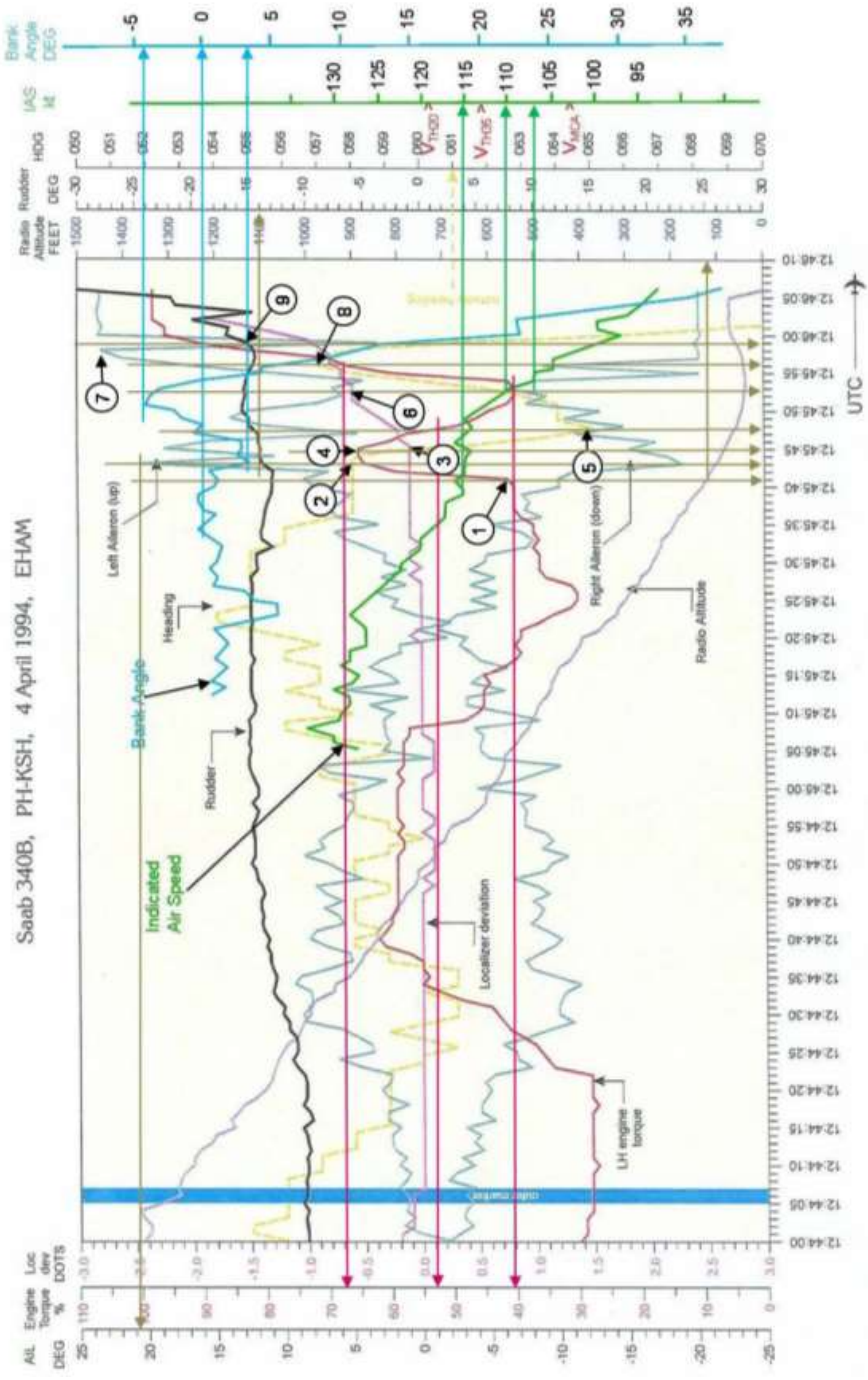
7.2. The thrust asymmetry could in this case have been reduced by either adding thrust on the idling right engine after which the thrust would have been symmetrical again and the airplane would have had normal performance to climb away, or by temporarily reducing the thrust of the left engine, but only as much as required to regain directional control and until the favorable 3 – 5 degree bank angle away from the inoperative engine is achieved. This thrust reduction option was effective during the first loss of control, as was discussed before (§ 4.6): as the pilot reduced the thrust on the left engine (event ④), directional control was restored.
At low altitude, the thrust reduction might not be considered a good option. However, if the airplane has become uncontrollable at low altitude, control can only be regained by closing all throttles. A straight ahead, but controlled landing in the dirt with the wings level is more survivable than hitting the ground uncontrolled and with a wing tip first, as happened here.

The best option after engine failure and during flight with an inoperative engine is always to minimize the adverse effects of the thrust asymmetry on airplane control and performance by applying rudder to control the yaw and maintaining a bank angle of 5 degrees away from the inoperative engine, both as soon as the throttles are moved forward. This way the *actual* V_{MCA} is kept as low as possible, which is good for maintaining control (and for the safety). In addition, the sideslip is kept to a minimum, which is favorable to the remaining one engine inoperative climb performance.
This is how V_{MCA} is determined during experimental flight-testing and hence also how V_{MCA} should be used by airline pilots. The V_{MCA} that is listed in Flight Manuals is valid only if the bank angle is the same as the bank angle used by the experimental test pilots of the manufacturer of the airplane to determine V_{MCA}. Any other bank angle will lead to an *actual* V_{MCA} that can be much higher and that unexpectedly might increase above the IAS, rendering the airplane uncontrollable. Please refer to ref.'s B and/ or C for a thorough explanation of V_{MCA} and for the prevention of accidents after engine failure. ■

Attachment 1: Combined graph with all required data from the Aircraft Accident Report (Ref. A).
Attachment 2: Graph with bank angle and airspeed.

Attachment 1: Combined graph with all required data from the Aircraft Accident Report.

Bank angle and airspeed data were copied from the plot in Attachment 2 for easier analysis.



Refer to § 4 for explanatory text

Attachment 2: Graph with bank angle and airspeed out of the Aircraft Accident Report.

The bank angle (roll angle) and airspeed data from this plot were copied into the plot in Attachment 1 on the previous page to allow for easier analysis. This plot is included for reference purposes only.