

# True Airspeed, Calibrated Airspeed, Indicated Airspeed, and Minimum Control Speed Explained

## As Taught at Test Pilot Schools

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### 1. Introduction

- 1.1. During reviewing Airplane Flight Manuals (AFM), the meaning and use of Calibrated Air Speeds (CAS) and Indicated Air Speeds (IAS) was found to be neither in compliance with the way these airspeeds are defined and used in Airworthiness Standard 14 CFR FAR 23<sup>2</sup> and equivalent EASA Certifications Specifications, nor as used during airplane design as taught at aeronautical universities<sup>3</sup>, and nor as taught at test pilot schools for experimental flight testing, including the calibration of pitot-static systems. Pilot Operating Handbook (POH) and AFM-writers, approving authorities, and pilots seem to struggle with understanding why these airspeeds exist and what their function is. Therefore, a few general remarks are presented in this paper to become aware of the real values of the used airspeeds. Misuse of the CAS and IAS in a POH or an AFM has led and still leads to fatal accidents. Reference is made to the applicable airworthiness and other regulations. The MSc level source of this paper is the *Pitot-Statics and the Standard Atmosphere* course book of the USAF Test Pilot School<sup>4</sup> that is approved for public release and is available for download from the US Archives. Instructors of all test pilot schools teach and conduct pitot-static system testing, i.e. airspeed system calibrations, many times each year to and with the students; they know what they are talking about, and share their knowledge to learn from.
- 1.2. Most manufacturers of Part 23 twin-engined normal and commuter class airplanes use the General Aviation Manufacturers Association (GAMA) Specification No. 1<sup>5</sup> for preparing their POH/AFM; the FAA and EASA have approved its use. AvioConsult reviewed a number of such POHs and AFMs and concluded that this Specification is regrettably not prepared with a high level of aeronautical competence and did not put the POH/AFM-writers of the GAMA member companies on the wrong foot, on several subjects. The review of GAMA Specification No. 1 is available separately<sup>6</sup>; therein it is recommended to withdraw the Specification, or at least improve it.
- 1.3. In the POH/AFM reviews, it was considered necessary to include a recap on the subject of the airspeeds used in an airplane, including the minimum control speed, based on the mentioned USAF Test Pilot School coursebook<sup>4</sup> and on FAR 23 and equivalent aviation regulations. This recap is presented in this paper. POH/AFM reviews are available from the downloads page of the website of AvioConsult(.com).

### 2. The Speeds of an Airplane

- 2.1. Pilots need to know what the airspeed of their airplane is, not only for navigation purposes, but also for the piloting task, for using operational and limiting speeds. Complicating is that the

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<sup>2</sup> Code of Federal Regulations, Title 14, Chapter I, FAR 23, 1–1–10 Edition was used in this review. Link to 2017 version: <https://www.ecfr.gov/on/2017-01-03/title-14/chapter-I/subchapter-C/part-23/subpart-B>.

<sup>3</sup> *Stability and Control during Steady Straight Flight*, Airplane Design Part VII, Dr. Jan Roskam, DAR Corporation, Kansas: <https://shop.darcorp.com/index.php?route=product/category&path=60>

<sup>4</sup> *Pitot-Statics and the Standard Atmosphere*, 4th edition (July 2020), Russell E. Erb, USAF Test Pilot School, <https://apps.dtic.mil/sti/pdfs/AD1115005.pdf>.

<sup>5</sup> GAMA Specification No. 1, Specification for Pilot's Operating Handbook, Rev. No. 2, 1996, <https://gama.aero/facts-and-statistics/consensus-standards/publications/gama-and-industry-technical-publications-and-specifications/>.

<sup>6</sup> Limited Review of GAMA Specification No. 1 for Pilot's Operating Handbook, Harry Horlings, AvioConsult, [https://www.aviiconsult.com/downloads/GAMA Specification No.1 for Pilot's Operating Handbook, Limited Review.pdf](https://www.aviiconsult.com/downloads/GAMA%20Specification%20No.1%20for%20Pilot's%20Operating%20Handbook,%20Limited%20Review.pdf).

airplane operates in a moving atmosphere at altitudes between ground level and the maximum operating altitude of the airplane. The temperature and air pressure in the atmosphere, also called density, change during the day and with altitude, and have effect on the performance of engines, on the aerodynamic (control) surfaces of the airplane, and on measuring the airspeed (and altitude).

Four speeds that are in use today are briefly explained, and in addition also the Minimum Control Speed  $V_{MC(A)}$ , because this limiting speed, that applies in anticipation of and following an engine failure, is misunderstood by most pilots, leading to accidents.

- 2.2. **True Air Speed (TAS, or  $V_t$ )** is the airspeed (velocity) at which the airplane is plowing the air mass which is not yet disturbed and influenced by the airplane (e.g. its bow wave), and which

$$V_t = \sqrt{\left(\frac{1}{\rho_a}\right)^7 P_a \left[ \left(\frac{P_T - P_a}{P_a} + 1\right)^{\frac{2}{7}} - 1\right]}$$

Figure 1. True Airspeed (TAS,  $V_t$ ) equation.

generates the aerodynamic lift and control power with respect to the ambient temperature (density  $\rho_a$ <sup>7</sup>) and pressure  $P_a$  at the flying altitude (Figure 1).

TAS is not useful for the piloting task, i.e. for control and performance, because of the influence of both ambient temperature and altitude. The use of TAS would require computing different speeds for each

combination of ambient temperature and altitude. In addition, it is quite complicated to build an accurate mechanical TAS indicator to account for the temperature and altitude effects, which was the reason to introduce the **Calibrated Air Speed (CAS)**, for which the *standard atmospheric pressure and temperature at sea level* are used as a reference, rather than the ambient pressure and temperature at flight altitude. CAS makes the piloting task and the use of pre-determined and flight-test acquired performance data, operating, and limiting speeds a lot more convenient.

TAS is the airspeed used by pilots for the navigation task, for calculating the speed and time enroute and is calculated from CAS using both the actual ambient pressure altitude and the outside air temperature, using a flight computer (E6-B), or by an on-board computer.

A proper definition of True Airspeed (TAS) is:

**TAS is the true airspeed of the airplane in an undisturbed airstream with respect to the ambient pressure and temperature**

As the standard atmospheric pressure and density (temperature) at sea level were used as references for the CAS, TAS is equal to CAS at sea level in a standard atmosphere.

- 2.3. **Calibrated Air Speed (CAS, or  $V_c$ )** is the airspeed (velocity) of the airplane in the undisturbed free airstream with reference to standard atmospheric pressure and temperature at sea level, as explained in the previous paragraph. The air pressures that are representative of the speed should be sensed by a long pitot-static boom that sticks out in front of the bow wave, which is not always practical. Therefore, the total pressure ( $P_T$ ) is sensed by a pitot tube mounted on fuselage or wings in disturbed air and the ambient (static) pressure ( $P_a$  or  $P_s$ ) by one or two flush ports, as shown in Figure 3 below. Both air pressures are fed into an Air Speed Indicator (ASI) which is constructed to sense the differential pressure  $P_T - P_a$  and indicate the corre-

$$V_c = \sqrt{\left(\frac{1}{\rho_{SL}}\right)^7 P_{SL} \left[ \left(\frac{P_T - P_a}{P_{SL}} + 1\right)^{\frac{2}{7}} - 1\right]}$$

Figure 2. Calibrated Airspeed (CAS,  $V_c$ ) equation.

sponding *calibrated airspeed with respect to the standard atmospheric pressure and density at sea level* ( $P_{SL}$  respectively  $\rho_{SL}$  in Figure 2), which are the references for CAS. The only variable is the differential pressure  $P_T - P_a$ .

At a constant differential pressure, the CAS will always be the same. Changes in sea level pressure and temperature will not affect CAS. Hence, CAS on one day is CAS on another day. Therefore, CAS is

<sup>7</sup>  $\rho$  is pressure P divided by (R (gas constant) times T (temperature)). Is the Equation of State  $P = \rho RT$ .

convenient for the piloting task (as compared to TAS); the AFM-published speed limitations such as  $V_S$ ,  $V_{MC}$ , and  $V_{MO}$ , and operational speeds such as  $V_1$ ,  $V_R$ ,  $V_2$  and  $V_{REF}$  are proportional to CAS for a given gross weight. CAS is also used to present performance data in an AFM. CAS in one airplane is CAS in another airplane of the same type. The CAS of two airplanes flying in formation should be equal. CAS is often inappropriately explained as being the abbreviation of Computed Air Speed, even by accident investigators.

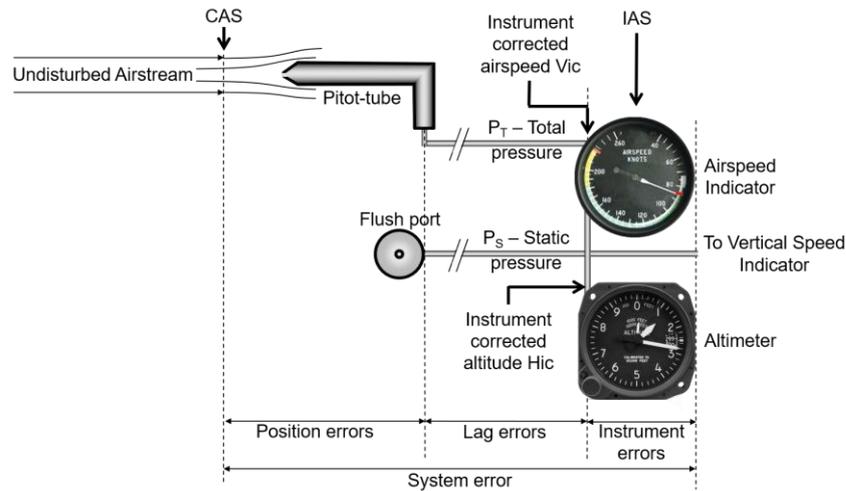


Figure 3. A common pitot-static system and its errors; from Calibrated Airspeed (CAS) in undisturbed airstream to Indicated Airspeed (IAS) on the Airspeed Indicator (ASI).

- 2.4. The definition of CAS in an AFM is almost always how to calculate CAS from IAS, like GAMA inappropriately recommends in Specification No.1: "Calibrated Airspeed means the indicated airspeed of an airplane corrected for position and instrument error". CAS is indeed IAS corrected for instrument and position error, in this order though, but CAS "means" much more. CAS is used during flight-testing to determine and report limiting and operational speeds, and performance data. The use of CAS allows the manufacturer or operator to use (copies of) the same POH/AFM for a series of airplanes of the same type that have identical pitot-static systems (position errors). The FAA or equivalent authority then must approve only one AFM. Finally, CAS is the origin of the other airspeeds and deserves a better, appropriate, and explaining definition.

Therefore, the definition of Calibrated Airspeed (CAS) should be:

**CAS is the calibrated airspeed in the undisturbed airstream with respect to the standard atmospheric pressure and temperature at sea level**

CAS is the IAS corrected for position and instrument errors.

- 2.5. **Errors In Pitot-static system.** Prior to explaining Indicated Airspeed, the pitot-static system errors (Figure 3) need some clarification. The system errors consist of position, lag, and instrument errors which will be discussed briefly.

2.5.1. **Position Error.** The consequences of positioning the pressure sensors in disturbed air and flush on the fuselage are errors in the pressure measurements, called position errors. The error due to angle of attack and angle of sideslip in the normal flight range is usually close to zero. FAR § 23.1323 (b) determines: "the pitot-static system error, excluding the ASI calibration error, to not exceed the maximum of 3% of CAS or 5 kt". Position errors are determined during in-flight calibration for several configurations (flaps, gear, weight) over a range of airspeeds and altitudes and are furnished in graphs in the AFM for use by pilots.

2.5.2. **Instrument Errors.** An ASI has errors too, the instrument errors, as shown in Figure 3 and requires **calibration** as well. Calibration of both the pitot-static system and the ASI gave the calibrated airspeed its name; CAS is the airspeed with maximum obtainable accuracy (for subsonic flight). The expansion of the aneroid (diaphragm or bellows) within a mechanical ASI

due to the difference between  $P_T$  and  $P_S (= P_a)$  is translated by mechanical parts to the pointer of the ASI which rotates above an airspeed scale indicating the IAS. The mechanism in the ASI is designed and constructed to indicate the airspeed with respect to the standard atmospheric pressure and temperature (ISA) at sea level (equation in Figure 2).

The errors between the air pressures  $P_T$  and  $P_a$  at the entrance ports of the ASI and the eyes of the pilot(s), caused by the mechanical parts within the ASI, such as manufacturing discrepancies, magnetic fields, hysteresis or friction, altitude, temperature changes, vibration, inertia of moving parts, and the parallax, contribute to the total instrument error. The instrument error of each individual ASI over a range of airspeeds is determined in an instrument laboratory during calibration at sea level in a standard atmosphere, as required by FAR § 23.1323(a). SAE AS 8019 presents detailed ASI specifications, but this document is not freely accessible. In another AFM, the permissible instrument error is mentioned to be  $\pm 4$  kt at speeds above 50 kt. In addition, the friction of the pointer "*must not produce an error exceeding 3 kt*".

Hence, in a worst-case situation, the difference between the IAS indicated on two ASIs connected to the same pitot-static system is allowed to be up to 8 kt (if one error happens to be  $-4$  kt and the other  $+4$  kt) while the CASs, calculated after adding the known instrument correction of each ASI and the (common) position error correction of the pitot-static system, are equal.

2.5.3. The pressure difference  $P_T$  minus  $P_a$  (or  $P_S$ ) at the entrance of the ASI is a measure of the IAS plus or minus the instrument error, and is also called the *instrument corrected airspeed* Vic (Figure 3), which is to be used as the entry variable for the position error chart in the AFM when calculating CAS from IAS.

2.5.4. **Lag errors.** The pressure lag errors are caused by the friction, the pressure drop and the inertia of the air mass in the air tubes causing a small delay, but are considered not to have influence except when changing airspeed or altitude. These errors will not be further discussed.

2.5.5. **Errors in Electronic Air Data systems and displays.** Modern air data systems do not have a mechanical ASI anymore (except for a backup/ alternate). Such a system however, still has the errors as shown in Figure 3. Pressure transducers in the air data system convert the analog air pressures  $P_T$  and  $P_S$  into digital output data for further processing and display. Besides analog to digital conversion errors, also drifting of the output can occur over time; fluctuations of electrical power supply voltage and equipment temperature might affect the output data as well. Such an air data system would require calibration, which might include both pitot-static position and "instrument" calibrations, of which the result could be entered in the computerized air data system for correcting the errors. Then the airspeed indicated on the ASI (speed tape) has become the CAS of the airplane, the only relevant, accurate speed for the piloting task which is also the only airspeed that should be used in the POH/AFM. The piloting task becomes easier and faster. Less failures will be made if the pilot only works with CAS. In most older airplanes though, the pilot must still work with both the position and instrument errors and hence with both CAS and IAS.

2.5.6. **Total system error.** The sum of both position and instrument errors comprises the relationship between CAS and IAS. FAR § 23.1587(d)(10) requires this relationship to be furnished to the pilot for commuter category airplanes. The maximum regulations-approved airspeed error, being the sum of the approved instrument and position errors, is in a worst case allowed to be as high as  $(4 + 5 =) 9$  kt (FAR § 23.1323(b) and SAE AS 8019). An additional friction error of up to 3 kt might occur during acceleration (takeoff) or deceleration. These are numbers that a pilot needs to be made aware of for being able to plan and conduct the takeoff, approach, and landing safely, and for handling the airplane, including in case one engine fails or is inoperative.

2.5.7. Hence, the airspeed indicated by the pointer of the (mechanical) ASI is not the CAS anymore; the inherent system errors (Figure 3) affect the air pressures  $P_T$  and  $P_a$  enroute from the undisturbed air ahead of the airplane to the ASI, and the conversion of the air pressures

within the ASI up to the airspeed indicated by the pointer. Hence, CAS cannot be directly indicated in the cockpit but must be calculated by the pilot by adding both the pitot-static position error and the ASI instrument error to the airspeed indicated by the Airspeed Indicator (ASI), and the results written on a Takeoff and Landing Data card, or by positioning bugs on the ASI. The errors can be positive, zero or negative. Backwards, when the pilot needs performance data out of the AFM while in-flight, IAS values read from the ASI need to be corrected with the instrument error (=Vic), which is then used to find the position error to be added to calculate the CAS to enter the performance graphs in the AFM.

- 2.6. **The Indicated airspeed (IAS)** is the speed indicated or displayed on an Airspeed Indicator (ASI), which is the CAS including the inherent pitot-static position and instrument errors (Figure 3), and hence is not the airspeed anymore at which the airplane moves through the air. IAS is a speed that is not directly useful for pilots, however, it is the only speed that the pilot can work with; it needs corrections to become a valuable airspeed.

IAS exists because an ASI is simple in design and construction and is easy to calibrate, but also has unavoidable manufacturing and other errors, which were already mentioned in § 2.5.2 above. The errors of individual ASIs differ from each other, reason why each ASI needs to be calibrated individually in a laboratory and its error published in a calibration report (small table) and furnished to the pilot (FAR 23.1323). *The IAS indicated by two ASI's in one cockpit may disagree with  $\pm 4$  kt (total of 8 kt) due to different instrument errors.* The difference of instrument errors between ASIs in the same cockpit and in the fleet of airplanes of the same type for which a single AFM applies, and changes in instrument errors due to future maintenance replacements of ASIs, are the reasons that limiting and operational airspeeds cannot be furnished as IAS in a single AFM that applies to a series of airplanes. The indicated airspeed IAS is not accurate enough to be of direct value to pilots. The IAS of two airplanes flying in formation are most probably not equal, while their CASs should be-

As noticed during reviews of manuals, many if not all AFMs consider the instrument error to be zero, which is not in compliance with FAR 23. It makes the IAS less accurate ( $\pm 4$  kt). IAS is not really the airspeed of the airplane, but an airspeed comprising errors.

A proper definition of Indicated Airspeed (IAS) is:

**IAS is the airspeed indicated on an airspeed indicator and is CAS including the error due to the position of the pitot tube and the ASI instrument error**

- 2.7. **Ground Speed (GS).** The flow of the airmass through the atmosphere, such as the wind, also has influence on navigation. The speed of the airplane relative to the ground, called the Ground Speed, is the TAS plus or minus a tail- or headwind component. Ground speed allows calculating the distance travelled in a period.

Finally, the definition of Ground speed (GS) is:

**GS is the airspeed relative to the ground, and is the TAS corrected for the wind**

- 2.8. **Equivalent Airspeed (EAS)** is still taught at test pilot schools and universities, and was used by pilots before World War II, but the difference with Calibrated Airspeed is small and within acceptable tolerances for Part 23 airplanes.
- 2.9. **Further reading.** Refer to the (free) book *Pitot-Statics and the Standard Atmosphere* in footnote 4 on page 1 for a complete course at MSc level on pitot-statics, airspeeds, altitudes, and the standard atmosphere.
- 2.10. This paper is about airspeeds, the altimeter errors were not mentioned but are addressed in FAR 23. The calibration is required in FAR § 23.1325(e).

### 3. Calibrated and Indicated Air Speeds in Federal Aviation Regulations (and equivalent)

- 3.1. FAR 23 "prescribes airworthiness standards for the issue of type certificates, and changes to those certificates, for airplanes in the normal, utility, acrobatic, and commuter categories. Each person who applies under Part 21 for such a certificate or change must show compliance with the applicable requirements of this part".

Hence, FAR 23 is intended to be used by airplane design engineers for designing airplanes (including sizing the vertical tail); and for the certification of the airworthiness of the airplanes. Non-compliance with FAR 23 renders the type certificate and hence, the certificate of airworthiness of an individual airplane invalid. Below, a few relevant FAR paragraphs are described and explained that are needed during this review.

- 3.2. GAMA Specification No. 1 is originally intended for Normal Category Airplanes, but it is also used for Commuter Class POH/AFM. Therefore, several Regulatory paragraphs of FAR 23 (1-1-10 Edition) for normal category (< 9 pax), commuter category (< 19 pax and MTOW < 19,000 lb), and SFAR No. 23 (> 10 occupants/Part 135), about airspeeds are partly copied below with some remarks added. This chapter was originally written for an FAA certified airplane, which is the reason for references to FAR § 23. The review also applies to EASA CS 23 paragraphs.

#### 3.3. FAR § 23.1581

*"(c) The units used in the Airplane Flight Manual must be the same as those marked on the appropriate instruments and placards".*

*"(d) All Airplane Flight Manual operational airspeeds, unless otherwise specified, must be presented as indicated airspeeds".*

These requirements did not yet exist in the 1970 edition of FAR 23, and must have been included after the issue of GAMA Specification No. 1, which was regrettably not written with a high level of aeronautical expertise, as described in the *Limited Review of GAMA Specification No.1 for Pilot's Operating Handbook*<sup>6</sup>.

"Units" refers to mph or knots, not to KCAS or KIAS. Since the word "marking" is used in the same sentence, the writer might mean that the markings on the ASI must be in KIAS (of course), but that KIAS must also be used in the AFM, which is not possible.

Presenting all operational airspeeds as IAS requires a single POH/AFM for each and every airplane of the same series/type because the errors of the installed ASI's might differ, unless the instrument error is neglected (is assumed zero), which introduces unacceptable inaccuracies that affect the safety of flight, and which is not in compliance with other FAR 23 and Advisory Circular requirements.

- 3.4. **FAA Flight Test Guide AC 23-8C**<sup>8</sup> in Section 2, § 3 d specifies for commuter category airplanes: *"(1) Takeoff Speeds. The following speed definitions are given in terms of calibrated airspeed"*. The "following speed definitions" are those of:  $V_{EF}$ ,  $V_1$ ,  $V_R$ ,  $V_{LOF}$  and  $V_2$ . Not included are  $V_S$  and  $V_{MC}$ , although both are used to calculate  $V_R$  and  $V_2$ . Limiting speeds  $V_S$  and  $V_{MC}$  should therefore also be specified here as calibrated airspeeds, like they are in FAR § 23.51 and § 23.149. These operational airspeeds are determined and/or calculated following (experimental) flight tests, and usually presented as CAS for reasons described in the paragraphs above and in § 4 below. These obviously do not need to be presented in IAS in an AFM.

AC 23-8C continues with: *"The AFM presentations are required, by 23.1581(d), in indicated airspeed (IAS)",* except for the "following" operational and limiting airspeeds, that were mentioned above. AFM presentations cannot be (accurate) in IAS in an AFM that applies to a series of airplanes, and of which the instrument errors are assumed zero. This requirement must have been included following the issue of GAMA Specification No. 1 which, as already mentioned, is not written with competence at a high aeronautical level of knowledge. What a pilot must do is find the appropriate and needed operational and limiting airspeeds in CAS for a particular flight in the AFM data tables and/or graphs, and correct these to IAS by applying both

<sup>8</sup> FAA Flight Test Guide, AC 23-8C: [http://www.faa.gov/documentLibrary/media/Advisory\\_Circular/AC\\_23-8C.pdf](http://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_23-8C.pdf).

the position error in the AFM and the instrument error found in the calibration report of the ASI (a small table) installed in the particular airplane during preflight and present these IAS values on the Takeoff and Landing Data (TOLD) card for use in the cockpit, one for each ASI. Presenting IAS in an AFM that is issued for a series of airplanes is intolerable and asking for fatal accidents, and is not in compliance with FAR 23 either. See further § 4 below.

- 3.5. **Pt. 23, SFAR No. 23, § 5(b)(1)** requires decision speed  $V_1$  to be in CAS.  $V_1$  is calculated using  $V_S$  and  $V_{MCG}$ , so these speeds must also be provided in CAS (FAR § 23.51 and § 23.149).
- 3.6. **Pt. 23, SFAR No. 23, § 7** and FAR § 23.73 also requires the landing approach speed  $V_{REF}$  in CAS, because the source speeds  $V_{MC}$  and  $V_S$  are in CAS (FAR § 23.51 and § 23.149).
- 3.7. **Pt. 23, SFAR No. 23, § 20 (f)** determines that the performance information in the AFM must include: "Airspeeds, as indicated airspeeds, corresponding to those determined for takeoff in accordance with section 5(b)". Section 5(b) defines takeoff speeds  $V_1$  and  $V_R$  in CAS, because  $V_S$  and  $V_{MC}$  are also determined in CAS (FAR § 23.51 and § 23.149). The instrument errors between airplanes differ, hence the takeoff speeds in IAS (as required here) will not be accurate in an AFM that applies to a series of airplanes of the same type. This is not in compliance with other paragraphs in FAR 23 either, such as § 23.51.
- 3.8. **FAR § 23.51(a)** requires rotation speed  $V_R$  for normal category airplanes to be not less than  $1.05 V_{MC}$  or  $1.1 V_{S1}$ . As  $V_{MC}$  and  $V_S$  are determined in CAS,  $V_R$  will also be in CAS (see also the Flight Test Guide quote in § 3.4 above). For commuter category airplanes (§ 23.51(c)),  $V_1$ ,  $V_R$ , and  $V_2$  must be established/selected in terms of CAS as well. Hence, FAR § 23.51 specifies the operational takeoff speeds  $V_1$ ,  $V_R$ , and  $V_2$  and stall speed  $V_S$  to be presented as CAS in the AFM. FAR § 23.73 specifies the landing approach speed  $V_{REF}$  as CAS, and FAR § 23.149 specifies both  $V_{MC}$  and  $V_{MCG}$  as CAS. Hence, these are the operational and limiting airspeeds that are "otherwise specified" (§ 3.3 above) and hence, should not be presented as indicated airspeeds in an AFM, the reason being that these speeds are critical to flight safety and need to be quite accurate and reliable. As mentioned in § 3.4 above, the pilot must calculate the corresponding IAS values of the operational and limiting speeds by adding both the position error and the instrument error of the installed ASI to the CAS values and present these on a Takeoff and Landing Data card for use in the cockpit.
- 3.9. **FAR § 23.1323(a) and Pt. 23, SFAR No. 23, § 13(a)** require: "Each airspeed indicating instrument must be calibrated to indicate true airspeed (at sea level with a standard atmosphere) with a minimum practicable instrument calibration error when the corresponding pitot and static pressures are applied". Each ASI is calibrated in a laboratory to determine its instrument error, being the error between the air pressures at the entrance ports ( $P_T$  and  $P_s$ ) and the airspeed indicated by the pointer on the dial of the ASI. The IAS + the instrument error is also called  $V_{ic}$  (§ 2.5.3). There is no requirement for ASI calibration at higher altitudes, only for a range of speeds at sea level, because the reference airspeed and temperature used in the ASI are standard atmospheric sea level pressure and density (Figure 2).
- 3.10. **FAR § 23.1323 (b)** requires: "Each airspeed system must be calibrated in flight to determine the system error. The system error, including position error, but excluding the airspeed indicator instrument calibration error, may not exceed three percent of the calibrated airspeed or five knots, whichever is greater, throughout the following speed ranges: ...". A similar requirement in **Pt. 23, SFAR No. 23, § 13(b)**: "The airspeed indicating system must be calibrated to determine the system error, i.e., the relation between IAS and CAS, in flight and during the accelerate takeoff ground run", and in **§ 13(d)**: "information showing the relationship between IAS and CAS must be shown in the Airplane Flight Manual". The system error is the position error plus the lag error (Figure 3 above), but excluding the instrument error. The lag error is often neglected because it has effect only during pressure changes, which do not occur during steady flight. Hence, the relationship between IAS and CAS is the sum of the instrument error of the ASI and

the position error of the pitot-static system:  $CAS = IAS + \text{instrument error} + \text{position error}$ . The instrument error cannot be presented in an AFM for a series of airplanes of the same type, as explained above, only the position error must be provided in a chart or table. The instrument error should be mentioned though in the AFM, certainly in the legend of the position error chart, because the pilot must read the airspeed instrument correction from an instrument error correction table and add this to the IAS to calculate the instrument corrected airspeed ( $V_{ic}$ ) which is then used to enter the position error chart to read the position error or CAS. An IAS to  $V_{ic}$  conversion table is to be made and be available for each individual ASI (for each serial number).

- 3.11. So, **FAR § 23.1323** requires both the pitot-static system and the airspeed indicator instrument to be calibrated separately. The calibration data of both must be made available to the pilot to be able to calculate the CAS from the IAS during flight, and to calculate pre-flight determined performance data and takeoff speeds from CAS in the AFM to IAS for use in the cockpit (on the Take Off and Landing Data (TOLD) card). The GAMA Specification No. 1 seems not to mention the instrument calibration error, on the contrary, GAMA assumes and recommends zero instrument error and therefore does not comply with several FAR 23 paragraphs. It should not have been approved by the aviation authorities.
- 3.12. **FAR 23.1581.** *"An Airplane Flight Manual must be furnished with each airplane, and it must contain the following:*  
*(1) Information required by §§23.1583 through 23.1589.*  
*(2) Other information that is necessary for safe operation because of design, operating, or handling characteristics."*  
 §§ 23.1583 and 23.1587 are copied in the next paragraph. Not only minimum control speed  $V_{MC}$  must be furnished as number, but also other information necessary for safe operation after engine failure.  $V_{MC}$  and its associated conditions will be explained in § 5 below.
- 3.13. **FAR 23.1583** requires that *"the AFM must contain operating limitations"*, including:  
*"(1) Information necessary for the marking of the airspeed limits on the indicator as required in §23.1545, and the significance of each of those limits and of the color coding used on the indicator.*  
*(2) The speeds  $V_{MC}$ ,  $V_O$ ,  $V_{LE}$ , and  $V_{LO}$ , if established, and their significance"*.  
 Hence, the airspeed limits that require marking on the indicator must be furnished in the AFM, these are in CAS. The marks must be located at the corresponding indicated airspeeds, meaning at CAS plus the position error of the pitot-static system and plus the instrument error of the to be marked airspeed indicator. The errors can be positive or negative. If the instrument error is considered zero in the POH/AFM, then the markings are on a wrong location on the indicator. The error can be up to  $\pm 4$  kt, a range of 8 knots.  
 In addition to the markings, the significance of the speeds in (2) must be contained in the AFM.
- 3.14. **In FAR § 23.1587(d):** *"In addition to paragraph (a) of this section, for commuter category airplanes, the following information must be furnished— (10): The relationship between IAS and CAS determined in accordance with §23.1323 (b) and (c)";* (is an error, must be (a) and (b)).  
 The relationship between IAS and CAS is the sum of the position error ( $\leq 5$  kt) and the instrument error ( $\leq 4$  kt), i.e. is between 0 and 9 kt depending on the airspeed, and can be 3 kt higher due to the approved friction error when the airspeed decreases or increases.  
 This FAR paragraph requires both the position error and the instrument error to be furnished. The position error is usually published in a chart in the AFM, but the separately to be provided instrument error seems forgotten, while it can be larger than the position error. Not furnishing instrument errors, or assuming instrument errors to be zero is not in compliance with this FAR paragraph.
- 3.15. **Summary IAS and CAS in FAR.** The use of IAS and CAS in Regulations is confusing and, given the GAMA Specification No. 1, is not understood either, is even misinterpreted. The impression is that several paragraphs were changed to match GAMA Specification No.1, while other paragraphs are not, causing inconsistencies (§ 3.3). The GAMA Specification No. 1 is indeed

mentioned in the FAA Flight Test Guide (page 163 and more). The consequences of changing airspeeds from CAS to IAS in POH/AFMs might not have been obvious to the rule makers, because of lack of proper high-level knowledge of pitot-static systems and its errors, and of the effect of small airspeed errors on the controllability of airplanes (§ 4.4 below).

- 3.16. The (improper) FAR requirement for the use of IAS in AFMs can only be met if, besides the position error, also the instrument errors of each individual ASI in all airplanes of the same type, for which the AFM applies, are known to the AFM-writer, including the errors of a second or third (alternate) ASI in the same cockpit. This would lead to a large data table, the use of which would be prone to errors. Requiring presenting IASs in an AFM requires a separate AFM for each individual ASI (due to its instrument errors), and not just one AFM for a series of airplanes of the same type. This is expensive, and not acceptable for controlling the manuals. A maintenance replacement of a defective ASI would lead to a change in all IASs published in the AFM of the airplane. Changing limiting or operational indicated airspeeds in the FAA approved part of an AFM requires approval of the FAA and printing new manuals, which takes quite some time during which the airplane is grounded, unless the instrument error of the new ASI is the same as of the replaced ASI.

In addition to the amendment of the AFM of the specific tail number, the required red radial line indicating  $V_{MC}$  on the ASI (FAR § 23.1545(b)(6)), or for airplanes >6000 lb and turbine engine-powered airplanes the placard in the cockpit (FAR § 23.1563(c)) with airspeed limitations also needs to be amended and/or replaced. If the instrument error is considered zero, then the AFM will not include the instrument error with the consequence that the markings on the new ASI and/or placard will not be at the correct location (FAR § 23.1583). Safety is at stake.

This cannot be the intention of these GAMA-amended and -added FAR requirements; they obviously are unworkable, and must be in error (or are misunderstood). An ASI must be accompanied by an instrument correction table for a range of airspeeds on the instrument panel, for the pilot to be able to calculate the indicated airspeed that corresponds with the CAS value, and the markings must be at the right location. When the author of this review started flying Part 23 airplanes in the early seventies, such a table could still be found on the instrument panel.

It seems that many manufacturers avoid the use of the instrument error by prescribing a zero-knot instrument error in their AFM, unaware of the consequences for flight safety. The relationship between CAS and IAS is then only the pitot-static position error, but this is not in compliance with FAR 23, and leads to inaccurate indication of limiting and operational speeds, and to fatal accidents.

- 3.17. **Conclusion.** FAR and SFAR 23, and FAA Flight Test Guide AC 23-8C are not very clear and consistent on the requirement for the use of CAS and/or IAS in an AFM. It appears that some paragraphs were amended following the issue of GAMA Specification No. 1, and others were not. Hence, the regulatory paragraphs are not understood. They might have been written or amended by people who never studied pitot-static systems, airspeed properties, and calibrating at a level higher than (airline) pilots have. FAR § 23.51, § 23.73 and § 23.149 specify the limiting and operational speeds to be established and selected as CAS. The relationship between CAS and IAS, being the sum of the position and the instrument errors, needs to be furnished to the pilot, to be able to calculate IAS from CAS and vice versa. The markings on the ASI and the placard, must not only include the position error, but include the instrument error as well. It is neither required in FAR 23, nor possible, to present accurate operational airspeeds, that are determined as CAS, as indicated airspeed in an AFM, if the instrument errors are unknown or are considered zero. Doing so affects flight safety.

#### 4. Calibrated and Indicated Air Speeds in an AFM

- 4.1. The takeoff, stall, minimum control, cruise and landing approach speeds, and the handling qualities of the airplane were determined during experimental flight tests with a calibrated airspeed measuring system, and were reported as CAS for a given gross weight (mass). These, for

flight operations important speeds are usually also published as CAS in an AFM because then they are valid for all airplanes of the same series/type, for which the AFM applies. As also mentioned above, another reason for publishing airspeeds as CAS is that the AFM-writer does not know the instrument error of each individual ASI installed in any production airplane (at any one time, now or in the future). The position error of the pitot-static system must be published for a range of airspeeds in a chart in the AFM, and an airspeed instrument error correction table should be available showing the airspeed correction for each individual installed ASI, except for a few categories of airplanes, unless the errors are compensated for in a computerized air data system (§ 2.5.5 above). The airspeed instrument correction table should be mentioned in the AFM, like all required placards are. With this table, and with the position error chart in the AFM, the pilot can determine the Indicated Airspeed to maintain the corresponding Calibrated Airspeed (that is published in the AFM as limitation, operational, or performance speed) and write these on the Take Off and Landing Data card.

- 4.2. GAMA Specification No. 1 requires airspeeds to be published in IAS, because *"the pilot exclusively works with IAS"* (Preface). The pilot who wrote this, or who approved this on behalf of all GAMA members is not a competent pilot, and probably never studied pitot-statics at a higher level. It is also incomprehensible that GAMA members approved this; none of them obviously consulted a graduate of one of the test pilot schools or an aeronautical engineer. They might not even employ one, which proves incompetence, leading to the question whether their airplanes are well developed and flight-tested.
- In addition to the quote in the Preface of GAMA Specification No. 1, § 2.3 requires to *"Provide airspeed limitations and the operational significance of such limitations. The name, symbol, value in knots, CAS, and LAS (assuming zero instrument error) and the significance of each airspeed, shall also be provided"*. The requirement to provide IAS data might cause confusion, and certainly also errors because the instrument errors of all individual airspeed indicators are and cannot be included in a POH/AFM that applies to a series of airplanes of the same type, only the position error in the relationship between IAS and CAS can (§ 3.10 above).
- This requirement is not in compliance with FAR 23. A recommended instrument error of zero knot might lead to controllability problems, while the pilot believes to be safe when reading the ASI, as an example will show.
- 4.3. *An example:* The minimum control speed  $V_{MC}$ , determined during experimental flight-tests, is 66 KCAS. With a position error CAS to IAS of  $-2$  kt, and an instrument error of  $+4$  kt, the  $V_{MC}$  on the ASI is  $66 - 2 + 4 = 68$  KIAS. In an AFM that publishes indicated airspeeds with a zero instrument error, as GAMA recommends, the measured  $V_{MC}$  of 66 KCAS is indicated on the ASI as 66 KCAS minus only the 2 kt position error,  $66 - 2 = 64$  KIAS, which speed might also be the POH/AFM published, red-lined, or placarded  $V_{MCA}$ . When maintaining this 64 KIAS, the red-lined or placarded  $V_{MCA}$ , the pilot believes to be safe, but his airspeed is 4 kt, the magnitude of the instrument error, below the published  $V_{MC}$  (68 KIAS), and he will lose control when an engine fails, the other engine is set at maximum thrust, and the small favorable bank angle is not maintained. The takeoff speeds (in IAS), if calculated using  $V_{MC}$  as IAS with zero instrument error, will also be too low. If the  $V_{MC}$  marking on the ASI of normal category Part 23 airplanes is positioned using both the position and the instrument errors, then the pilot will notice the pointer is below the published  $V_{MC}$  as IAS and he needs to accelerate.
- These data are for straight flight only, while maintaining a small  $5^\circ$  bank angle away from the inoperative engine. The increase of  $V_{MC}$  with the wings level or during a turn is not included and will be discussed below (§ 5.25). CAS and both errors are required to provide safe indicated  $V_{MC}$  and other limiting and operational speeds to the pilot.
- 4.4. Readers, like the writers of the GAMA Specification No. 1 and the reviewers of the FAA, might believe 1, 2 or even 4 kt is not that big of an (instrument) error, so why all the fuzz. But it is not about the few knots, it's all about physics, about the forces and moments generated by the freestream air at the calibrated airspeed around the wings and the aerodynamic control surfaces that produce the lift and the control forces which are required to maintain the

equilibrium of forces and moments, i.e. to maintain control of the airplane. The aerodynamic forces are proportional to the square of the airspeed ( $V^2$ ), as shown in the lift equation:  $Lift = C_L \frac{1}{2} \rho V^2 S$ . A few knots difference at a higher speed has a larger influence on the generated control forces, which decreases with decreasing airspeed ( $V^2$ ).  $V_{MC}$  testing proves that a speed of only one knot below  $V_{MC}$  results in the loss of control when an engine fails; rudder and/or ailerons lost the control power required to maintain the equilibrium of forces and moments. On the other higher speed side, a rudder ratio changer in large airplanes prevents overloading the vertical fin, by reducing the rudder deflection per degree of rudder pedal travel with an inverse quadratic function of the increasing airspeed rather than with a few knots.

- 4.5. **Conclusion.** FAR 23 requires airspeeds to be provided accurately; rules were made many years ago with competence and should not be amended or neglected by ignorance, because **physics has no mercy.** **Pilots have the right to be made aware of the errors in the pitot-static systems for them to be able to apply the correct speed corrections and hence, apply the correct and safe operational and limiting airspeeds, which were determined in CAS, to conduct a flight and return home safely, including after engine failure.** Pilots cannot be allowed to "*exclusively work with IAS*". If they do, their airplane is not airworthy as required by FAR 23. Pilots must work with CAS in graphs and tables in a type-generic AFM, and must add the position error in the AFM and the instrument error of the particular ASI in the airplane to the CAS to obtain IAS to be able to relate to, to work with, airspeed indications and markings on the ASI in that specific airplane (tail number) that indeed correspond to the CASs in the AFM.
- 4.6. In GAMA Specification No. 1 many more statements are found that are not in agreement with FAR 23 and FAA Flight Test Guide. The writers and/or advisors of the Specification obviously had a disappointing low-level understanding of airplane speeds, performance, and control, and of FAR 23. A POH/AFM prepared with their Specification No. 1 did not contribute to preventing many fatal accidents referred to in the *List of Reported Accidents with Multi-Engine Airplanes After Engine Failure*<sup>9</sup>. GAMA made a huge mistake by not hiring aeronautical expertise at MSc or test pilot school level. It is also incomprehensible that the FAA and EASA approved GAMA Specification No. 1 and the many different AFMs that were prepared using the Specification.
- 4.7. An AFM is designated by number in the Type Certificate Data Sheet of the airplane, and is mandatory for the airplane to be operated airworthy. Many accidents occurred and were investigated by TSBs around the globe, but obviously none of these boards reported errors in the AFM and recommended or mandated improvements during the past 50 years. Aviation is drifting into failure due to incompetence of key-personnel that the public relies on.

## 5. Minimum Control Speed $V_{MC}$ or $V_{MCA}$

- 5.1. When an engine of a multi-engine airplane fails or is inoperative, the pilot needs to counteract the asymmetrical thrust yawing and rolling forces and moments using the rudder and ailerons continuously. Therefore, a flight with asymmetrical thrust is not a coordinated flight. The forces and moments generated by the aerodynamic controls rudder and aileron are proportional to the square of the airspeed ( $V^2$ ). So, whatever the attitude or configuration of the airplane, there always is an airspeed below which the asymmetrical thrust, the gravity induced forces, and other forces and moments can no longer be counteracted with rudder and ailerons, and an equilibrium of forces and moments can no longer be maintained. This airspeed is called the minimum control speed. FAR 23 defines minimum control speed as  $V_{MC}$  for the takeoff configuration which is to be published in the AFM. Other publications also use  $V_{MCA}$ , for  $V_{MC}$  "*in the Air, or Airborne*". Both refer to the same speed. This review uses both abbreviations separately or combined as  $V_{MC(A)}$ , but in addition also "*actual  $V_{MCA}$* ", which is the  $V_{MC}$  when the configuration, flap setting, bank

<sup>9</sup> List of Reported Accidents with Multi-Engine Airplanes After Engine Failure, Harry Horlings, AvioConsult, <https://www.avioconsult.com/downloads/List%20of%20accidents%20after%20engine%20failure.pdf>.

- angle, etc. are not as prescribed in FAR 23.149 for the takeoff configuration, and a higher airspeed is required to maintain the equilibrium of forces and moments during actual circumstances, such as a larger bank angle, a non-feathered propeller, or other asymmetrical drag. A minimum control speed applies always in-flight in anticipation of, and following an engine failure, not only during takeoff. The *actual*  $V_{MCA}$  increases to a value higher than the published  $V_{MC}$  with bank angle, i.e. during turns, as will be explained below.
- 5.2. During reviewing the GAMA Specification No. 1, several AFMs, and many investigation reports of accidents after engine failure, it was noticed that the AFM-writers, the mishap pilots, and accident investigators were not aware of the real value of  $V_{MC}$ , and of the associated conditions for  $V_{MC}$  to be valid. Therefore below, in addition to the papers presented on the website of AvioConsult, a few highlights of  $V_{MC}$  are explained in this paper below using FAR/EASA CS 23, the FAA Flight Test Guide AC 23-8C, and courses of a test pilot school, one of which is for the prediction of  $V_{MC}$  prior to conducting  $V_{MC}$  testing. Copies of the applicable Regulatory paragraphs, Flight Test Guide and course manuals are brought together in one *Background  $V_{MCA}$  Info* pdf file<sup>10</sup> for the reader to be able to verify what is written below.
  - 5.3.  $V_{MC}$  is defined in FAR § 23.149(a) (and equivalent) as follows: " $V_{MC}$  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".
  - 5.4. This definition, although intended for the design and certification of airplanes for which FAR and CS 23 apply, is also often copied into Airplane Flight Manuals (AFM) but is usually misunderstood by pilots and accident investigators. To improve the understanding of  $V_{MC}$ , this paragraph briefly explains the sizing of the vertical tail, the effect of bank angle on  $V_{MC}$ , and the flight test techniques used to determine  $V_{MC}$ . Readers will become familiar with the real value of the  $V_{MC}$  that is published in the AFM of multi-engine airplanes and with the conditions for which the published  $V_{MC}$  is valid, which is of vital importance for preventing engine failure related accidents and for getting home safely after an engine failure. Accident Investigations will also improve.
  - 5.5. **Limitations Due To the Size of the Vertical Tail.** In Figure 4 below, the most important forces and moments are shown that act on a multi-engine airplane during steady straight flight when engine #1 is inoperative and the wings are kept level. As for any physical body, an airplane is in equilibrium if both the sum of the forces and the sum of the moments that act on the airplane are zero. To counteract the asymmetrical thrust yawing moment, the deflected rudder generates a side force that causes a rudder yawing moment opposite of the thrust yawing moment. The rudder side force however, also causes an acceleration to the dead engine side which results in a sideslip angle and in an opposite side force due to sideslip. The sideward acceleration continues and the resulting side force due to sideslip increases, until the sum of the side forces is zero. The aerodynamic rudder side force is proportional to the (square of the) airspeed ( $V^2$ ). The lowest airspeed at which straight flight can just be maintained while either the rudder or the ailerons are maximum deflected and the asymmetrical thrust is maximum is called  $V_{MC}$ , in this case  $V_{MC}$  with the wings level. The sideslip angle, which can be up to 14°, also causes drag which reduces the remaining climb performance significantly and should therefore be kept to a minimum, especially during initial climb when an engine is inoperative, but also during cruise for maximum range. To achieve minimum sideslip hence drag, a small bank angle of "*not more than 5°*" can be used during "*maintaining straight flight*", as explained next.
  - 5.6. For explaining turns, pilots use the centripetal force, being a horizontal component of the lift of the wings in the earth axis coordinate system. However, following an engine failure, the required counteracting rudder side force affects the magnitude of the centripetal force. In addition, the increased drag due to sideslip might affect the remaining wing lift. Hence, the

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<sup>10</sup> AvioConsult, Background information for the definition, theory, flight test and use of  $V_{MC}$ , [https://www.avioconsult.com/downloads/Background\\_VMC\(A\)\\_Regulations\\_and\\_Flight\\_Test.pdf](https://www.avioconsult.com/downloads/Background_VMC(A)_Regulations_and_Flight_Test.pdf)

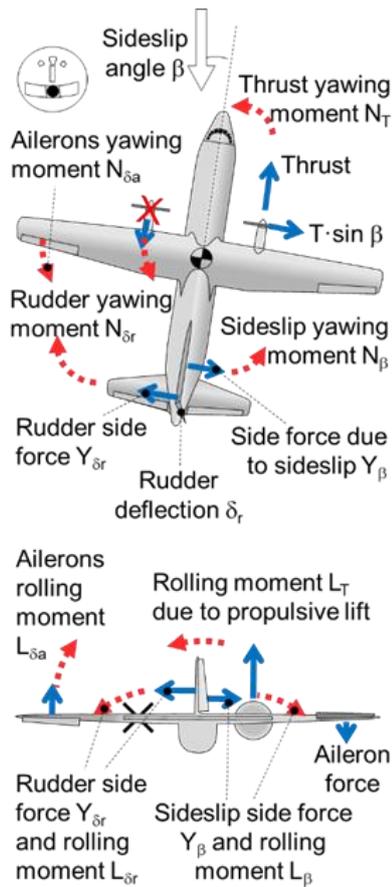


Figure 4. Lateral-Directional forces and moments in body axis coordinate system, OEI, wings level, straight flight. Forces are not to scale.

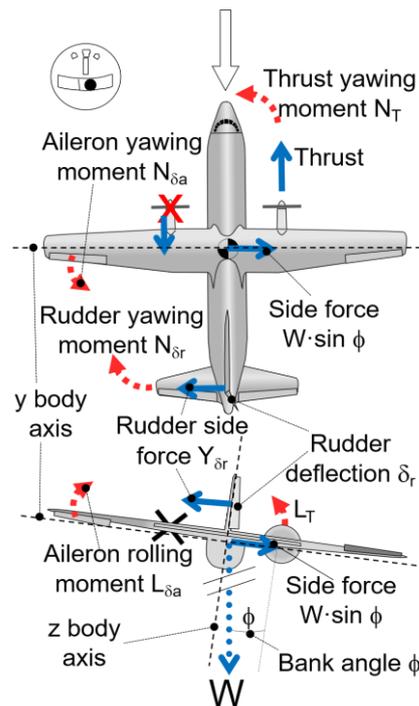


Figure 5. Lateral-Directional forces and moments in body axis coordinate system, OEI, bank angle 5° into good engine, steady straight flight.

centripetal force can only be used for coordinated flight, i.e. when all engines are operating and the controls are near center. This cannot be the case following an engine failure, therefore airplane design engineers and test pilots use the *body axis coordinate system* in which a component of the weight, rather than the wing lift, provides the side force, because gravity (Weight) always acts on an airplane, whatever the bank angle or attitude. The lift of the wings acts in the direction of the z-body axis and hence, has no side component in the body-axis system, but the Weight does ( $W \cdot \sin \phi$ ). In the body axis system, a knife-edge maneuver (straight nose-up flight with 90° bank) can be explained.

- 5.7. When banking, a component of the weight ( $W$ ) results in a side force due to bank angle ( $W \cdot \sin \phi$  in Figure 5), that can replace the side force due to sideslip that was a consequence of the rudder deflection (Figure 4). Hence, the small bank angle decreases the sideslip angle of the airplane to a minimum, decreasing the total drag and hence, increasing the engine-out (climb) performance. Side force  $W \cdot \sin \phi$  acts in the center of gravity (moment arm is zero) and therefore does not cause a yawing moment. As the rudder side force, generated by the vertical tail with rudder, no longer must act against the side force due to sideslip as well (see Figure 5), but only against the thrust yawing moment, the rudder deflection can be smaller, or the vertical tail can be designed smaller to save manufacturing cost and weight, and still comply with the Regulations. A smaller rudder deflection makes it possible to reduce the speed further until again the rudder is maximum deflected to counteract the same thrust yawing moment and hence, the  $V_{MC}$  is lower than  $V_{MC}$  with the wings level, and the sideslip angle, hence drag is minimal and the Rate of Climb maximal. This is why FAR 23.149 allows the engineer designing the vertical tail to use a bank angle of "not more than 5°" (away from the inoperative engine),

while "maintaining straight flight", for sizing the vertical tail with rudder; it is for engine-out control and performance. The AFM-published  $V_{MC}$  is the  $V_{MC}$  with the small bank angle.

- 5.8. A smaller vertical tail requires a higher airspeed to counteract the same maximum thrust yawing moment;  $V_{MC}$  will be higher. FAR 23.149(b) however, does not allow the vertical tail to be made so small that  $V_{MC}$  for takeoff, i.e. during straight flight with max. 5° of bank, exceeds 1.2 times the stall speed ( $V_S$ ). Hence, the vertical tail is made just large enough to be able to maintain straight flight at airspeed  $V_{MC}$  while the thrust of the opposite engine is at the maximum takeoff setting, the rudder is maximal deflected and a small bank angle is being maintained as opted during sizing the vertical tail, which is usually between 3° and 5° away from the inoperative engine. Refer to *Airplane Design Part VII*, Dr. Jan Roskam of Kansas University<sup>11</sup>.

**The vertical tail with rudder is only sized large enough for maintaining straight flight at  $V_{MC}$  at maximum asymmetrical thrust and with 5° bank into the good engine**

- 5.9. In-flight, the pilot controls the bank angle (if control is not lost) and hence, determines the magnitude of side force  $W \cdot \sin \phi$ , hence, the pilot controls the *actual*  $V_{MCA}$  with bank angle and thrust (yawing moment – required rudder deflection). Therefore, the effect of bank angle ( $\phi$ ) and weight on  $V_{MCA}$  is worth reviewing in greater detail for other bank angles than 5° into the good engine.

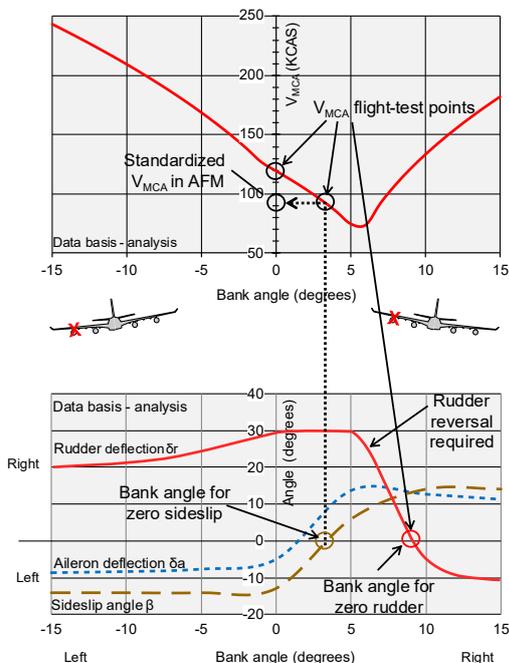


Figure 6. Effect of bank angle on  $V_{MCA}$  and on rudder, aileron, and sideslip angles during equilibrium flight at maximum thrust, for a sample airplane.

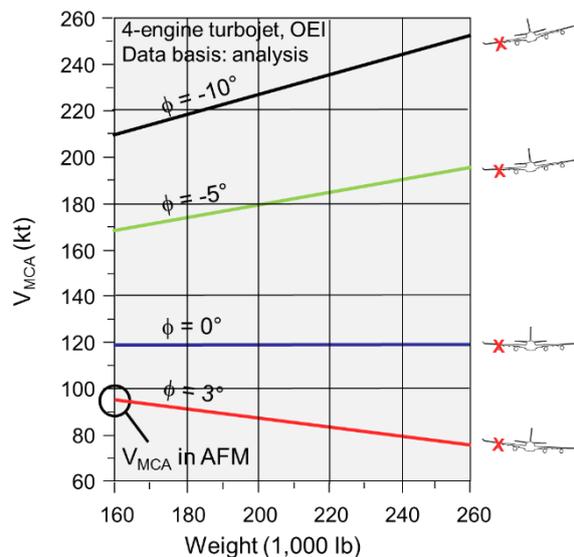


Figure 7. Effect of bank angle and weight on  $V_{MCA}$ .

NOTE. C-130 pilots know this figure, because it is like the Weight and Bank Angle figure in the C-130 Performance Manual SMP-777.

- 5.10. **Effect of Bank Angle and Weight on  $V_{MCA}$ .** When, during the design phase of the airplane, the size of the vertical tail with rudder is either known or assumed, graphs can be calculated using lateral-directional equations of motion with the stability derivatives of the airplane to show the effect of bank angle and weight on  $V_{MCA}$  while the thrust is maximum asymmetrical. Such calculations are usually also done to predict  $V_{MC}$  prior to conducting  $V_{MC}$  flight-testing with prototype airplanes. The  $V_{MC}$  prediction method was used to calculate the airspeed for every bank

<sup>11</sup> *Stability and Control during Steady Straight Flight*, Airplane Design Part VII, Dr. Jan Roskam, DAR Corporation, Kansas: <https://shop.darcorp.com/index.php?route=product/category&path=60>

angle between  $-15^\circ$  and  $+15^\circ$  at which either the rudder or the aileron deflection is maximum, or the sideslip angle is  $14^\circ$ , being the stall angle of attack of the fin with deflected rudder (large camber). The results are presented in Figure 6 and Figure 7 above. The  $V_{MC}$  data on the left edge (lowest weight) of Figure 7 coincide with the  $V_{MC}$  data in Figure 6. Figure 7 shows that a higher weight affects the *actual*  $V_{MC}$ . With zero bank angle, weight has no effect (side force  $W \cdot \sin 0^\circ = 0$ ).

The graphs in Figure 6 and Figure 7 are calculated using stability derivative data of a sample 4-engine turbojet airplane used at the USAF Test Pilot School, because data of a twin-engine airplane were not available; the shape of the graphs is approximately similar for all multi-engine airplane types, though. The prediction is explained in paper *The Effect of Bank Angle and Weight on  $V_{MCA}$* <sup>12</sup>.

- 5.11. Figure 6 shows that the sideslip angle  $\beta$  is near zero, i.e. the drag is minimal, when the bank angle is  $3^\circ$  away from the inoperative engine for this swept wing airplane. The corresponding *standardized*  $V_{MC}$  (with maximum rudder deflection) that is published in the AFM is 95 kt. The small bank angle should be and sometimes is included as an associated condition in the legend of one engine operating performance diagrams for the presented data to be valid.
- 5.12. As already mentioned above, bank angle not only has great effect on sideslip, hence on drag and performance, but bank angle ( $\phi$ ) and Weight ( $W$ ) both have also great influence on the *actual*  $V_{MCA}$  of the airplane, being the  $V_{MCA}$  which the pilot will experience in-flight, through side force  $W \cdot \sin \phi$ , which is illustrated in Figure 5. Figure 6 and Figure 7 show that the *actual*  $V_{MCA}$  of this sample airplane increases from the published 95 kt to 119 kt if the wings are only kept level. For small twins this increase will be  $\approx 6$  kt. In addition, keeping the wings level or banking to either side results in a large sideslip. Sideslip is a result, not a cause, and increases the drag and hence, reduces the climb performance or leaves no positive climb performance at all (in small twin engine airplanes).
- 5.13. Another important observation in Figure 6 should be that when banking more than  $6^\circ$  into the good engine, the rudder deflection should be reduced and reversed to maintain the balance of forces and moments, i.e. to maintain control. Sometimes, experimental test pilots increase the bank angle to the point where the rudder deflection is zero, the third test point in Figure 6. At that point, the sideslip angle is near  $14^\circ$ , the angle at which the fin with rudder is very close to a stall, and hence, the drag very large. Figure 6 proves that it is a myth that banking into the good engine(s) is favorable to the safety margin above  $V_{MCA}$ .  $V_{MCA}$  increases considerable with banking to either side to values above  $V_{MC}$  for straight flight (when the asymmetrical thrust is maximum).
- 5.14. Figure 7 shows the effect of bank angle and weight on  $V_{MC}$ .  $V_{MC}$  when maintaining a  $3^\circ$  bank into the good engine decreases with increasing weight. When the wings are kept level, weight has no influence on  $V_{MC}$ ; the side force due to weight ( $W \cdot \sin \phi = 0$ , Figure 4). This graphs also shows that  $V_{MC}$  with a small bank angle away from the failed engine is highest at low weight, which is the worst-case weight for  $V_{MC}$  during straight flight while maintaining a small bank angle, and which is the reason that low weight is used to determine  $V_{MC}$  (for straight flight – FAR 23.149). When the bank angle into the dead engine increases,  $V_{MC}$  not only increases with bank angle, but also with weight. At high weight (takeoff),  $V_{MC}$  increases considerable above the low weight values in Figure 6 when not maintaining a small bank angle into the good engine(s), and so does the drag.
- 5.15. It will be clear that the requirement for maintaining straight flight while also maintaining a small bank angle away from the inoperative engine must be made well known to the pilots of multi-engine airplanes to avoid the loss of control when maximum thrust is needed on the operating engine. The saved weight and manufacturing cost of a smaller vertical tail (hardware) needs to be replaced by a quite 'heavy' associated condition / warning in the AFM (software)

<sup>12</sup> Harry Horlings, AvioConsult, *The Effect of Bank Angle and Weight on  $V_{MCA}$* , <https://www.avioconsult.com/downloads/Effect-of-Bank-Angle-and-Weight-on-Vmca.pdf>

for only maintaining straight flight and a small bank angle while an engine is inoperative and the asymmetrical power setting is, or is increased to maximum. This prerequisite for being able to maintain control after engine failure is regrettably not presented anymore in most AFMs, in multi-engine rating coursebooks for pilots, and in investigator training manuals; this knowledge is 'forgotten' during the past 50 years, except at test pilot schools.

- 5.16. **Flight-Testing To Determine  $V_{MC}$ .** During the flight-tests to determine  $V_{MC}$  in accordance with the FAA Flight Test Guide<sup>8</sup>, the airplane is in the same configuration as was used to design the vertical tail, of which the most important factors are the *lowest* weight possible (smallest side force  $W \cdot \sin \phi$ ), an *aft* center of gravity (smallest rudder moment arm), maximum power setting that the pilot can set from the cockpit on the operating (critical) engine (maximum thrust yawing moment) and a feathered propeller, if applicable and automatic (lowest propeller drag). This configuration results in the 'worst-case'  $V_{MC}$  (for straight flight). Two types of  $V_{MC}$  are determined, first the static  $V_{MC}$  and then the dynamic  $V_{MC}$ .
- 5.17. The *static*  $V_{MC}$  is the  $V_{MC}$  for maintaining straight flight while an engine is inoperative. The airspeed is slowly reduced (keeping the wings level) until the heading can no longer be maintained using maximum rudder or aileron deflection, or up to the FAR defined maximum control force limits (150 lbf for rudder pedal, 25 lbf for roll control). This first data point is the wings-level  $V_{MC}$  (Figure 6 - top). Then, while increasing the bank angle to the same value that was used to design the vertical tail ( $3^\circ$  to  $5^\circ$  away from the inoperative engine), the speed is (and can be) further reduced until again the heading can no longer be maintained. This speed is the *static*  $V_{MC}$  of the airplane and is usually between 6 (small twin) and 25 knots (B707) lower than the wings-level  $V_{MC}$ . This  $V_{MC}$  is obviously only valid during straight flight when the small favorable bank angle is being maintained. When the bank angle for zero rudder (Figure 6) is attained,  $V_{MC}$  is a bit lower, but the sideslip (drag) increases considerable.  $V_{MC}$  for other bank angles than wings-level and  $3^\circ - 5^\circ$  (at the option of the manufacturer) is never determined because of the many variables that affect the balance of forces and moments and therewith  $V_{MC}$ ; it would be too costly and the use of the huge amount of data by pilots would be prone to errors.
- 5.18. The *dynamic*  $V_{MC}$  is important for regaining control immediately following the sudden failure of an engine during the resulting dynamics, and is determined by cutting the fuel flow to the critical engine at several speeds down to the speed at which either the heading change is maximum  $20^\circ$ , the bank angle does not exceed  $45^\circ$  and no dangerous attitudes occur.
- 5.19. The static  $V_{MC}$  is usually higher than the dynamic  $V_{MC}$ . The highest of static and dynamic  $V_{MC}$  will be published as the  $V_{MC}$  of the airplane in the AFM, but a  $V_{MC}$  applies during the remainder of the flight, including the final turn for landing. Flight testing (and demo) of  $V_{MC}$  is not without danger; therefore, the test data are acquired at a safe altitude and extrapolated to sea level.
- 5.20. FAR 23.149(b) defines  $V_{MC}$  for the takeoff configuration, for straight flight (climb out) at maximum thrust, while maintaining a small  $5^\circ$  bank angle. This  $V_{MC}$  is marked with a red (radial) line on the ASI or is placarded as IAS after adding both the position and the instrument errors to the  $V_{MC}$  as CAS (§ 3.13 above). But a  $V_{MC}$  applies during the whole flight when an engine is inoperative, which might be the reason that  $V_{MCA}$  ( $V_{MC}$  in the Air) is used in many publications, including in POH/AFMs. As was shown above,  $V_{MCA}$  during turns is much higher than the published standardized  $V_{MC}$  for straight flight.
- 5.21. **Definition Of  $V_{MC}$  in an AFM.** FAR 23 prescribes the airworthiness standards to be used by airplane design engineers (§ 3.1 above), including requirements for the case one of the engines is inoperative, including furnishing the minimum control speed  $V_{MC}$ . The  $V_{MC}$  definition in an AFM is often copied out of Federal Aviation Regulation (FAR 23.149) or equivalent, as quoted in § 5.3 above. Once the airplane is in operational use, for which the AFM applies, pilots should not keep the wings level to within  $5^\circ$  of bank, left or right, as the definition suggests. On the contrary, in order to ensure that control of their airplane after engine failure can be maintained when maximum thrust is set on the other engine, and that the remaining climb

performance is maximum achievable, pilots need to maintain straight flight and the same small bank angle that was used to design the vertical tail and that was also used to determine the AFM-published  $V_{MC}$  during flight testing, which is usually between  $3^\circ$  and  $5^\circ$  away from the inoperative engine, as was illustrated in Figure 6 and Figure 7 above. A larger bank angle, or a bank angle into the inoperative engine, will disturb the balance of side forces and yawing moments and will result in lateral accelerations and yawing moments (and sideslip) that cannot guaranteed be balanced using the aerodynamic controls, simply because the vertical tail with rudder (and the ailerons) were not sized large enough to do so when the thrust is maximum and the airspeed is  $V_{MC}$ . The words "*suddenly made inoperative*" and "*critical engine*" in the  $V_{MC}$  definition in an AFM do not make sense at all for, and are misleading to, pilots; a  $V_{MC}$  applies during the entire flight, in anticipation of and following the failure of *any* engine, not only the critical engine, and during climb, cruise and approach or go-around when any of the engines already failed during takeoff. The above quoted FAR definition of  $V_{MC}$  is deficient for use in an AFM.

- 5.22. **The actual  $V_{MCA}$**  that a pilot will experience in-flight will be affected by any change of lateral or directional forces and moments, for instance by an accidentally deployed thrust reverser or engine or nacelle cowling, an opened cargo hatch, a non-feathering propeller, a camera mounted on a wingtip, unbalanced wing fuel, or a bad functioning throttle friction and, last but not least, yet often occurring, intentional or uncontrolled banking at too low a speed and too high an asymmetrical thrust level (to quickly return to the runway for landing).
- 5.23. The *actual*  $V_{MCA}$  is in fact and in general the lowest airspeed which can be obtained with full directional or lateral control deflection and should be a factor of concern when the asymmetrical thrust is or is increased to maximum (during a turn). The need to use near maximum rudder or aileron is a strong signal that the airspeed is close to the *actual*  $V_{MC}$ , or the *actual*  $V_{MC}$  is close to the current airspeed, and that the loss of control is imminent. The pilot has no choice but to increase the speed ASAP, or reduce the asymmetrical thrust a little, temporarily, until straight flight is again established.
- The one engine inoperative climb performance is only maximal if a small bank angle is being maintained away from the inoperative engine; the bank angle for minimum sideslip can be less than  $5^\circ$  when the airspeed increases; usually at  $V_{YSE}$   $3^\circ$  is required. The manufacturer should include this bank angle in the legend of the performance graphs of the AFM.
- 5.24. **In the new FAR § 23.2135 (c)** the  $V_{MC}$  definition is: " *$V_{MC}$  is the calibrated airspeed at which, following the sudden critical loss of thrust, it is possible to maintain control of the airplane. For multiengine airplanes, the applicant must determine  $V_{MC}$ , if applicable, for the most critical configurations used in takeoff and landing operations*". After reading the explanation of  $V_{MC}$  above, readers will agree that this definition is even worse than the old one (§ 5.3 above).  $V_{MC}$  does not only apply during takeoff and landing operations, as accident statistics prove.  $V_{MC}$  is determined for recovery and thereafter maintaining straight flight only, while also maintaining a specific bank angle (FAA Flight Test Guide AC 23-8C<sup>8</sup>). The rule makers were obviously still not highly educated aeronautical engineers who understand the forces and moments acting on an airplane. It is now entirely up to the manufacturer to provide a definition that explains  $V_{MC}$  and/or  $V_{MCA}$  so excellent and unambiguous to pilots, that accidents after engine failure will never ever occur anymore. POH/AFM reviews and GAMA prove that manufacturers are not ready to do so. Supervision with higher level knowledge is still required.
- 5.25. **Takeoff Speeds.** The AFM-published  $V_{MC}$  is one of the factors used for calculating the takeoff speeds, including the rotation speed  $V_R$  and the takeoff safety speed  $V_2$ . Since the published  $V_{MC}$  is valid only while maintaining a small bank angle ( $3^\circ$  to  $5^\circ$  away from the inoperative engine at the option of the manufacturer), both calculated takeoff speeds are also valid only while maintaining this bank angle, unless the 6 – 25 kt higher  $V_{MC}$  for wings level (depending on the type of airplane), which is also determined during flight-testing, is being used. Manufacturers regrettably never include this higher wings-level  $V_{MC}$  in their AFM, which could be the

cause of many occurrences of Loss of Control just after liftoff. They don't mention the increased sideslip hence drag, i.e. the reduced or negative Rate of Climb, either.

- 5.26. The  $V_{MCA}$  data presented in Figure 6 and Figure 7 above apply for maximum asymmetrical thrust. The actual  $V_{MCA}$  decreases when reducing the asymmetrical thrust a little. This decrease can be temporarily used by pilots to conduct a turn, following a straight climb to a safe altitude. This asymmetrical thrust reduction reduces the thrust yawing moment and therewith the required counteracting rudder deflection; the actual  $V_{MCA}$  is lower. During turns, the sideslip increases though, and therewith the Rate of Climb decreases. Some altitude might have to be sacrificed during turns, but control will be maintained. Engine-out flight is never a coordinated flight. Pilots need to be made aware and reminded of the significance of  $V_{MCA}$  for engine-out flight in the AFM, as FAR 23.1583(a)(1) requires, not only of  $V_{MC}$  for takeoff.
- 5.27. Examples of **controlling  $V_{MC(A)}$**  and of the **significance of  $V_{MC(A)}$**  are included in the following abbreviated accident reports:

*The distribution of engine thrust for keeping the actual  $V_{MCA}$  under control, and for allowing safe turns, when one or more engines are inoperative, was applied by a competent Boeing 707 flight crew after both engines #3 and #4 separated off the right wing above the French Alps (31 March 1992). 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 total thrust level. He in fact decreased the actual  $V_{MCA}$ . He also recommended a minimum speed of 200 kt to the captain, who was the pilot-flying, and selected flaps one to unlock the outboard ailerons, therewith increasing the lateral control power. They landed safely on Airbase Istres – Le Tubé in France. Knowledge of forces and moments saved lives. Well done! Not all pilots think of managing forces and moments.*

*Six months later, on 21 Dec. 1992 a Boeing 747 freighter also lost the two right engines #3 and #4 shortly after takeoff from Amsterdam Airport. Despite the damaged leading edge of the right wing, the airplane remained controllable and completed nearly two full descending turns at less than maximum thrust on engines #1 and #2. When, during a right-hand turn to position for the approach, the thrust on both left-hand engines was increased to maximum, control was lost and the airplane went down in a suburb of the city. The asymmetrical thrust yawing moment had increased above the level that could be counteracted by the aerodynamic controls. The pilots were regrettably never made aware of the effect of bank angle and thrust on the actual  $V_{MCA}$  of their airplane. The investigators of the accident interviewed the Boeing 707 pilots, but did regrettably not conclude the increase of  $V_{MCA}$  due to the inappropriate increase of thrust during the turn as cause of the accident.*

- 5.28. **Conclusion** of the above is that  $V_{MC(A)}$  varies with bank angle and thrust level. Manufacturers are regrettably not required to publish the bank angle that was used to determine  $V_{MC}$ , neither in the  $V_{MC}$  definition, nor with  $V_{MC}$  data in the AFM, while some manufacturers do publish the bank angle for minimum drag/maximum performance in the legend of OEI performance charts (Piper in the PA-44 POH, and Lockheed in C-130 manuals). The AFM should remind pilots with: **'Published  $V_{MC(A)}$  is valid for straight flight only while maintaining a 5° bank angle into the good engine when the asymmetrical thrust is maximum.  $V_{MC(A)}$  increases during turns'**, and: **'The pilot controls the actual  $V_{MC(A)}$  with bank angle and (asymmetrical) level of thrust'**.
- 5.29. To prevent accidents after engine failure, the manufacturer should describe how the published  $V_{MC(A)}$  is determined, when this  $V_{MC(A)}$  is valid, and elaborate on the variation of  $V_{MC(A)}$  with bank angle, thrust, and other effects. An improved  $V_{MC(A)}$  definition for pilots could be:

**'Minimum Control speed  $V_{MC(A)}$  is the lowest airspeed which can be obtained during steady straight flight while maintaining 5° bank towards the good engine, with full rudder and/or aileron control inputs when one engine fails or is inoperative, and the opposite engine is set at maximum thrust.**  
**The actual  $V_{MC(A)}$  increases while banking to either side and with the thrust level of the good engine and hence, is controlled by the pilot'.**

- 5.30. Pilots receive their multi-engine rating in Part 23 airplanes, and take this experience with them during their whole career in Part 23 and Part 25 airplanes. Wrong learned is wrong applied. Even Boeings 747 crashed after engine(s) separation because the pilots were not made aware of the increase of  $V_{MC(A)}$  to a much higher actual  $V_{MC(A)}$  while banking at maximum asymmetrical thrust. ICAO would call this a Systemic Error.
- 5.31. The actual  $V_{MCA}$  depends on many factors, the worst cases of which are used during flight-testing. Actual  $V_{MCA}$  can also be lower than the AFM-published  $V_{MCA}$ , for instance due to a forward center of gravity. The paper *Airplane Control and Analysis of Accidents after Engine Failure*<sup>13</sup>, explains almost all about  $V_{MCA}$ , and analyses a few accidents after engine failure.

## 6. Stall and Climb speeds

- 6.1.  **$V_S$  Stall Speed** is often defined as: " *$V_S$  is the lowest speed at which the aircraft is controllable*".
- 6.1.1. There is no pilot who makes a yaw or roll control input when the stall horn sounds, i.e. when a stall is imminent, because the trailing wing, or the wing with the down going aileron will (partially) stall, and control might be lost. So, at  $V_S$ , the aircraft is not controllable, but can only maintain straight flight, just like is the case for  $V_{MCA}$ . A better definition of  $V_S$  would be: 'The stall speed is the minimum flight speed attainable during steady straight flight'.
- 6.2.  **$V_{YSE}$  Best Rate of Climb Speed – One Engine Inoperative** (Single Engine) is often defined as: "*is the speed which results in the greatest gain of altitude within a given period of time, while flying one engine feathered and the other engine at MTOP or Maximum Continuous Power*".
- 6.2.1. The greatest gain of altitude is only achieved when the sideslip, hence the drag, is minimal which will only be the case when maintaining straight flight with a small bank angle, usually  $3^\circ$  at  $V_{YSE}$ , or  $5^\circ$  as mentioned in some POH/AFMs, into the good engine. This straight flight requirement as well as the small bank angle should therefore not only be included in the  $V_{YSE}$  definition, because these are essential "*for greatest gain of altitude*", but also in the legend of the One Engine Inoperative climb performance charts for the presented data to be valid as, for instance, Piper did in the PA-44-180 POH on page 5-23. ■

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<sup>13</sup> Harry Horlings, AvioConsult, *Airplane Control and Analysis of Accidents after Engine Failure*, [https://www.avioconsult.com/downloads/Airplane Control and Analysis of Accidents after Engine Failure.pdf](https://www.avioconsult.com/downloads/Airplane%20Control%20and%20Analysis%20of%20Accidents%20after%20Engine%20Failure.pdf).