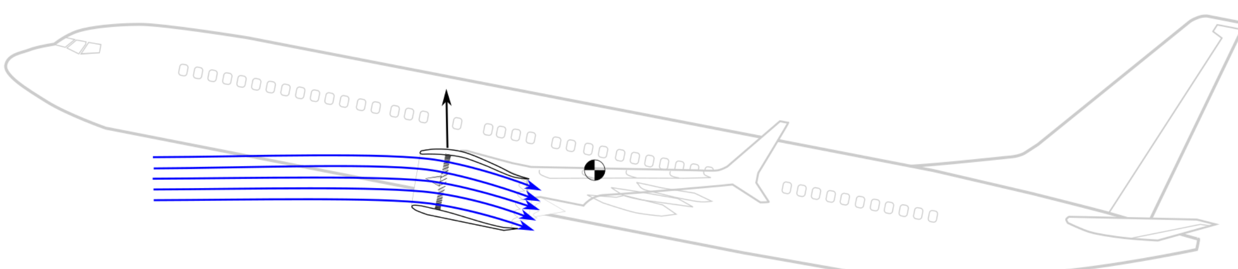
Background on Boeing's 737 MAX
Maneuvering Characteristics Automation System (MCAS)

The Maneuvering Characteristics Automation System (MCAS) was installed on the B737 MAX aircraft presumably because the MAX aircraft had objectionable characteristics at high angles of attack. The MAX has larger engine nacelles relative to earlier generations of the B737 due to the higher bypass LEAP-1B engines. The nacelles for the MAX are larger and placed higher and further forward of the wing to provide adequate ground clearance:

Boeing 737NG (left) and MAX (right) nacelles compared. Source: Boeing 737 MAX brochure.

By placing the nacelle further forward, the aircraft is destabilized in pitch at elevated power settings relative to the earlier B737 models. The momentum change at the inlet face at elevated angle of attack results in a pitch up moment, which destabilizes aircraft in pitch.



Description of the B737 pitch control system (from B737-800 flight manual)
All B737 primary flight controls uses conventional control wheel, column and pedals linked mechanically to hydraulic power control units which command the primary flight control surfaces; ailerons, elevators and rudder. The flight controls are powered by redundant hydraulic sources; System A and System B. Either hydraulic system can operate all primary flight controls. The ailerons and elevators may be operated manually if required.

Pitch control is provided by:
• Two elevators
• A movable horizontal stabilizer.

The horizontal stabilizer has much more control power than the elevators. The intent of the B737's pitch axis flight controls is to use the horizontal stabilizer to trim for an airspeed, then use the elevators to maneuver about the trim point. The position of the horizontal stabilizer is critical because if mistrimmed, it can exceed the capability of the elevators to control the aircraft.

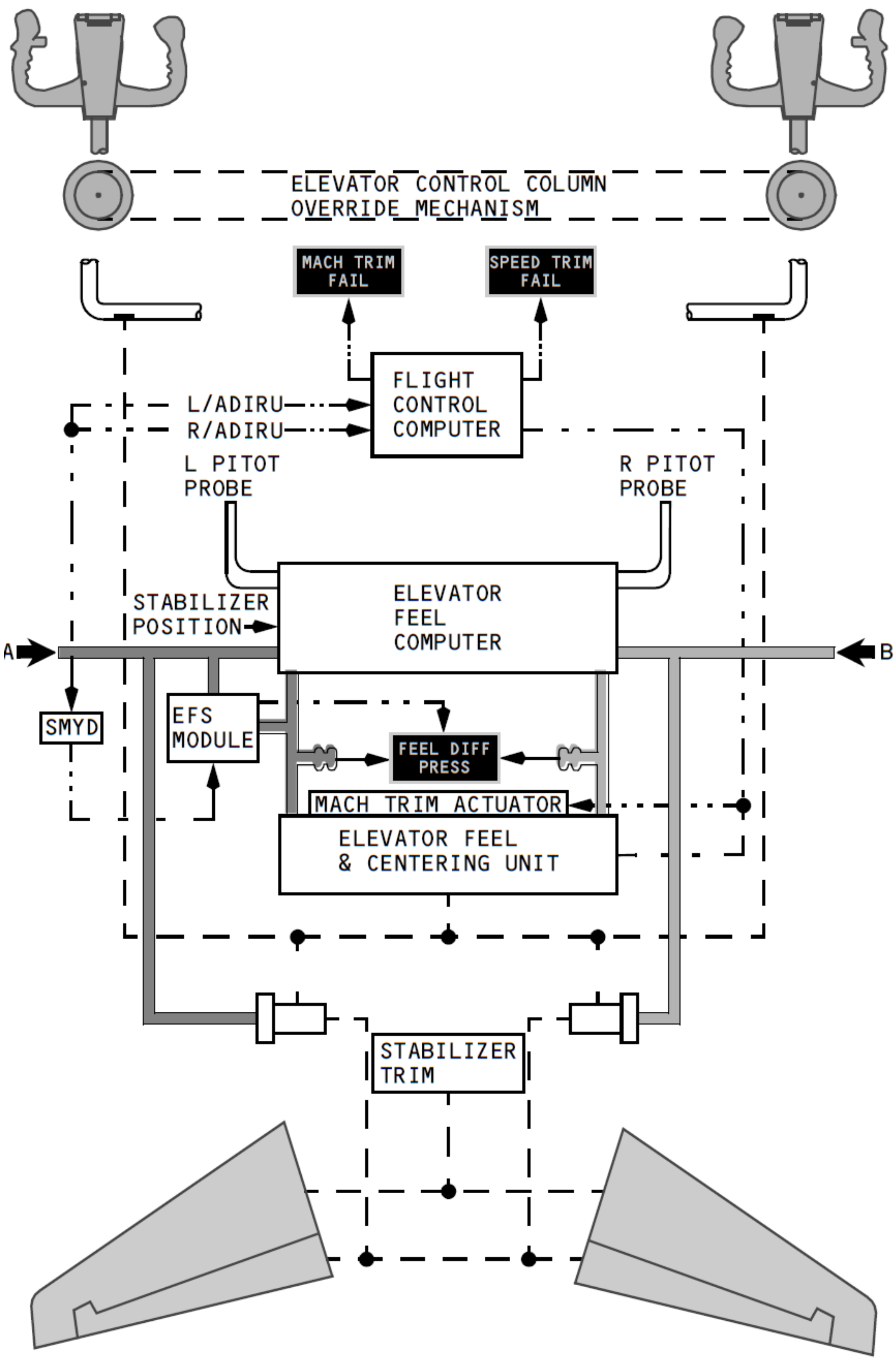
Cables connect the pilots' control columns to elevator Power Control Units (PCUs) which are powered by Hydraulic System A and B. The elevators are interconnected by a torque tube. With loss of Hydraulic System A and B the elevators can be mechanically positioned by forward or aft movement of the pilots' control columns. Control forces are higher due to friction and aerodynamic loads.

Pilot elevator control forces are provided by an elevator feel computer which provides simulated aerodynamic forces using airspeed (from the Elevator Pitot System) and stabilizer position. Feel is transmitted to the control columns by the elevator feel and centering unit. To operate the feel system the elevator feel computer uses either Hydraulic System A or B pressure, whichever is higher.

The horizontal stabilizer is positioned by a single electric trim motor controlled through either the Stab Trim Switches on the control wheel or autopilot trim. The stabilizer may also be positioned by manually rotating the stabilizer trim wheel.

Stabilizer Trim Switches on each control wheel actuate the electric trim motor through the main electric stabilizer trim circuit when the airplane is flown manually. With the autopilot engaged, stabilizer trim is accomplished through the autopilot stabilizer trim circuit. The main electric and autopilot stabilizer trim have two speed modes: high speed with flaps extended and low speed with flaps retracted. If the autopilot is engaged, actuating either pair of Stabilizer Trim Switches automatically disengages the autopilot. The stabilizer trim wheels rotate whenever electric stabilizer trim is actuated. The STAB TRIM MAIN ELECT Cutout Switch and the STAB TRIM AUTOPILOT Cutout Switch, located on the control stand, are provided to allow the autopilot or main electric trim inputs to be disconnected from the stabilizer trim motor. Control column actuated Stabilizer Trim Cutout Switches stop operation of the main electric and autopilot trim when the control column movement opposes trim direction. When the STAB TRIM Override Switch is positioned to OVERRIDE, electric trim can be used regardless of control column position.

Manual stabilizer control is accomplished through cables which allow the pilot to position the stabilizer by rotating the stabilizer trim wheels. The stabilizer is held in position by two independent brake systems. Manual rotation of the trim wheels can be used to override autopilot or main electric trim. The effort required to manually rotate the stabilizer trim wheels may be higher under certain flight conditions. Grasping the stabilizer trim wheel will stop stabilizer motion.



B737- Pitch control

Pitch axis flight control augmentation present in B737 MAX Flight Crew Operations Manual (FCOM).

The following augmentation systems were present on the B737 MAX. The description of these systems in the MAX FTCM is nearly identical to the description in the B737 NG FCOM.

1. A Mach Trim System provides speed stability at the higher Mach numbers. Mach trim is automatically accomplished above Mach .615 by adjusting the elevators with respect to the stabilizer as speed increases. The Flight Control Computers use Mach information from the ADIRU to compute a Mach trim actuator position. The Mach trim actuator repositions the elevator feel and centering unit which adjusts the control column neutral position.

Comment: Mach trims systems are common on swept wing transports and prevent the natural pitch down moment in the transonic region from both the wing's center of pressure moving aft, and the reduction in downwash on the horizontal tail. The B737's Mach trim system is likely a left over from the JT3D –powered models (B737-100/200), as the inlet spillage drag from high bypass engines make it difficult to accelerate the aircraft into the Mach tuck.

2. The Speed Trim System (STS) is a speed stability augmentation system designed to improve flight characteristics during operations with a low gross weight, aft center of gravity and high thrust when the autopilot is not engaged. The purpose of the STS is to return the airplane to a trimmed speed by commanding the stabilizer in a direction opposite the speed change. The STS monitors inputs of stabilizer position, throttle position, airspeed and vertical speed and then trims the stabilizer using the autopilot stabilizer trim. As the airplane speed increases or decreases from the trimmed speed, the stabilizer is commanded in the direction to return the airplane to the trimmed speed. This increases control column forces to force the airplane to return to the trimmed speed. As the airplane returns to the trimmed speed, the STS commanded stabilizer movement is removed. STS operates most frequently during takeoffs, climb and go-arounds.

Conditions for speed trim operation are listed below:
- Airspeed between 100 KIAS and Mach 0.5
- 10 seconds after takeoff
- 5 seconds following release of Trim Switches
- Autopilot not engaged
- Sensing of trim requirement.

Comment: The speed trim system was likely installed due to the strong pitch up moment provided by the engines when power is advanced, which may be able to overpower the elevator, especially at low dynamic pressures (slow speed), high power settings, and if some of the nose down elevator authority is already used due to the aircraft is being out of trim. The horizontal stabilizer has much more control power than the elevator, beyond a certain point of mistrim, the elevator will be insufficient to recover from the mistrim.

3. Stall identification and control is enhanced by the yaw damper, the Elevator Feel Shift (EFS) module and the Speed Trim System. These three systems work together to help the pilot identify and prevent further movement into a stall condition. During high AOA operations, the Stall Management / Yaw Damper (SMYD) reduces yaw damper commanded rudder movement. The EFS module increases Hydraulic System A pressure to the elevator feel and centering unit during a stall. This increases forward control column force to approximately four times normal feel pressure. The EFS module is armed whenever an inhibit condition is not present. Inhibit conditions are: on the ground, radio altitude less than 100 feet and autopilot engaged.

However, if EFS is active when descending through 100 feet RA, it remains active until AOA is reduced below approximately stickshaker threshold. There are no flight deck indications that the system is properly armed or activated. As airspeed decreases towards stall speed, the speed trim system trims the stabilizer nose down and enables trim above stickshaker AOA. With this trim schedule the pilot must pull more aft column to stall the airplane. With the column aft, the amount of column force increase with the onset of EFS module is more pronounced.

Comment: The Elevator Feel Shift (EFS) module and the Speed Trim System probably ensure enough nose down elevator authority to recover from a stall. They indicate that the elevator may not have enough control power at certain corners of the envelope.

The Maneuvering Characteristics Automation System (MCAS)
The Maneuvering Characteristics Automation System (MCAS) is unique to the B737 MAX. Boeing has not provided engineering rationale for its installation, but it was likely necessary because the MAX aircraft had objectionable characteristics at high angles of attack and elevated thrust settings, likely during accelerated stalls. There were likely corners of the envelope where the elevator had insufficient authority to reduce the angle of attack.

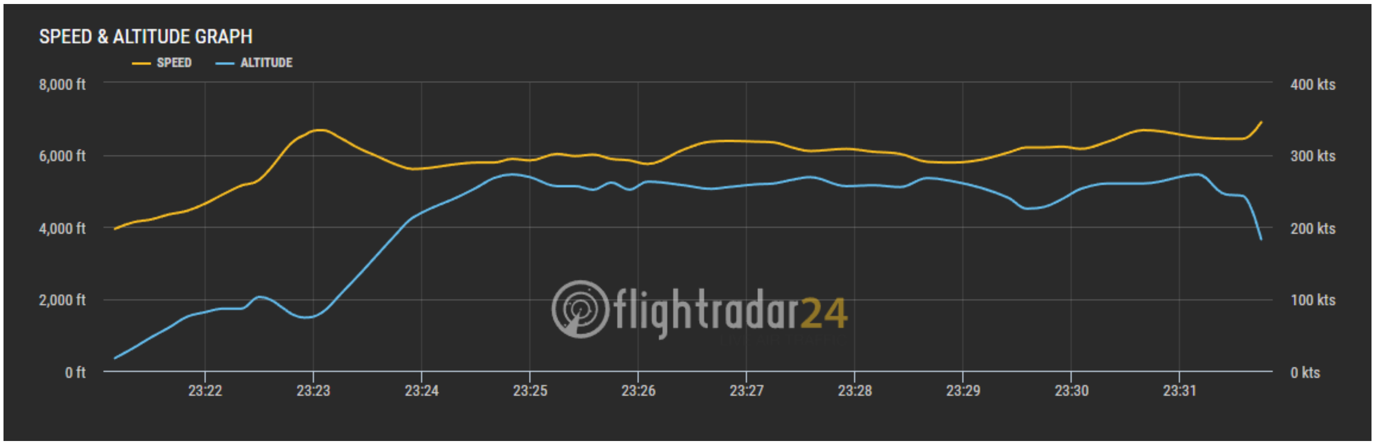
Boeing description of the MCAS:
The Maneuvering Characteristics Automation System (MCAS) allows the stabilizer to move in the nose down direction when approaching high angles of attack at high speed. This requires the stabilizer to move in the opposite direction that the pilot is pulling on the control column for nose up pitch. The MCAS operates only at extreme high speed pitch up conditions outside the normal operating envelope. [Reference: Boeing 737-7/8 Systems Difference Training Manual Volume 1, Flight Controls, Section 27-41]

The conditions when the MCAS activates the stabilizer in a nose down direction:

- High AoA, and AoA rate, as measured by only a single AoA vane
- Altitude and dynamic pressure
- Autopilot is not engaged
- Flaps are up
- Elevated load factor

The MCAS can provide up to 10 second increments of nose down elevator.

Particulars of the Lion Air 610 Crash (29 Oct 2018)
Shortly after takeoff, the pilots of Lion Air 610, B737-8 MAX reported flight control issues and requested a return to the airport. The following is the speed and altitude from Lion Air 610:



Lion Air 610 Time Line [Preliminary Aircraft Accident Investigation Report, Lion Mentari Airlines Boeing 737-8 (MAX); PK-LQP Tanjung Karawang, West Java Republic of Indonesia 29 October 2018, published November 2018]

> At 2320 UTC, (0620 on 29 October 2018 LT), the aircraft departed from Jakarta with intended destination of Pangkal Pinang. The DFDR recorded a difference between left and right AoA of about 20° and continued until the end of recording. During rotation the left control column stick shaker activated and continued for most of the flight. During the flight the SIC asked the controller to confirm the altitude of the aircraft and later also asked the speed as shown on the controller radar display.
>
> The SIC reported experienced “flight control problem”.
>
> After the flaps retracted, the FDR recorded automatic aircraft nose down (AND) trim active for 10 seconds [this would seem to indicate the MCAS was providing the nose down stabilizer] followed by flight crew commanded aircraft nose up (ANU) trim. The flaps extended to 5 and the automatic AND trim stopped.
>
> At 23:25:18 UTC, the flaps retracted to 0 and several seconds later, the automatic AND trim and flight crew commanded ANU trim recorded began again and continued for the remainder of the flight.
>
> The LNI610 PIC advised the controller that the altitude of the aircraft could not be determined due to all aircraft instruments indicating different altitudes and requested to the controller to block altitude 3,000 feet above and below for traffic avoidance.
>
> From the above altitude and speed tape, it appears the pilot was fighting the MCAS nose down inputs.

Shortly after the accident, Boeing released the following Airplane Flight Manual (AFM) revision B737 MAX operators:

> **Required by AD 2018-23-51**
>
> **Runaway Stabilizer**
>
> Disengage autopilot and control airplane pitch attitude with control column and main electric trim as required. If relaxing the column causes the trim to move, set stabilizer trim switches to CUTOUT. If runaway continues, hold the stabilizer trim wheel against rotation and trim the airplane manually.
>
> Note: The 737-8/-9 uses a Flight Control Computer command of pitch trim to improve longitudinal handling characteristics. In the event of erroneous Angle of Attack (AOA) input, the pitch trim system can trim the stabilizer nose down in increments lasting up to 10 seconds.
>
> In the event an uncommanded nose down stabilizer trim is experienced on the 737-8/-9, in conjunction with one or more of the indications or effects listed below, do the existing AFM Runaway Stabilizer procedure above, ensuring that the STAB TRIM CUTOUT switches are set to CUTOUT and stay in the CUTOUT position for the remainder of the flight.
>
> An erroneous AOA input can cause some or all of the following indications and effects:
>
> - Continuous or intermittent stick shaker on the affected side only.
> - Minimum speed bar (red and black) on the affected side only.
> - Increasing nose down control forces.
> - IAS DISAGREE alert.
> - ALT DISAGREE alert.
> - AOA DISAGREE alert (if the option is installed).
> - FEEL DIFF PRESS light.
> - Autopilot may disengage.
> - Inability to engage autopilot.
>
> Initially, higher control forces may be needed to overcome any stabilizer nose down trim already applied. Electric stabilizer trim can be used to neutralize control column pitch forces before moving the STAB TRIM CUTOUT switches to CUTOUT. Manual stabilizer trim can be used before and after the STAB TRIM CUTOUT switches are moved to CUTOUT.

This is the B737 MAX AFM runway stabilizer procedure current at the time of the Lion Air 610 accident:

Runaway Stabilizer

Condition: Uncommanded stabilizer trim movement occurs continuously.

1 Control column. . . . . Hold firmly

2 Autopilot (if engaged) . . . . .Disengage

Do **not** re-engage the autopilot.

Control airplane pitch attitude manually with control column and main electric trim as needed.

3 Autothrottle (if engaged). . . . . .Disengage

Do **not** re-engage the autothrottle.

4 **If** the runaway **stops** after the autopilot is disengaged:

■ ■ ■ ■

5 **If** the runaway **continues** after the autopilot is disengaged:

STAB TRIM CUTOUT
switches (both) . . . . CUTOUT

If the runaway **continues**:

Stabilizer
trim wheel . . . . Grasp and hold

6 Stabilizer. . . . . .Trim manually

7 Anticipate trim requirements.

▼ **Continued on next page** ▼

8 **Checklist Complete Except Deferred Items**

Deferred Items

Descent Checklist

Pressurization . . . . LAND ALT ____

Recall . . . . Checked

Autobrake . . . . ____

Landing data . . . . VREF ____, Minimums ____

Approach briefing . . . . Completed

Approach Checklist

Altimeters . . . . ____

Airspeed and Trim

Establish correct airspeed and in-trim condition early on final approach.

Landing Checklist

[Without automatic ignition]
ENGINE START switches . . . . CONT

Speedbrake . . . . ARMED

Landing gear . . . . Down

Flaps . . . . ____, Green light

■ ■ ■ ■

Discussion
What is controversial about the **Maneuvering Characteristics Automation System (MCAS)** is that it was not documented in the aircraft flight manuals or pilot training at the time of the Lion Air 610 crash.

1. There are numerous issues in the corners of almost any aircraft envelope that aren't explained in training. Examples include the DC-8-62/72 pitch up in Mach Buffet, the DC-10's rolling tendency with a 1-2 or 2-3 dual hydraulic failure, the C-130's loss of directional stability at slow speeds and high power settings, the earlier B737's inability to recover from a stall with elevator alone at high power settings, and the B747/B777 auto throttle logic in FLCH, etc.

2. There is a strong economic incentive to minimize the amount of material presented in aircraft manuals and training documents. Anything present in the manual must be trained and tested, which increase the duration of training during which pilots are not productive to the company. In modern aircraft are much more complex than earlier aircraft, however, much of that complexity is hidden from the aircrew.

3. In theory, Boeing was correct in that the Airplane Flight Manual (AFM) runway stabilizer procedure should have covered the any failures of the MCAS.

Spurious MCAS nose down inputs can be stopped by the pilot counter-trimming using the yoke stabilizer trim switch, selecting the stabilizer CUTOUT switches on the center pedestal, or grabbing the stabilizer wheel. The MCAS's nose down trim input is not stopped by the pilot pulling aft on the yoke, which for normal trim from the autopilot or runaway manual trim trigger trim hold sensors (essentially, a stabilizer trim brake). In this respect, the MCAS runway trim is different from the majority of simulator trained runway stabilizer trim scenarios.

It is likely the Lion Air pilot's exposure to stabilizer runway trim in training consisted solely of unwanted autopilot trim or manual trim runaway, where they would have learned that holding against the trim stopped the runway trim input, stabilizing the situation from where they then could take deliberate action. However, with the MCAS failure, immediately after the yoke stabilizer trim was released, the MCAS would again run the stabilizer trim nose down for 10 seconds. It is not until step 5 of the runway stabilizer trim procedure that the flight crew gets to the step that would eliminate the nose down trim input in the event of a MCAS failure.

4. The FAA Aircraft Evaluation Group (AEG) responsible for the B737 MAX concurred with Boeing's engineering/flight operations decision not to include a description of the MCAS into the B737 MAX's Airplane Flight Manual (AFM). The AEG was in a position to require MCAS to be trained if they thought it important.

5. Had the MCAS been described in the AFM, there is at least the possibility that the Lion Air 610 pilots would have been familiar enough with the potential failure modes that they would have immediately cut out the stabilizer trim, disabling the MCAS. Whether this would have made a difference depends on the quality of the training, and the background/competence of the pilots.

7. The MCAS introduces an additional failure mode, with the potential to drive the horizontal stabilizer sufficiently out of trim where elevator authority is insufficient to recover the aircraft. The MCAS is essentially envelope protection, but without the redundant sensor management schemes that are typical of high authority protections. The probability of placing the aircraft in an unrecoverable situation is increased because it can be caused by single point failure. The combination of consequences and probability of the MCAS failure mode imply that it should have been trained during B737 MAX difference training.