National Transportation Safety Board
Response to Final Aircraft Accident Investigation Report
Ethiopian Airlines Flight 302
Boeing 737-8 MAX, ET-AVJ
Ejere, Ethiopia
March 10, 2019

In accordance with Annex 13 to the Convention on International Civil Aviation, as the accredited representative of the State of Design and Manufacture of the airplane, the National Transportation Safety Board (NTSB) participated in the Aircraft Accident Investigation Bureau of Ethiopia's (EAIB) investigation of the subject accident. Technical advisors from Boeing, Collins Aerospace, and the Federal Aviation Administration assisted the NTSB, as provided by Annex 13.

On December 23, 2022, the EAIB issued its final accident report on the Ethiopian Airlines flight 302 accident. Overall, the NTSB concurs with the EAIB's investigation of the Maneuvering Characteristics Augmentation System (MCAS) and related systems and the roles that they played in the accident.[1] However, the NTSB's comments (dated May 12, 2022) on the EAIB's last draft report (dated March 30, 2022) were not appended to the final report, as requested by the NTSB and provided by section 6.3 of Annex 13.[2] Instead, the EAIB's final report included a hyperlink to an earlier and outdated version of the NTSB's comments. In response, on December 27, 2022, the NTSB published a news release and the report comments that were most recently provided to the EAIB.

The news release indicated that the EAIB's final accident report included significant changes from the last report draft and that the NTSB was carefully reviewing the final report and determining whether any other comments might be necessary. The NTSB's review found that the final report contained new information that the EAIB had not afforded the NTSB the opportunity to review before the report was issued.

According to the EAIB's final report, electrical problems that existed since the time of the accident airplane's production caused the left angle-of-attack (AOA) sensor heater to fail, which resulted in the AOA sensor providing erroneous values that caused the MCAS to pitch the nose of the airplane downward, resulting in

[1] MCAS is an extension of the Boeing 737 speed trim system. It was designed to improve airplane handling characteristics and decrease pitch-up tendencies at elevated angles of attack. As the development of the Boeing 737 MAX progressed, the MCAS function was expanded to low Mach numbers. MCAS was also designed to function only during manual flight (autopilot not engaged), with the airplane's flaps up, and at an elevated angle of attack.

[2] The NTSB received the first draft accident report on January 12, 2021, and provided its comments to the EAIB on February 26, 2021. The NTSB received the second draft accident report on May 26, 2021, and provided its comments to the EAIB on June 11, 2021.

ground impact. However, the final report does not provide any details to support the EAIB's statements about the existence of an electrical problem related to the left AOA sensor.

The US team found that the erroneous AOA sensor output was caused by the separation of the AOA sensor vane due to impact with a foreign object, which was most likely a bird.[3] During the accident investigation, the NTSB provided the EAIB with the evidence supporting this finding. In fact, each set of NTSB comments detailed this evidence.

The following comments, which address several findings in the EAIB's final report, supplement the comments that the NTSB released on December 27, 2022:[4]

<u>EAIB Finding Nos. 20, 50, 54, 55, 64, and 65</u>

The above-mentioned findings in the final report state the following:

> 20. Post-accident analysis reveals [the] new Airplane [the Boeing 737 MAX] experienced unexplained electrical and electronic faults within weeks of entering service, and in the weeks and days prior to their accidents.[5]
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> 50. MCAS and the lack of pilot training did not trigger the accident; however it was the failure of the sensors due to the production quality defects. If the intermittent defects did not cause the AOA Sensors to fail on the accident flight, MCAS would not have activated, and the accident would not have occurred. The MCAS would have remained as [a] hidden threat until its true nature is exposed by some other valid or erroneous causes.
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> 54. The failure of originally installed and tested Boeing AOA Sensor parts [were] associated with fatal plane crashes likely involving an open circuit, wire fatigue, evidence of multiple arcing events, unexplained electrical/electronic anomalies, and the loss of heater power.[6]

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[3] The AOA sensor consists of an external vane that rotates to align with the local airflow.

[4] The NTSB provided the comments in this document to the EAIB on January 13, 2023.

[5] In addition to the Ethiopian Airlines flight 302 accident, this and other findings in the EAIB's final report referred to the Lion Air flight 610 accident, which involved a Boeing 737-8 MAX airplane that crashed on October 29, 2018, in Tanjung Karawang, West Java, Indonesia.

[6] Page 83 of the EAIB's report stated the following: "Despite the two fatal accidents and the electrical problems associated with the AOA Sensors, Collins Aerospace did not evaluate the electrical installation and testing procedures being performed by Boeing production." This criticism was not appropriate given that Collins, as a supplier of the AOA sensors, does not evaluate electrical installation and test procedures for any aircraft original equipment manufacturer customer, consistent with generally accepted industry practices.

55. Boeing has never acknowledged the electrical malfunctions that occurred on both MAX airplanes in the months, weeks, and days leading up to their accidents before MCAS was activated on their fatal flights.

64. Boeing has never discussed this AOA Sensor electrical design error publicly, [and] did not inform the EAIB about this error either. A loss of power can be a symptom of [an] EWIS [electrical wiring interconnection system] failure, power quality issue and/or a defect inside the AOA Sensor.

65. The AOA Sensor malfunction likely occurred as the result of [a] power quality problem that resulted in the loss of power to the left AOA Sensor Heater. Evidence indicates that the loss of power was likely due to a production related intermittent electrical/electronic failure involving the airplane's Electrical Wiring Interconnection System (EWIS) and the AOA Sensor part.

For the following reasons, the US team believes that an electrical failure affecting the left AOA sensor did not occur before the left AOA vane's impact with a foreign object:

- The AOA sensor vane heater's function is to prevent ice formation that could restrict vane movement. The conditions present at the time of the accident were above freezing temperatures with no moisture present (that is, ice could not form regardless of the heater's operational status). Thus, a loss of electrical current through the vane heater at any time during the accident flight would not explain the event because the loss of electrical current would have had no effect on the AOA sensor output. Another factor that occurred simultaneously with the loss of the AOA sensor vane heater's electrical current would have been required to cause the observed change in the AOA output signal.

- The AOA sensor vane is connected to two internal resolvers that independently measure the vane's angle. The AOA sensor vane heater and the two internal AOA resolvers are on different electrical circuits, so a loss of electrical current in the AOA sensor vane heater does not indicate an electrical failure of the two internal AOA resolvers. The accident FDR data showed no indication of an electrical issue with the resolvers. Specifically, because the electrical input voltage to the AOA resolvers and the signal output voltage from the AOA resolvers were monitored, an out-of-range condition, including an open or a short circuit, would have been recorded by the FDR if such a condition had occurred. Also, the resolvers continued to provide valid electrical output signals throughout the accident flight, even after the loss of electrical current for the left AOA vane heater.[7] Thus, the accident FDR data showed no electrical problems with the AOA resolvers' circuit.

- During the investigation, the EAIB requested assistance with evaluating the most likely failure modes for the AOA sensor based on the accident data. Collins Aerospace, the manufacturer of the airplane's AOA sensors, performed a fault tree analysis, which evaluated possible AOA vane failure scenarios caused by internal and external electrical faults. This analysis also considered every short circuit path to the AOA connector pins. The analysis found no electrical failure mode that was consistent with the circumstances of the accident. This information was subsequently provided to the EAIB.

On the basis of the following evidence, the NTSB believes that the erroneous AOA signals provided by the left AOA sensor were instead caused by the separation of the AOA sensor vane due to impact with a foreign object, which was most likely a bird:[8]

- The output signal from AOA resolver No. 1 is relayed to the stall management yaw damper computer (SMYD) and the FDR, and the output signal from resolver No. 2 is relayed to the air data inertial reference unit (ADIRU). As discussed in section 1.16.3, Angle of Attack Values, of the EAIB's final report, FDR data revealed that the recorded ADIRU and SMYD parameters were consistent with both resolvers providing the same erroneous values. Thus, the US team's analysis of these data showed that both internal resolvers for the left AOA sensor had an instantaneous, simultaneous, and common shift in output signal.

- The AOA sensor vane is connected to a counterweight that provides a balanced rotating assembly (which is not affected by the force of gravity) within the AOA sensor. If the vane is missing or partially missing, then the change in the balance of the rotating assembly would result in a distinct resolver output behavior change during various flight profiles. When the US team compared the behavior (shown by the accident FDR data) of the left AOA sensor resolver output signal with FDR data from previous bird strike events involving AOA

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[7] Although the signal was valid, once the vane separated from the left AOA sensor, the AOA sensor output became erroneous because of the missing vane.

[8] Section 1.10.1, Aerodrome Inspection, of the EAIB's final report stated that "there was no evidence of a bird" in the area searched. However, the report did not mention that the search for bird remains occurred 8 days after the accident and did not include the area surrounding taxiway D, where the airplane would have been positioned when the left AOA sensor output became erroneous.

sensor vane separations, it was clear that the left AOA sensor on the accident airplane was subjected to an event that resulted in a vane separation. In addition, because the AOA sensor vane and counterweight are connected to a shaft that drives both AOA sensor resolvers, the output signal change caused by a vane separation would occur in both resolvers. As previously stated, the accident FDR data showed a simultaneous and common shift in both resolvers' output signal.

- A vane separation will result in an open circuit of the AOA vane heater if the heater wires are broken. Current flow through the left AOA vane heater is monitored on the FDR, and the accident FDR data showed that this parameter indicated a loss of electrical current through the left AOA vane heater at a time that was consistent with the instantaneous change in the AOA sensor resolver outputs.

- The AOA sensor fault tree analysis evaluated possible AOA vane failure scenarios caused by manufacturing defects, internal component failures, heater failures, non-impact structural failures of the AOA vane/attachment hardware, and AOA vane impact failures. As stated above, the fault tree analysis also assessed internal and external electrical faults and considered every short circuit path to the AOA connector pins. Only one failure mode—a foreign object impact leading to an AOA vane separation—could result in a simultaneous loss of electrical current through the vane heater and a common shift in both resolver output values and remain consistent with all circumstances of the accident flight.[9]

EAIB Finding No. 78

The above-mentioned finding in the final report states the following:

> MCAS would never have activated repeated nose down trim if the flaps were still left down, even in the presence of erroneous AOA. This critical information was not included in the FCOM [Flight Crew Operating Manual] bulletin or in the airworthiness directive.

The NTSB acknowledges that information about the flap position required for MCAS to activate did not appear in Boeing's FCOM bulletin and the Federal Aviation Administration's airworthiness directive in response to the Lion Air flight 610

[9] The fault tree analysis found that a bird weighing at least 0.5 pounds impacting the vane at 170 knots (the estimated airspeed of the airplane at the time of the left AOA sensor performance deviation) would be sufficient to cause the vane to break at the hub and separate from the AOA sensor.

accident. However, Boeing provided that information in a multi-operator message (MOM-MOM-18-0664-01B), which was sent to all "737NG/MAX Customers, Regional Directors, Regional Managers and Boeing Field Service Bases" on November 10, 2018 (after the Lion Air accident but before the Ethiopian Airlines accident). Although the EAIB appended Boeing's multi-operator message to the final report, the EAIB failed to mention that the flaps information appeared in that document; thus, this finding is misleading.

EAIB Report Section 2.9.3, Functional Hazard Assessment for MCAS-Related Failures

Page 244 of the final report states the following:

> Much has been written about the engineering design errors associated with the 737 MAX especially the design errors associated with the development of the MCAS software. Similar design and testing errors were made with the MAX's AOA Sensor part (hardware).[10] In a June 28, 2019, revision to the System Safety Analysis, Boeing informed the NTSB that Erroneous data from the Captain's AOA Sensor is revised to show three separate conditions combined with an OR gate, meaning any one by itself could result in erroneous AOA data: Erroneous AOA-L [left] Sensor, Incorrect AOA output from ADIRU-L output, OR Loss of Power to AOA-L Heater.

Page 244 also states that, after the Ethiopian Airlines flight 302 accident, "Boeing informed the NTSB they had made an engineering design error in their initial AOA Sensor Hazard Analysis" but "neither Boeing, the NTSB, nor the FAA informed Ethiopian authorities about this critical error."

The NTSB notes that the "engineering design error" was an error in a fault tree that was developed for the Boeing 737 MAX air data inertial reference system. The relevant information about the fault tree error was addressed in the NTSB's System Safety and Certification Specialist's Report (dated August 21, 2019), which was provided to both the National Transportation Safety Committee of Indonesia (as part of the Lion Air flight 610 accident investigation) and the EAIB.[11] Further, this information was made publicly available in the Lion Air flight 610 final accident report (issued in October 2019) and in the NTSB docket for that accident (which opened to the public on June 3, 2021). As outlined in the certification specialist's report, the initial fault tree and the fault tree that was revised after the error was discovered both determined that the top event "Misleading Air Data from L & R ADIRU –

[10] The intent of this sentence is unclear given that the investigation found no design or testing errors with the AOA sensor hardware itself.

[11] The EAIB received its copy of the report on December 2, 2019.

Airspeed/Altitude" was extremely improbable, which met the requirement in Title 14 *Code of Federal Regulations* 25.1309, Equipment, Systems, and Installations.