Boeing 737 MAX Return to Service Report

Overview of the Technical Investigation Activities Performed by EASA

FOREWORD

The grounding of the Boeing 737 MAX fleet in March 2019 – in the wake of a second tragic accident with total loss of aircraft and many fatalities within just six months – was a moment of reckoning for aviation safety. Never in the recent history of commercial aviation had two such similar accidents occurred on a relatively new aircraft and at such cost for human life.

For the European Union Aviation Safety Agency (EASA), the grounding marked the start of over 20 months of intense analysis of the aircraft's safety and work with the manufacturer, Boeing, and the Federal Aviation Administration (FAA), as primary certification authority, to rectify the problems which had caused the crashes. We stated publicly that we would take every step needed to ensure the plane was truly safe before it could return to service. We were clear from the outset that EASA would make its own entirely independent assessment of the aircraft's safety: we would request information from Boeing and the Federal Aviation Administration (FAA) but would draw our own conclusions and define actions required accordingly.

As with other authorities, our investigation began with the Maneuvering Characteristics Augmentation System (MCAS) which had been pinpointed immediately as the main contributing cause for both accidents. But we very quickly expanded the scope of our work to an in-depth review of the entire flight control system – reflecting our concern that much more needed to be done to verify its overall integrity. We identified also that human factors – the interface between the pilot and the aircraft – would be of critical importance in assessing the safety of a modified 737 MAX.

Understanding that passengers' confidence in aviation safety had been thoroughly rattled, the Agency has aimed from the outset to be as transparent as possible about our processes, the conclusions reached and the actions prescribed to ensure that the aircraft can return to service. We are publishing this closing report as part of that transparency: we want interested parties to understand the steps we took and trust that this will help them to share our confidence that no stone has been left unturned in EASA's review of the aircraft.

The actions prescribed in EASA's Airworthiness Directive are a combination package, complete only in its entirety. They comprise updates to the aircraft's software, physical changes such as rewiring and, critically, pilot training, updates to manuals and revised operational procedures. We want not only to make the aircraft itself safe, but also to increase pilots' understanding of and confidence in the design of the flight control system. The requirement for a test flight without passengers before the first commercial service allows for an additional check that the plane is fully airworthy.

The return to service in Europe is undoubtedly a milestone – but it is definitively not the end of EASA's work on the 737 MAX. We have committed to follow the aircraft closely after the return to service – analysing any operational problems that may occur and taking action as appropriate. We have also secured commitments from Boeing that it will make proposals to further enhance the safety of the aircraft in the long term.

It is my firm conviction, shared by the entire EASA team, that the Agency has done everything possible to ensure that the Boeing 737 MAX is now truly safe.

Patrick Ky
Executive Director, European Union Aviation Safety Agency

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DISCLAIMER

The report provides a summary of the results of the extended design review of the Boeing 737 MAX aircraft performed by the European Union Aviation Safety Agency (EASA), as well as the conditions under which the Boeing 737 MAX may return to service in the European Union. The findings of the technical investigation presented therein are without prejudice to the conclusions of the safety investigations into the two fatal accidents involving Boeing 737 MAX aircraft performed by the relevant accident investigation authorities in accordance with ICAO Annex 13.

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1. Overview

The tragic losses of Lionair JT-610 and Ethiopian Airlines ET-302, which triggered the grounding of the Boeing 737 MAX fleet by the global aviation authorities, created an unprecedented situation in modern civil aviation history. The design of a new flight controls function (i.e. the Maneuvering Characteristics Augmentation System, MCAS) certified as part of the 737 MAX original approval was identified as a key contributor to these events by the aircraft accident investigation bodies[1].

EASA defined a Return to Service (RTS) strategy designed to ensure the safety of the aircraft design. The associated technical activities encompassed two aspects: (i) a fully independent review of all certification activities associated with the design changes required to address the direct causes of the accidents, and (ii) an extended independent design review of the 737 MAX flight control system and associated functions. This work was enabled by the understanding gained on the causes and circumstances leading to the two accidents: the progress made in this area and the ensuing EASA technical investigation paved the way for the precise definition of the conditions necessary to bring the model back into service safely.

Indeed, EASA was fully engaged in the process that yielded the set of acceptable technical modifications of the 737 MAX and the operational and training updates that came with it. Furthermore, the extended design review by EASA provided additional confidence and, in some cases, generated additional operational limitations for the safe return to service of the 737 MAX.

EASA has additionally defined and agreed a set of post-RTS actions that Boeing has to complete for certain technical issues not representing an unsafe condition[2], i.e. not impacting the immediate safety of passengers. The operation of the 737 MAX is indeed already considered safe with the approved changes and actions mandated in the EASA Airworthiness Directive 2021-0039. The post-RTS actions should be seen as enhancements to contribute to the long-term safe operation of the 737 MAX and to support subsequent design developments of the aircraft family.

2. 737 MAX Flight Control System

The technical investigation on the MCAS had to start from very basic principles as this system was not adequately highlighted to EASA either as a novel or as a critical function at the time of the original 737 MAX validation, which was regulated by the EU- US BASA and its TIP[3]. During this investigation, shortcomings were identified concerning Boeing's safety assessment process, development assurance techniques and validation and documentation of assumptions made about crew reactions to aircraft failures. These process-related weaknesses resulted in Boeing failing to identify the risks associated with the reliance on single-source Angle of Attack (AOA) data, and thus allowed the design of an unsafe flight controls system architecture.

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[1] The investigation of the ET-AVJ (Ethiopian Airlines Flight ET-302) accident has not been concluded but an interim report is available. For more background information please refer to the Annex.

[2] For a definition of this term refer to Acceptable Means of Compliance (AMC) to point 21.A.3B(b) of Annex I (Part 21) to Commission Regulation 748/2012.

[3] Agreement between the USA and the EU on cooperation in the regulation of civil aviation safety (BASA) and the associated FAA-EASA Technical Implementation Procedures, Revision 5

The EASA RTS technical effort has focused on ensuring the correction of the above-mentioned MCAS safety issues. Nonetheless, a prerequisite activity had to be carried out: to thoroughly understand the technical needs for having a MCAS function in the first place. As one of the outcomes of the EASA RTS investigation, MCAS has been established to play only a limited role in augmenting the stability and stall characteristics of the aircraft in certain conditions. The MCAS' limited effect is in fact needed to ensure the stability margins that make the aircraft fully compliant to the applicable regulations on stall demonstration and pitch control characteristics. This explains its inclusion in the original 737 MAX design. These stability margins are required by regulation in order to support the flight crew handling of the aircraft during certain manoeuvres such as approach to stall. The EASA flight tests confirmed that MCAS was needed to provide full compliance but also that the loss of this function does not preclude the safe flight and landing of the aircraft; i.e. the 737 MAX remains stable following the loss of the MCAS function.

The key to ensuring the safe introduction of the MCAS function in the flight controls system was then to review the conditions under which the erroneous activation of the MCAS could lead to an unmanageable nose-down automatic command (caused by a stabilizer runaway) as seen in the accidents. Because of the intricacies of 737 MAX design, the technical investigation quickly turned into a review of all possible causes that may lead to the generation of such spurious nose-down commands and not only of those caused by the MCAS function logics themselves.

This effort required a two-fold approach: on the one hand, to ensure that adequate procedures were being used by Boeing to support a safety-driven development process and, on the other hand, to review in detail the resulting changed design. The first aspect was managed through the introduction of adequate model-based techniques to meet the development assurance goals[4] and through the update of the safety assessment process to ensure alignment with industry-wide accepted methodologies[5]. A series of audits at system and equipment level were performed by EASA at Boeing and Collins Aerospace, the supplier for the Flight Control Computer (FCC), to check the correct application of these processes. The second aspect required a thorough review of the resulting safety analyses as well as piloted evaluations of critical scenarios.

The resulting changed stabilizer trim control system features a vastly modified cross-channel control architecture and AOA processing algorithms. The new design ensures that any unintended nose-down trim command that cannot be easily recovered manually by the crew is stopped automatically by the monitoring system. In this way, no stabilizer runaway like the ones seen in the accidents may result from single failures in the flight control system or its source signals, including those of an AOA probe. These changes are accomplished via the installation of the new FCC P12.1.2 software standard.

The review, as part of the EASA RTS activities, of the flight control system common mode analysis identified the risk that a failure in one of the wire bundles carrying the command and power signals from the cockpit to the stabilizer could lead to an uncommanded stabilizer runaway. This discovery highlighted the shortcomings of the original 737 MAX certification where – based on the use of the applicable Electrical Wiring Interconnection System (EWIS) rules – such risks should have been eliminated. As a result, a wiring separation modification was defined to remove this risk and bring the system back to compliance before RTS.

The crew reaction assumptions used by Boeing in the design of the new architecture were thoroughly reviewed by EASA. Special attention was given to the management of the remaining uncommanded stabilizer

[4] These objectives are set in the Society of Automotive Engineers' (SAE) Aerospace Recommended Practice (ARP) 4754A.
[5] As per SAE's ARP4761.

runaway failure cases not shown to be extremely improbable and the use of the manual trim wheel. Given the monitoring logics incorporated in the changed FCC proposed for the RTS, the EASA technical investigation did not identify any unreasonable assumptions and found the maximum required trim wheel forces to be acceptable[6]. This conclusion is based on the use of the updated non-normal procedures and training requirements for 737 MAX flight crews. Indeed, the following related Aircraft Flight Manual (AFM) procedures have been updated for the 737 MAX RTS: Runaway Stabilizer, Stabilizer Trim Inoperative, Speed Trim Fail, and Stabilizer out of Trim[7]. The updated Flight Crew Operational Suitability Data (OSD-FC) training program requirements were validated during the Joint Operational Evaluation Board (JOEB), which included European flight crews. Besides the new Computer-Based Training (CBT) or classroom requirements, three new Training Areas of Special Emphasis (TASEs) require practical training on the following areas: Stabilizer Trim, Runaway Stabilizer, and Flight Control Computer and MCAS functionalities. A one-time mandatory training exercise ensures that all 737 MAX flight crews are adequately trained in these areas before the RTS.

The return to service of the modified 737 MAX also requires an update of the Master Minimum Equipment List (MMEL) to further restrict the conditions under which an aircraft can be dispatched. Additionally, new Certification Maintenance Requirements (CMRs) have been defined that provide mandatory maintenance tasks[8] related to several dormant failures identified within the flight control system.

3. Crew Management of Multiple Failure Effects

During the Boeing 737 MAX accidents, multiple alerts and indications occurred that increased the flight crew workload. This degraded the capability of the crews to identify the cause of the observed cockpit effects and to take the subsequent corrective actions in due time. Additionally, the flight crew reactions were not consistent with the assumptions made by Boeing regarding their capabilities to manage an unintended MCAS activation. Moreover, the flight crew were not adequately trained on the behaviour of the MCAS.

To address this set of observations and analyse the overall impact on the safety of the 737 MAX including issues beyond the specific case of the MCAS, EASA's technical investigation in this subject area took a bidirectional approach through: (i) a review of the failure scenarios (initially focused on AOA-related failures and then performed with a broader scope) that may result in multiple cockpit effects, and (ii) an assessment of how the 737 MAX cockpit design, and more specifically its alerting system, supports the crew when such high-workload scenarios take place.

The Boeing 737 AOA system consists of two vanes, one on either side of the forward fuselage. Due to the legacy design and federated architecture, the electrical signals from these sensors are not acquired in a

[6] All the related test cases involved full EASA involvement (including EASA-piloted simulator or flight tests) except for a particular failure case (trim re-sync failure) for which the EASA technical assessment was based partially on the testing performed by the other Certification Management Team (CMT) authorities (the availability of the Boeing engineering simulator for the EASA flight test team was limited due to the ongoing COVID 19 pandemic). This activity will be completed by EASA post-RTS.

[7] While reviewing the updated Non-Normal Checklists (NNCs), it was noted some non-normal procedures were not provided in the AFM as expected (being only available through the Flight Crew Operations Manual, FCOM). This discrepancy has been corrected for the RTS-related NNCs and a further post-RTS action has been agreed with Boeing to assess the need of incorporating in the AFM additional non-normal procedures corresponding to NNCs not modified under the current activity.

[8] The full definition of some implementation aspects for the newly established CMRs will be completed post-RTS. This has been accepted by EASA considering that the time required for the new required maintenance tasks amounts to several thousand flight hours.

centralised manner but are processed by independent computers. The evolution of the 737, from its original design conception to the current 737 MAX, made its aircraft systems more and more dependent on AOA data. The 737 NG and MAX architectures rely heavily on the crew reaction capabilities and performance to manage single AOA failure scenarios. The issue was further aggravated in the accident scenarios by the error that led to the unavailability of the “AOA disagree” alert for certain aircraft configurations.

A key aspect of the EASA RTS investigation was the simulator-based evaluation that confirmed the excessive flight crew workload level associated with the Unreliable Airspeed procedure defined at the time of the original 737 MAX validation (an AOA failure will ultimately lead the crew to perform this procedure). This finding led to the redefinition of this procedure for the RTS – including in particular the possibility to deactivate the stick shaker using the relevant circuit-breaker (CB) – to reduce the induced crew workload to manageable levels. Additionally, EASA identified and agreed with Boeing an objective to implement a 737 MAX AOA Integrity Enhancement to further reduce crew workload following single AOA failures and to improve the systems reliability, thus alleviating the aircraft architectural AOA-dependency noted previously. These modifications will be embodied in the 737-10 from the start of production and retrofitted on in-service MAX airplanes.

The review performed of the consequences of a single AOA failure was further expanded to other air data failure cases through the review of Boeing’s Single & Multiple Failures (S&MF) process. EASA examined this process, which was implemented by Boeing to analyse the consequences of both cascading and multiple failures, and decided to have the EASA flight crew evaluate a number of these failure scenarios at the engineering simulator. The outcome revealed discrepancies between the results obtained in the EASA-piloted simulation versus what was recorded as the expected result in the Boeing technical documentation. In addition, EASA identified a significant lack of consideration of human factors elements in the Boeing process. While the EASA re-evaluations did not identify an unsafe condition, EASA has defined and agreed improvements to the S&MF process, which will be reviewed in the context of the 737-10 validation.

The Crew Alerting System (CAS) in the 737 MAX follows the architecture and cockpit philosophy established early in the 737 design history, in which independent and simple annunciations are used to indicate the faulty system to the crew. During the initial 737 MAX certification project Boeing made use of the Changed Product Rule (CPR), which, under certain conditions, allows systems or parts of the design that are inherited from the predecessor aircraft to be assessed against the certification standard applicable when the system or part was first introduced, rather than applying the latest standard, which in this case would have led to the implementation of a modern centralized alerting system.

However, the activities undertaken to support the 737 MAX RTS and the related evaluations and reports (e.g. EASA simulator sessions, S&MF evaluation, Human Factors evaluation with line crews, accident investigation reports) highlighted several weaknesses in the 737 CAS. While the extensive 737 NG in-service experience does not suggest the presence of a related unsafe condition, the concerns on the CAS have been mitigated for the 737 MAX RTS by the introduction of elements in the AFM equivalent to the so-called Standard Operating Procedure (SOPs). These new AFM procedures provide a more structured method for interacting with the crew alerting system and conducting checklists. In addition, with a view to identifying possible future improvements, two post-RTS actions have been defined and agreed with Boeing: (i) the undertaking, within 12 months of RTS, of a full human factors assessment of the crew alerting system in conjunction with the FAA and EASA, and (ii) the implementation of a Safety Management System (SMS) driven approach to monitor and assess, based on flight operation and training data, the performance of the CAS and associated flight crew procedures and training, as regards to the risks of crew errors and excessive flight crew workload.

The following AFM procedures related to the present subject have been updated for the 737 MAX RTS: Airspeed Unreliable, AOA Disagree, ALT[9] Disagree, IAS[10] Disagree as well as the aforementioned SOPs. The updated OSD-FC training program requirements include two new TASEs which will require practical training on the following areas: Unreliable Airspeed, and Multiple Flight Deck Alerts during Non-Normal Conditions. The one-time mandatory RTS training will include these subjects as well.

4. EASA Extended Design Review

The extended design review performed by EASA sought to ensure that no issues similar to those found in the stabilizer trim control system would be present in other areas of the 737 MAX. As such, the technical investigation focused on the 737 MAX flight control systems and all associated functions (display, alerting system, autopilot, air data system, etc.) with special emphasis on the review of the associated Functional Hazard Assessments (FHAs), the assumptions made about flight crew reactions to aircraft failures, and the methodology used to define the flight crew training differences between the 737 MAX and the 737 NG.

FHA Maturity. The FHA review covered six different systems; while no potential unsafe conditions were identified, significant observations were made during the review to the extent that adherence to system safety assessment applicable practices was questioned. As a consequence, EASA has requested and agreed with Boeing a set of improvements to the safety assessment process and the update of several System Safety Assessments (SSAs) completed at the time of the original 737 MAX certification. The completion of these actions will need to be presented to EASA and verified in the context for 737-10 validation.

Flight Guidance System / Autopilot (AP) / Autothrottle (AT) Review. The focus was set on the performance of these systems and their behaviour in case of receiving erroneous input parameters (e.g. air data). The risk that these systems may disengage in such a way that resuming manual flight could be difficult was assessed as well. The EASA review outcome was satisfactory except in the following areas.

- Minimum Use Height (MUH) Determination: The documentation and analyses provided by Boeing were not deemed to be enough to justify the recognition times used for MUH determination. Consequently, the EASA RTS AFM was modified to reflect an MUH corresponding to a recognition time of one second instead of the 0.5 second figure used at the time of the original 737 MAX validation.
- Required Navigation Performance Authorisation Required (RNP AR): EASA evaluated the impact of AOA or other air data sensor failures on the accuracy of the position, altitude or airspeed that is required to conduct RNP AR operations. As Boeing had not conducted suitable simulator or flight tests to evaluate such RNP significant failures at the time of certification, EASA performed a Full Flight Simulator (FFS) based assessment for several relevant scenarios. The test results did not fully support the EASA regulatory objective; therefore, the EASA AFM was modified to include a limitation prohibiting RNP AR operations.
- AP improvements: Observations made during simulator tests regarding the autopilot behaviour when approaching stall led to the definition of the following design improvements: (i) AP disconnection and Flight Director (FD) removal one second after stick shaker activation (for some AP

[9] Altitude.
[10] Indicated Airspeed.

modes) and, (ii) Nose-up autotrim inhibition at three knots below the amberband speed, while flaps down, in order to improve pitch characteristics at autopilot disconnect.

OSD-FC differences training. EASA assessed the impact on the OSD-FC of all the modifications introduced between the 737 NG and the 737 MAX. This activity included the satisfactory review of the methodology used by Boeing to determine the impact of design changes on pilot training.

EWIS. Motivated by the finding that the stabilizer trim control wiring was not initially installed in compliance with the physical separation requirements (as per the applicable EWIS certification specifications), EASA expanded its EWIS compliance review to the 737 MAX fly-by-wire spoilers system, which included all the wiring for the Multi-functional and Ground Spoilers. The EASA review concluded that the protections and mitigations put in place were acceptable for EWIS compliance.

High Intensity Radiated Field (HIRF) & Lighting. EASA reviewed the criticality of a series of existing non-compliances in regards of the HIRF and Lightning Protection of aircraft systems. The identified non-compliances were checked to ensure they did not affect the MCAS system. For the other cases, dedicated reviews will be performed in the context of the continuing airworthiness process.

The 737 MAX extended design review has validated that the aircraft is safe for return to service. Within the scope of the review performed, the limited number of identified unsafe items were managed by the establishment of appropriate limitations. For other non-critical items, agreements for post-RTS design and process improvements were made with Boeing.

5. RTS Requirements

The EASA Airworthiness Directive (AD) that enforced the grounding of the 737 MAX is superseded with a new AD[11] that defines the conditions under which the model may return to service. The EASA RTS requirements include:

- the installation of the FCC P12.1.2 software standard (implementing the new stabilizer trim control architecture and new MCAS activation logics);
- the installation of the MAX Display System (MDS) software update to fully require on all aircraft the “AOA Disagree” annunciation functionality;
- changes in the stabilizer trim control wiring;
- the update of the AFM including changed operating procedures (Airspeed Unreliable, Runaway Stabilizer, Stabilizer Trim Inoperative, Speed Trim Fail, Stabilizer out of Trim, AOA Disagree, ALT Disagree, IAS Disagree), general procedures for the management of alerts, and additional limitations;
- the update of the MMEL to remove certain flight control system alleviations;
- the update of the OSD-FC training requirements including five new TASEs requiring practical training and a one-time pre-RTS flight crew mandatory exercise covering these areas;
- an AOA sensor system test;
- an operational readiness flight.

[11] Refer to EASA AD 2021-0039 https://ad.easa.europa.eu/

These elements constitute the totality of mandatory RTS actions[12] identified by EASA during its technical investigation.

6. Post-RTS actions

The following list summarizes the actions identified and agreed with Boeing that are to be implemented post-RTS:

- 737 MAX AOA Integrity Enhancement (to be developed and certified for the 737-10 validation);
- 737 MAX Crew Alerting Human Factors evaluation (to be performed within 12 months of RTS);
- evaluation of additional non-normal procedures of the operating manual for future inclusion in 737 AFM (to be performed within 6 months of RTS);
- non-critical Systems Safety Analysis (SSA) updates and supplemental technical verifications (to be verified for the 737-10 validation);
- updated demonstration of compliance with HIRF and Lightning requirements (in the frame of the standard continuing airworthiness process);
- completion of the documentation supporting the definition of newly defined mandatory maintenance actions;
- safety analysis process updates (to be verified for the 737-10 validation);
- Development Assurance process updates (to be verified for the 737-10 validation).

7. Concluding Statement

EASA is confident that the combination of the flight control system architectural update and associated wiring modifications, the revised flight crew procedures, and the new training requirements constitute the necessary elements to safely bring the 737 MAX aircraft back to service. The RTS requirements include also limitations linked to issues identified by EASA related to invalid assumptions about flight crew reactions to aircraft failures used by Boeing (AFM modifications related to RNP AR operations and MUH determination).

In order to ensure the long-term safety of the 737 MAX, EASA has also agreed with Boeing two key post-RTS actions: (i) the development of a modification to further improve the AOA integrity, to be integrated in 737-10 version and retrofitted on the in service fleet, and (ii) the further evaluation of the CAS.

The EASA technical investigation also revealed several systemic issues in the process-driven aircraft design activities performed by Boeing. In this sense, the methodological concerns identified with the MCAS development were not an isolated case. In view of this situation and for technical issues not considered to constitute an unsafe condition, EASA has defined and agreed with Boeing a set of improvements on the

[12] An additional AD will be released to define the necessary changes in the Instructions for Continuous Airworthiness (ICA) to support the 737 MAX RTS. The release of this second AD can be delayed as the time required for the new required maintenance tasks amounts to several thousand flight hours.

system safety assessment and development assurance processes to be applied systematically for the 737-10 and all future 737 developments.

The application of the EASA RTS strategy has yielded not only a complete set of conditions that will allow the safe return to service of the 737 MAX but has also – by taking a broader view beyond the specific MCAS concerns – identified a set of design and process improvements to support the long-term safety of the aircraft and prevent issues similar to the one found in the MCAS function from taking place again in future 737 MAX developments.

Appendix - Additional Background information

The Boeing 737 model has been for a long time – together with the Airbus A320 – the workhorse of the global airlines' fleet with over 10,000 aircraft delivered since its original conception. This narrow-body aircraft, produced by Boeing Commercial Airplanes at its Renton facility in Washington State, has evolved through four different generations. The incorporation at each step of new technologies has allowed the 737 to increase its efficiency while keeping a level of commonality at industrial or operational levels.

The original model of the family is the 737-100 which was envisioned in 1964 and made its first flight in April 1967; the model entered service the following year with Lufthansa. The original 737-100/-200 variants were powered by Pratt & Whitney JT8D low-bypass engines and offered seating for 85 to 130 passengers. The 1980s saw the introduction of the 737-300/-400/-500 variants (now referred to as the 737 Classic); these models included CFM56-3 engines turbofans and offered 110 to 168 seats. The third generation of the 737 (known as the 737 NG, Next Generation) was introduced in 1997; the 737-600/700/800/900 variants introduced updated CFM56-7 engines, a larger wing, and seated from 108 to 215 passengers. The 737 MAX is the fourth and latest generation of the 737 family; Figure 1 provides an overview of the 737 models evolution.

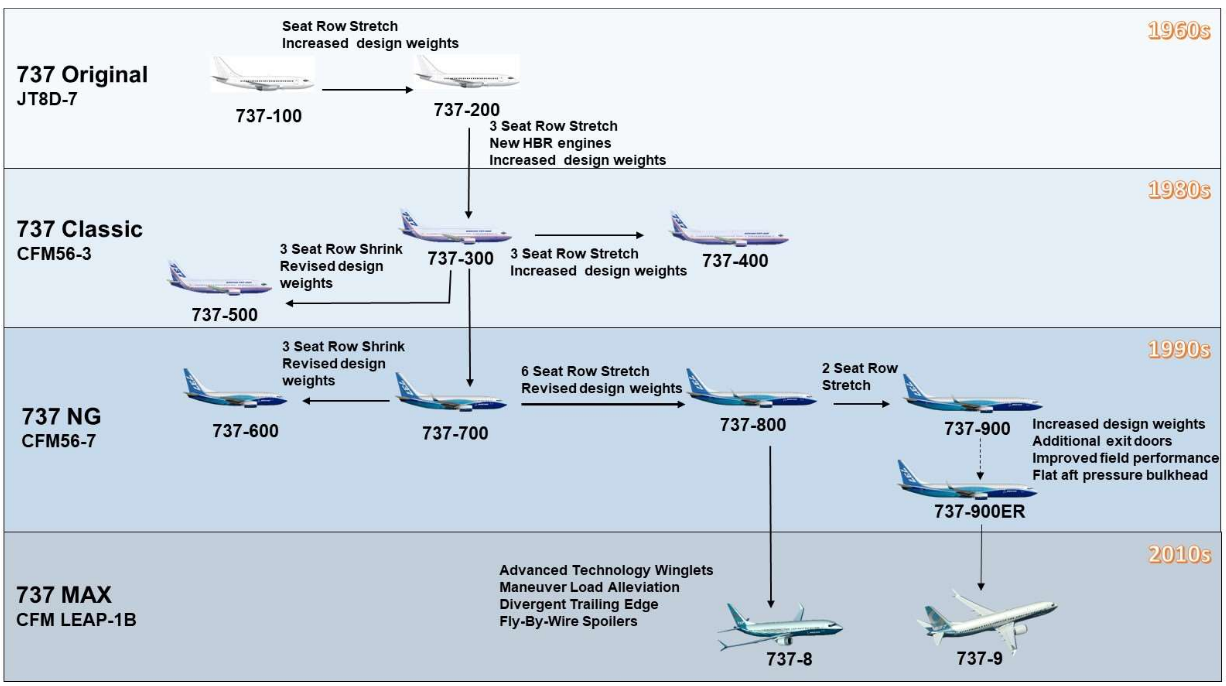

Figure 1: The Boeing 737 Family of Airplanes

(source: based on Boeing technical familiarization materials)

1. Initial Validation of the Boeing 737 MAX by EASA

In August 2011, Boeing approved the launch of a new 737 family that was to be powered by CFM International LEAP-1B engines. Like Airbus before with the A320neo, Boeing aimed to ensure the continuity of the program well into the 21st century thanks to the larger and more fuel-efficient engines. Thousands of orders were secured by the entry into service of the 737 MAX.

On June 28, 2012, Boeing applied to the FAA and EASA for the certification of a new derivative model of the 737-800 through an amendment of the existing Type Certificate. The denomination of the new model was to be 737-8. In accordance with the applicable Annex I (Part-21) to Commission Regulation (EC) No 748/2012 and the associated guidance material, the change related to the new powerplant installation was classified as significant at the product level.

The 737-8 incorporated not only the new CFM LEAP-1B engine. The 737-8 modifications included a new Advance Technology winglet, a lengthened nose landing gear to provide ground clearance for the new larger engine, and other improvements. The wing spoilers were changed from mechanically driven to fly-by-wire to support certification to reduce weight and build time. Additional systems and structures changes were made to meet the latest certification requirements. Figure 2 provides an overview of the modifications introduced for the 737-8.

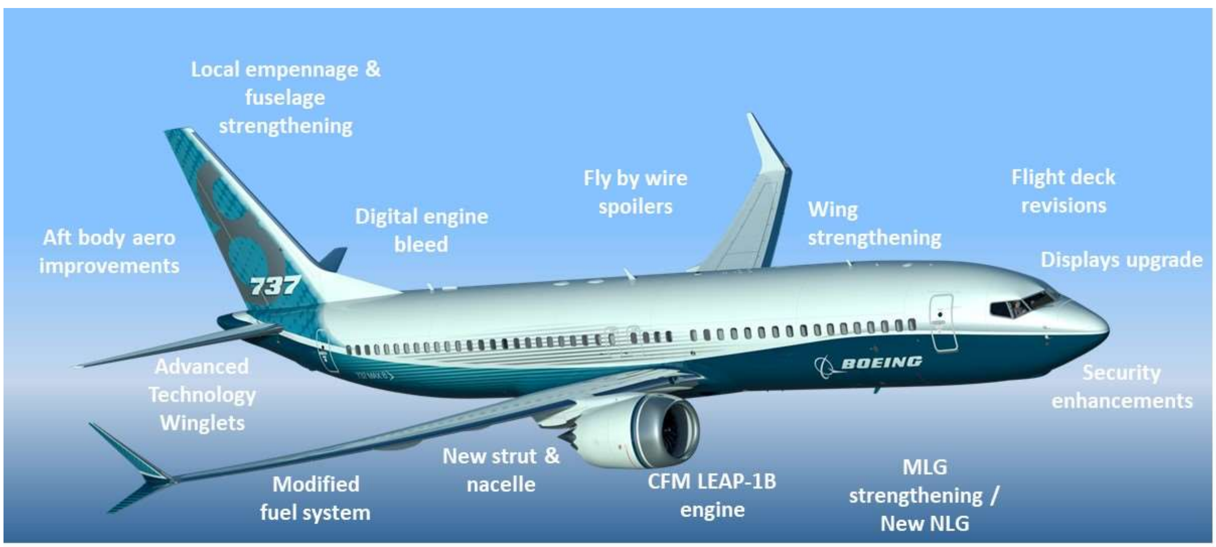

Figure 2: 737-8 Main modifications

(source: based on Boeing technical familiarization materials)

The establishment of the EASA 737-8 certification basis from the applicable CPR analysis was a major challenge as for the 737 MAX – being the fourth generation of the model – a complex combination of modern and original requirements was made applicable. The involvement of EASA as validating authority in the technical investigation activities for the 737-8 was regulated by the Agreement between the USA and the EU on cooperation in the regulation of civil aviation safety (BASA) and the associated FAA-EASA Technical Implementation Procedures for airworthiness and environmental certification (TIP), Rev.5 (FAA-EASA, 2015) in effect at the time.

The EASA team thus focused its efforts on the main technical novelties that had been highlighted, the new compliance challenges and the regulatory differences with the certificating authority (FAA). As such, close scrutiny was given to the installation of the new engine and other major modifications such as the fly-by-wire spoilers or the new cockpit displays. Additionally, EASA focused on topics such as the management of unreliable/erroneous air speed data, cybersecurity, the application of EWIS rules, the review of the wheel and tyre failure compliance demonstration, etc.

In March 2017, Boeing obtained the FAA certification and EASA validation for the 737-8 model. Malindo Air, a Malaysian air carrier subsidiary of the Indonesian carrier Lion Air, was the first to receive and fly the 737-8 and started its operations on May 22, 2017. In Europe, Norwegian Air Shuttle received the first delivery of the 737-8 model on June 29, 2017 with the aim of supporting its planned transatlantic flights between northern Europe and the east coast of the United States. The certification and validation activities for the subsequent model, denominated 737-9, ran in parallel and took advantage of the work performed for the 737-8. The 737-9 FAA certification was granted in February 2018 and the EASA validation in October 2018.

At time of the writing of this report, three additional 737 MAX variants (737-8200, 737-7, and 737-10) are in the process of being validated by EASA.

2. Events leading to the 737 MAX fleet grounding

2.1 737-8 MAX, PK-LQP, Lion Air JT-610 Accident

On October 29, 2018 a Lion Air Boeing 737-8 performing flight JT-610 from Jakarta to Pangkal Pinang (Indonesia) with 181 passengers and 8 crew was climbing out of Jakarta when the aircraft lost height and crashed into the Java sea at 06:31.54 Local Time (LT) – the time when the Digital Flight Data Recorder (DFDR) stop recording – causing the fatal injury of all occupants.

Consequently, the NTSC (National Transportation Safety Committee, also named KNKT – Komite Nasional Keselamatan Transportasi), opened an accident investigation in accordance with ICAO Annex 13. While EASA was not officially involved in the investigation process, EASA maintained contact with the National Transportation Safety Board (NTSB) and KNKT in order to follow up the investigation; the FAA and Boeing (advisor) were also part of the investigation.

On November 1, 2018 the DFDR was recovered from the sea at about 35 meters. It was then successfully read out to the KNKT recorder facility with the participation of the Australian Transport Safety Bureau (ATSB), the Transport Safety Investigation Bureau (TSIB) of Singapore, and the NTSB of United States of America as Accredited Representatives in addition to Boeing.

Following the preliminary data analysis, on November 7, 2018 Boeing issued an Operations Manual Bulletin (OMB) to all Boeing 737 MAX Operators stating that the investigation into the crash of PK-LQP found that one of the Angle of Attack (AOA) sensors had provided incorrect readings, which could cause the aircraft trim system to inadvertently trim nose-down (during manual flight). The OMB directed "*operators to existing flight crew procedures to address circumstances where there is erroneous input from an AOA sensor*." The OMB also reiterated the Stabilizer Runaway non-normal checklist.

On November 7, 2018 the FAA released Emergency Airworthiness Directive (EAD) 2018-23-51 concerning all Boeing 737 Max aircraft reading:

"This emergency AD was prompted by analysis performed by the manufacturer showing that if an erroneously high single angle of attack (AOA) sensor input is received by the flight control system, there is a potential for repeated nose-down trim commands of the horizontal stabilizer. This condition, if not addressed, could cause the flight crew to have difficulty controlling the airplane, and lead to excessive nose-down attitude, significant altitude loss, and possible impact with terrain."

The FAA AD furthermore required revising certain limitations and operating procedures of the AFM to provide the flight crew with runaway horizontal stabilizer trim procedures to be followed under certain conditions. EASA endorsed the FAA AD and published it on the EASA website on the same day as the FAA.

On November 28, 2018 KNKT released their **preliminary report** which makes also reference to the flight operated before the accident occurrence (October 28, 2018 from Denpasar to Jakarta). It was the first flight after a maintenance action that replaced the AOA sensor. The DFDR showed that the stick shaker activated during the rotation and remained active throughout the flight. At same time as the "IAS DISAGREE" warning appeared (together with other warnings), the crew noticed that as soon the manual trim input was stopped, the aircraft was automatically being trimmed aircraft nose-down (AND). After three automatic AND trim occurrences, the crew moved the STAB TRIM switches to the "CUT OUT" position. The crew continued the flight to destination with the stick shaker activated and landed safely to destination. The maintenance checked the aircraft and performed the flushing of the left Pitot Air Data Module (ADM) and static ADM, followed by the operational test on ground, which was satisfactory.

The report lists two Safety Recommendations (SR) addressed to the operator, concerning the continuation of the flight before the accident with the stick shaker activated and the operational documentation (the weight and balance sheet of the accident flight did not contain actual information).

On October 25, 2019 KNKT released the **final report**. The conclusions are organized in 89 findings and nine contributing factors, with part of them highlighting the previous flight (LNI043) where the aircraft experienced the same failure. Findings relate to many different topics, like the assessment of the "unintended MCAS-commanded stabilizer movement", which had been considered by Boeing as a failure condition[13] (FC) with a Major classification only (instead of Hazardous or Catastrophic) in the normal flight envelope; this FC classification allowed Boeing to perform a less rigorous analysis. Further findings addressed the "multiple alerts and indications in cockpit", "MCAS design", "FAA oversight of Boeing", "Flight Crew Training", "Crew reaction timing as per FAR requirements", "Crew Resource Management (CRM)", "Operator SMS", "Maintenance & Component repair procedures". The report identifies the possible failure of the left AOA vane as probably due to the improper vane calibration after the previous repair, which had been carried out by Xtra Aerospace.

[13] Certification Specification for Large Aeroplanes (CS-25) Book 2, AMC 25.1309 provides the definition and classification of failure conditions.

2.2 737-8 MAX, ET-AVJ, Ethiopian Airlines Flight ET-302 Accident

On March 10, 2019 Ethiopian Airlines flight 302, operated by a Boeing 737-8 MAX, registered ET-AVJ, took off from Addis Ababa, Bole International Airport bound to Nairobi, Jomo Kenyatta International Airport, with 157 persons on board: two flight crew, five cabin crew and one IFSO (In-flight Security Officer) and 149 passengers. Shortly after take-off, the AOA value became erroneous and the left stick shaker activated. The airspeed and altitude values from the left air data system began deviating from the corresponding right side values. Due to "flight control problems", the Captain was unable to maintain the flight path and requested to return back to the departure airport. The crew lost control of the aircraft, which crashed at 5: 44 UTC 28 nautical miles South East of Addis Ababa, near the Ejere village, after about 6 minutes of flight.

The Ethiopian Aircraft Accident Investigation Bureau (EAIB) opened immediately an investigation in accordance with ICAO Annex 13 and asked EASA to formally participate in the investigation in order to provide assistance for the reading and analysis of the Cockpit Voice Recorder (CVR) and DFDR data. An EASA Safety Investigation Officer joined the investigation team first in the Bureau d'Enquêtes et d'Analyses (BEA) facilities in Paris where the recorders readout was carried out, and then in Addis Ababa on 20 Mar 2019, to participate to the preliminary data analysis. NTSB (accredited representative), FAA and Boeing (advisors) were also part of the investigation, attending the operations on the recorded and the data analysis.

On March 11, 2019 the FAA issued a Continued Airworthiness Notification to the International Community (CANIC) for Boeing 737 MAX Operators stating they were engaged in the review of the pending changes in the MCAS system, AOA Sensor Signal improvements as well as training requirements associated with MCAS. On the same day the Civil Aviation Authority of China (CAAC) instructed all operators to immediately stop flying the Boeing 737-8 MAX.

On March 12, 2019, prompted by the technical evidence pointing to the similarity of the causes leading to the two 737-8 accidents, EASA published an Emergency Airworthiness Directive (EAD 2019-0051) and a Safety Directive (SD-2019-01) suspending all flight operations of all Boeing 737-8 and 737-9 aeroplanes in Europe, including all commercial flights performed by third-country operators into, within or out of the EU.

On March 13, 2019 Canada also forbid operations of Boeing 737 MAX aircraft in Canadian Airspace, while on the same day, the FAA Administrator issued an order prohibiting the operation of U.S.-registered Boeing 737 MAX aircraft and prohibiting the operation of foreign-registered Boeing 737 MAX aircraft in U.S. airspace.

A **preliminary report** was issued in April 2019 by the EAIB, based on the initial information gathered during the course of the investigation and included the following information about the accident:

- The take-off roll appeared normal, including normal values of left and right angle-of-attack (AOA).
- Shortly after lift-off, the value of the left AOA sensor reached 74.5 degrees (with the right AOA value at 15.3 degrees). The stick shaker activated and remained active until near the end of the flight.
- After the autopilot disengaged, the DFDR recorded four automatic uncommanded AND trim command (with three motions of the stabilizer trim), while the crew operated the electric manual trim to counter the automatic AND input.
  The crew performed the runaway stabilizer checklist and put the stab trim Cutout Switch to the "CUT OUT" position and confirmed that the manual trim wheel operation was not working.

Among others, the report lists:

- one SR to the manufacturer to address the need to review the aircraft flight control system related to the flight controllability issues;
- one SR to the Aviation Authorities to verify that the review of the aircraft flight control system related to the flight controllability issues be adequately addressed by the manufacturer before the release of the aircraft to operations.

An **interim report** was issued in March 2020, containing a detailed description of all the systems analysed during the investigation, with dedicated sections on the manual trim wheel forces and the impact of the AOA malfunction on the other aircraft systems. No "analysis" is present in the report, making reference to the still ongoing investigation, but there is a list of findings which highlight the main topics under review, for instance: the MCAS design, the 737 Crew Alerting System, or the difference training from 737 NG to 737 MAX.

This interim report does not conclude the accident investigation but provides sufficient understanding of the technical circumstances and contributors to the accident for the purpose of EASA's RTS investigation.

3. EASA strategy for the RTS

On April 1, 2019, with the aim of ensuring the safe return to service of the Boeing 737 MAX, EASA outlined to the FAA the intended scope of EASA activities needed to achieve this goal. Two main areas of technical involvement were identified, which are described in detail below. The scope of these activities was adapted as the circumstances of the accidents became better known and the initial findings highlighted some areas of special technical interest.

- The EASA approval and subsequent mandatory retrofit of the following 737 MAX changes (at the time designated as safety enhancements by Boeing):

    - Displays Software Block Point 1.5.1 to correct the problem report causing the inhibition of the AOA disagree annunciation in some cases;
    - update of the FCC software to modify the MCAS activation logics;
    - update of the OSD-FC, and therefore to the flight crew training program, to take into account the introduction of the MCAS functionalities.

    The key aspects of this activity were: (i) to ensure the full compliance of the changed and affected areas with the applicable type-certification basis as per point 21.A.97 of Part-21 and, (ii) to demonstrate that no feature or characteristic made the changed product unsafe.

- An additional extended design review of the Boeing 737 MAX. The objective was to ensure that no weaknesses similar to those found in the MCAS, and thought to have contributed to the accidents, would be present in the other 737-8 changed areas (i.e. the modifications performed on the previous 737 model, the 737 NG). The investigation was intended to focus on the 737 MAX flight control systems and all associated functions/systems (display, alerting system, autopilot, air data system, etc.). The following aspects were to be investigated:

- Functional Hazard Assessment completeness and correctness, with special emphasis on the review of the assumptions used when the flight crew actions were taken for credit to mitigate the severity of a failure condition;
- flight controls and autopilot design;
- flight crew training differences between the 737 MAX and the 737 NG.

In this case, the assessment and resolution of any issue was to be performed following the regular continuing airworthiness process, i.e. per point 21.A.3B(b) of Part-21.

The 737 MAX RTS activities were performed in collaboration with the FAA – in its role as primary certification authority – and with the other Certification Management Team (CMT) authorities; i.e. Transport Canada Civil Aviation (TCCA) and the Agência Nacional de Aviação Civil (ANAC) of Brazil. Nonetheless, EASA retained its full technical independence during the whole RTS investigation.

Acronyms, Abbreviations and Definitions

AFM	Aircraft Flight Manual
ALT	Altitude
ANAC	Agência Nacional de Aviação Civil
AND	Aircraft Nose Down
ANU	Aircraft Nose Up
AOA	Angle of Attack
AP	Autopilot
AT	Autothrottle
BASA	Bilateral Aviation Safety Agreement
BEA	Bureau d'Enquêtes et d'Analyses
CAS	Crew Alerting System
CB	Circuit-Breaker
CBT	Computer-Based Training
CMR	Certification Maintenance Requirement
CMT	Certification Management Team
CRM	Crew Resource Management
DFDR	Digital Flight Data Recorder
EAIB	Ethiopian Accident Investigation Bureau
EASA	European Union Aviation Safety Agency
EWIS	Electrical Wiring Interconnection System
FAA	Federal Aviation Authority
FCC	Flight Control Computer
FD	Flight Director
FFS	Full Flight Simulator
FHA	Functional Hazard Assessment
HIRF	High Intensity Radiated Field
JOEB	Joint Operational Evaluation Board
KNKT	Komite Nasional Keselamatan Transportasi
MCAS	Maneuvering Characteristics Augmentation System
MMEL	Master Minimum Equipment List
MUH	Minimum Use Height
NG	Next Generation
NNC	Non-Normal Checklist
NTSB	National Transportation Safety Board
OSD-FC	Operational Suitability Data – Flight Crew
RNP AR	Required Navigation Performance Authorisation Required
RTS	Return to Service
S&MF	Single and Multiple Failure
SMS	Safety Management System
SOP	Standard Operating Procedure
SR	Safety Recommendation
SSA	System Safety Assessment
TASE	Training Areas of Special Emphasis
TCCA	Transport Canada Civil Aviation
TIP	Technical Implementation Procedure