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Case Study of the Boeing 737 MAX 8 Crashes Using a Systems Thinking Approach

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Abstract: The Boeing 737 MAX 8 aircraft has been grounded due to two fatal crashes with a 6-month span. The purpose of this research is to apply a systems thinking approach to the causes that led to these two crashes. Little official data has been released detailing the causes of the crashes, but using systems thinking to analyze the bigger picture is still valuable. This research concluded that the two fatal crashes were a result of many technical, managerial, and operational issues throughout the development, testing, and implementation phase of the Boeing 737 MAX 8 system.

Keywords: Boeing 737 MAX 8, Aviation Accident, Safety System, Engineering Management, Technical Failures

1. Introduction

1.1 Framing the Issue

On May 22, 2017, the Boeing 737 MAX 8 flew with passengers for the first time. This was a milestone in the aviation community as the 737 MAX 8 was the most fuel-efficient, single-aisle passenger aircraft on the market, boasting a 14% higher fuel-efficiency than any other similar aircraft (Boeing, 2017). After receiving more than 4,800 orders worldwide, the 737 MAX 8 became Boeing's fastest-selling aircraft in history (Boeing, 2018). However, shortly after the MAX 8 began wide use, a pair of fatal accidents cast serious doubt on the safety of the aircraft. On October 29, 2018, 16 months after its introduction, a 737 MAX flying from Jakarta to Pangkal Pinang, Indonesia as Lion Air Flight 610 crashed, killing the 189 passengers and crew members on board. Before it crashed, the aircraft had self-initiated a nose-down pitching motion that the pilots could not physically overcome. Six months later, on March 10, 2019, a Boeing 737 MAX 8 flying as Ethiopian Air Flight 302 crashed en route from Bole, Ethiopia to Nairobi, Kenya. The aircraft's pilots encountered the same uncorrectable nose-down pitching behavior. Following this second crash, the 737 MAX was grounded worldwide and remains grounded to date.

New details emerge weekly regarding the two crashes, available to the public primarily in the form of news articles. However, investigations into the causes and circumstances of the crashes are ongoing by the National Safety Transportation Board (NTSB), the Federal Aviation Association (FAA), the equivalent safety and certification boards in Indonesia and Ethiopia, as well as many other international aviation agencies. Although some preliminary reports have been released, many final reports, which will help clarify the technical and managerial circumstances of the accidents, are still pending. However, the Komite Nasional Keselamatan Transportasi, Indonesia's NTSB equivalent, did release their final report regarding Lion Air Flight 610. Despite lacking considerable official data, there is still great value in attempting to explain why these aircraft crashed.

As with any aviation accident, the causes of these two crashes cannot be attributed to a single cause. Therefore, this research focuses on analyzing the crashes using a systems thinking approach. Systems thinking tasks the analyst with looking at the "whole picture" in systems design and analysis, revealing the network of causes and effects that lead to accidents such as these. The goal of this approach is to reveal details that will improve future aircraft development, design, production, and implementation.

Safety analysis using systems thinking is an important part of any system design process, as consumers expect system producers to design maximally safe systems. However, experts in the field of system safety have identified a gap in the traditional methods used to evaluate system safety. In her book *Engineering a Safer World: Systems Thinking Applied to Safety,*
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MIT Professor Nancy Leveson explains why she think this gap has formed. She believes the gap is due to the fast pace of technological change, the changing nature of accidents, new types of hazards, increased coupling and complexity within systems, more complex relationships between humans and automation, and changing regulatory and public views of safety (Leveson, 2011). Leveson argues for the need to break away from looking at traditional event-chain models to attempt to describe an accident. Instead she introduces the need to view the entire socio-technical system to adequately describe an accident (Leveson, 2011). Systems thinking is a way to do this. One tool to accomplish this is a Systemigram. Systemigrams are useful for visualizing systems and highlighting the complexities of its relationships (Mehler et al., 2010). Figure 1 is a systemigram that depicts some of the events that led to the unnecessary loss of life in the two crashes. The diagram is not all inclusive, but a good way to visualize some the, technical, managerial, operational components that contributed to the crashes. By stepping away from only analyzing the technical reasons of the crashes, the accidents can be described in their entirety to include managerial pressures, market pressures, and potential certification errors. In the case of the Boeing 737 MAX 8 accidents no research articles attempt to integrate systems thinking and safety systems analysis to analyze the crashes. This research will fill this gap.

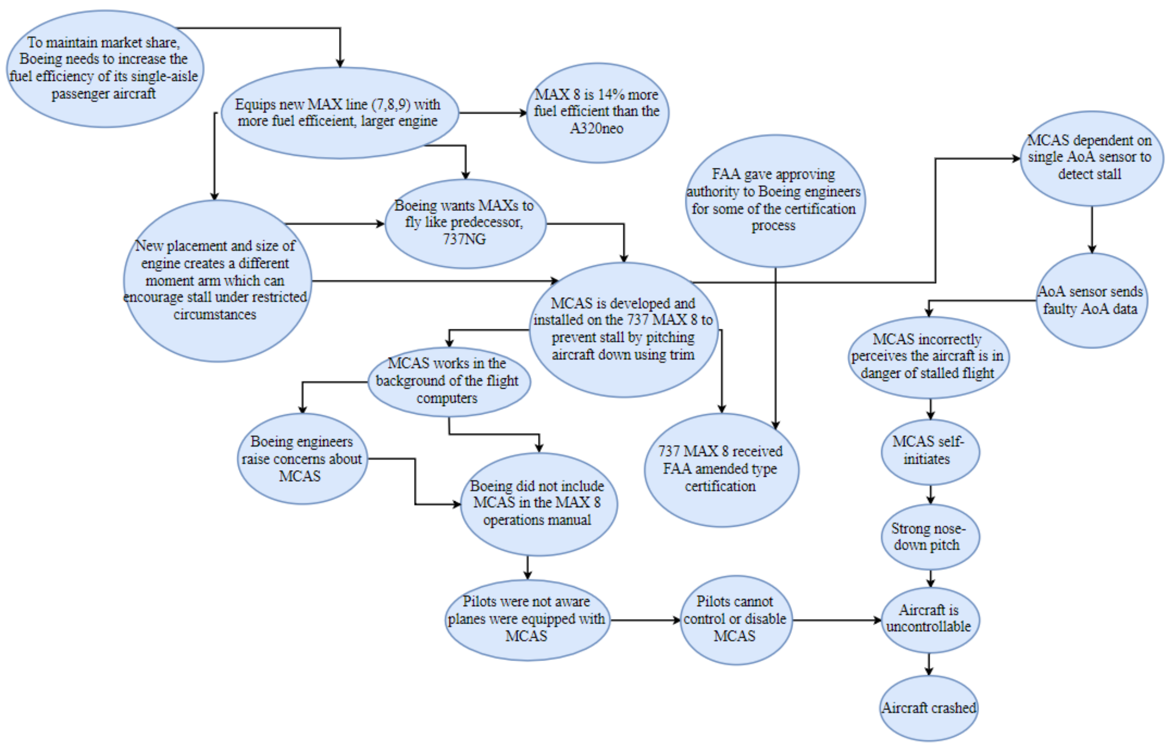

Figure 1. A Systemigram for the Boeing 737 MAX 8 crashes

1.2 Fundamental Aerodynamic Concepts

To fully understand why the aircraft crashed, it is important to understand three aerodynamic concepts*: angle of attack* (AoA), *trim,* and *stalled flight.* Angle of attack is the angle between an aircraft's wing chord and the relative wind. Figure 2 shows the relative wind, represented by the black arrows in the horizontal plane and a cross section of an aircraft wing. The chord of the cross-section is the imaginary line that connects the leading-edge of the wing to the trailing-edge. The AoA is the angle between the chord line and the relative wind, denoted as α in Figure 2. On large aircraft, AoA is measured by a wind-vane sensor attached to the outside of the aircraft, Figure 2. For the Boeing 737 MAX 8, there are two AoA sensors: one on each side of the nose of the aircraft.

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Angle of attack is important because it influences how much lift the wing of an aircraft is producing. As the AoA increases, the lift produced also increases, up to a point. When AoA gets too high, the aircraft stalls, meaning it produces much less lift and in turn begins a descent that is sometimes uncorrectable.

When an aircraft is in trim, it means that the aerodynamic forces of the aircraft are in equilibrium. This is important to the stability and maneuverability of the aircraft. The Boeing 737 MAX 8 is equipped with an electric trim tab stabilizer that automatically adjusts the horizontal stabilizer of the aircraft (the horizontal portion of the tail) to maintain a trimmed state. However, this electric trim tab can be disabled by pilots, requiring them to manually trim the aircraft using a trim wheel in the cockpit.

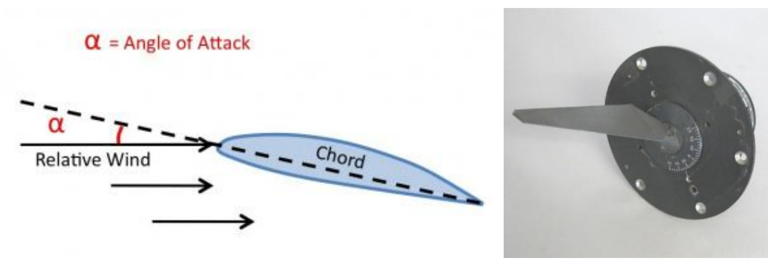

Figure 2. Angle of Attack Diagram and Sensor

1.3 Document Outline

Section 2 of this document provides detailed background information on the two aircraft crashes in detail and begins analysis on the safety system known as MCAS. Section 3 takes a step back and analyzes the reasons behind Boeing’s adaptation of their previous single-aisle passenger airlines, the 737 NG, and the need for the 737 MAX 8 to be outfitted with MCAS. Section 3 also details how Boeing attained its FAA amended type certification for the 737 MAX 8 and the hazard classification that MCAS was awarded. Section 4 shows the importance of looking at the bigger picture and focusing on integrating systems thinking into safety analysis.

2. The Boeing 737 MAX 8 Crashes

2.1 Background Information

On October 29, 2018, Lion Air Flight 610 crashed 12 minutes after take-off, killing the 189 passengers and crew members on board. Soon after the plane took off, pilots received a warning that the plane was in danger of stalling. The pilots could not ascertain their speed or altitude and told air-traffic controllers that they were "experiencing a flight control problem" (NTSB, 2019). As with the later Ethiopian Airlines flight, the nose of the aircraft was being forced downward (Slotnick, 2019). Additionally, as the pilots continued to feel the downward pitching motion, various alarms began to go off in the cockpit and alerts appeared on the Primary Flight Display (PFD), all due to the erroneous sensor readings (NTSB, 2019). The pilots’ checklists did not provide the answers they needed to stop the downward pitching moment. Additionally, there was no system in the cockpit interfaces that helped pilots prioritize which alerts and alarms needed to be addressed first. This may have caused the pilots to become overwhelmed and may have made it hard for them to react quickly enough to fix the issue causing the alarms.

Six months later, on March 10, 2019 one minute after take-off, the pilots on Ethiopian Flight 302 reported a flight-control issue. A minute later, the pilots felt a large force pitching the nose of the aircraft downward. The pilots struggled to control the plane but could not physically pull the nose of the aircraft up using their yoke. Eventually, the pilots halted the pitch-down moment by disabling the *electrical trim tab system*, per protocol. However, by that point they were physically unable to manually turn the wheel that would change the trim by hand (AAIB 2019). This inability was caused by the large aerodynamic forces on the trim system, which in turn were caused by the aircraft’s high speed in descent.

The large, uncontrollable pitch-down motion the pilots experienced was caused by the Maneuvering Characteristics Augmentation System (MCAS), a new feature of the 737 MAX intended to prevent aircraft stall by automatically pitching the aircraft down using the horizontal trim stabilizer. In the two crashes, it appears that MCAS perceived the aircraft were entering stalled flight based on erroneous data from one of the two AoA sensors. At the time, MCAS used only one of the two available AoA sensors to detect stall: either the left one of the right one, but never both at the same time.

According to the digital flight data recorder (DFDR) from Lion Air Flight 610, the AoA sensors on each side of the nose were averaging a difference of 21° from take-off until the crash. The automatic trim down activated 26 times from the time MCAS activated two minutes into the flight, to the end of the recording. The pilots tried to counteract this trim down motion through 34 electric trim up inputs. (KNKT, 2019). However, unlike on the Ethiopian Airlines flight, they never deactivated the electric trim tab stabilizer, which would have deactivated MCAS.

Following the release of both preliminary reports of Lion Air Flight 610 and Ethiopian Flight 302, Boeing CEO Dennis Muilenburg released a statement on April 4, 2019, citing an erroneous AoA reading activating MCAS and adding to an already high workload environment in the cockpit. Muilenburg stated Boeing is working to add training and additional educational resources to pilots, as well as a software update to MCAS (Boeing, 2019).

2.2 Safety System Analysis

To understand why the Lion Air and Ethiopian Airlines aircraft crashed, it is important to understand the relationship between MCAS, the AoA sensors present on the aircraft, and the pilots. Figure 3 is a Fault Tree Diagram that shows what must occur for an erroneous MCAS activation to lead to a crash. In both crashes, the erroneous sensor activation of MCAS was not the only cause of the fatal crashes. It was this coupled with the pilot's inability to correct the nose down pitching moment. It is important to understand that in the case of both accidents, if the pilots had disabled the electric trim system quickly after MCAS activated, then it is likely that they would have recovered control of the aircraft using the manual trim system and prevented the crashes.

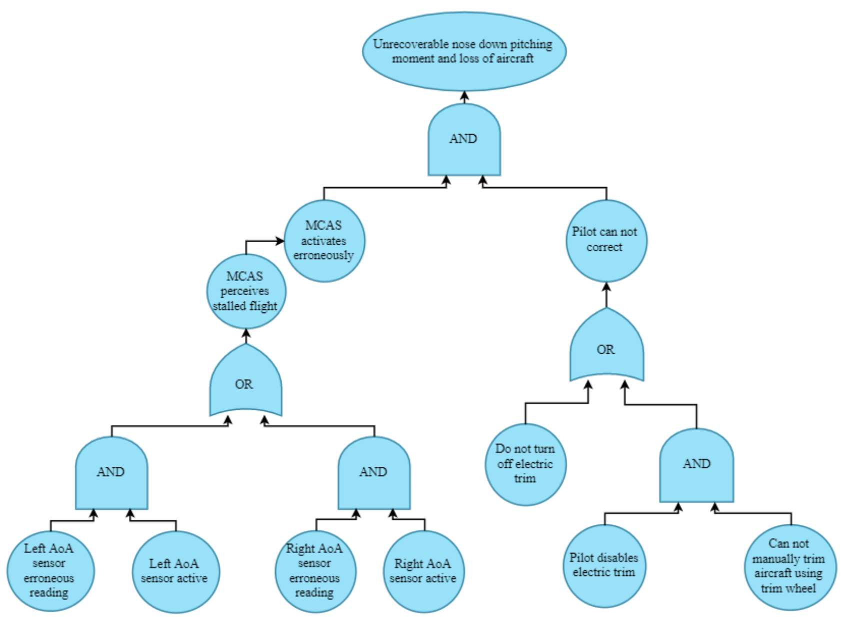

Figure 3. Fault Tree Diagram of Erroneous Sensor Readings

All of this encourages further questions: why was MCAS programmed such that it could only be activated be a single erroneous sensor? Why were the pilots unfamiliar with the steps necessary to regain control? These topics are explored in the next section.

3. Framing the "Bigger Picture"

In order to better understand the "whole picture" of the 737 MAX 8 it is important to understand how it came to be. The Boeing 737 MAX 8 was Boeing's response to the more fuel efficient A320neo that its competitor, Airbus, announced in December of 2010. Before this announcement, Boeing had been working on developing a completely new aircraft to fill the fuel efficient, single-aisle passenger aircraft market. However, following the interest from many large airliners for Airbus's new aircraft, Boeing abandoned their aspirations of a new aircraft and instead announced their new 737 MAX aircraft with three variants: the 737 MAX 7, 8, and 9

To compete with the A320neo, Boeing equipped the new 737 MAX 8 with larger, more fuel-efficient engines. These new engines were placed slightly forward and higher up on the body of the aircraft. This new placement was designed to accommodate the landing gear of the aircraft. However, one aerodynamic effect of these new engines was to encourage a pitch up moment. To prevent stalls introduced by this pitch up moment, Boeing equipped the 737 MAX with MCAS. MCAS was not present on the previous versions of the 737. Instead, it was added to make the 737 MAX "feel" like the previous versions of the 737 and to make the changes in the new model transparent to the pilots. There are at least two impacts of these design decisions. First, by making the 737 MAX fly like previous 737 models, 737 pilots would notionally not need to undergo costly training to fly the new model. Second, by limiting the substantive changes between the 737 MAX and previous models, the FAA certification process would be simplified.

Because the 737 MAX 8 was an update to a previously certified aircraft, Boeing did not have to seek a completely new certification from the Federal Aviation Administration (FAA). Instead, they only needed an amended type certification for the 737 NG. The FAA may amend a type certificate when the holder of the type certificate receives FAA approval to modify an aircraft design from its original design. An amended type certificate approves not only the modification, but also how that modification affects the original design. (FAA 2011). One of these modifications was the implementation of MCAS. Although MCAS was a major amendment to the original design of the 737, Boeing chose not to place it in the operations manual of the 737 MAX 8, citing that it operates in the background of the aircraft's software (Slotnick, 2019). As a result, 737 MAX 8 pilots were not trained on nor even told about MCAS. The 737 MAX 8 received its amended type certificate on March 9, 2017 (Boeing, 2017).

A crucial part of the certification process is the formulation of the *certification plan*. This is a document that manufactures provide to the FAA regarding the airframe they are seeking certification for. One of the required sections in this document is System Safety Assessment (AIA et al., 2017). In this section, an initial Functional Hazard Analysis (FHA) must be completed and summarized. FHA requires that the criticality of the systems should be identified, the classification of the failure condition(s) should be stated, and the methods to be used to show compliance with the airworthiness requirements defined (AIA et al., 2017). The FAA uses ARP 4761, Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment, to conduct hazard classification on aircraft systems. System safety analysis Table 1 shows the hazard levels, their definitions, and associated failure rate that must be met in order to be considered a specific hazard level.

MCAS was classified as a "hazardous" system (Gates, 2019). This means that the number of system failures per flight hour, known as the failure rate, cannot exceed one in a ten million. The failure rate is found during simulation and flight testing. Throughout the flight-testing phase of the Boeing 737 MAX 8, reports stated that many of the lead engineers on the 737 MAX team raised concerns regarding the functionality of MCAS. Boeing's lead test pilot on the project stated "MCAS was difficult to control" (Josephs et al, 2019). Additionally, the chief technical pilot stated that "the system was running rampant in the simulation" (Josephs et al., 2019). The comments were never acted upon by higher project management, and therefore MCAS was left in the aircraft as is (Josephs et al., 2019). These instances of the system acting in a way it should not, constitute system failures. The causes of the system failure in the simulation has not been released.

The classification of MCAS as hazardous in compliance with the definition in Table 1, suggests that pilots cannot be relied upon to perform the required tasks to recognize and disable MCAS accurately or completely. In the case of MCAS, the actions necessary to correct for its activation are to quickly recognize and override MCAS by turning off the automatic horizontal stabilizer and controlling it manually. As seen in both crashes, the pilots could not and did not quickly recognize and override the system. As stated in Section 2.2, the pilots in Lion Air Flight 610 never deactivated the electric trim tab stabilizer, while the Ethiopian Airlines Flight 302 pilots were able to recognize the need to disable the system, but not in time, the aircraft had gained too much speed. Both instances reinforce the notion that the pilots could not be relied upon to overcome issues raised by MCAS. This brings into question why MCAS was not included in the aircraft's Flight Operations Manual as well as not training the pilots on the system and how to override it. Boeing may have assumed that the pilots had the knowledge to quickly recognize and react to an erroneous MCAS activation.

Table 1. ARP 4761 Hazard Classification

Severity	Definition	Failure Rate (per flight hour)
Catastrophic	Results in multiple fatalities and/or loss of the system	10^{-9}
Hazardous	Reduces the capability of the system or the operator ability to cope with adverse conditions to the extent that there would be: large reduction in safety margin or functional capability, crew physical distress/excessive workload such that operators cannot be relied upon to perform required tasks accurately or completely, serious or fatal injury to small number of occupants of aircraft (except operators), fatal injury to ground personnel and/or general public	10^{-7}
Major	Reduces the capability of the system or the operator ability to cope with adverse conditions to the extent that there would be: significant reduction in safety margin or functional capability, significant increase in operator workload, conditions impairing operator efficiency or creating significant discomfort, physical distress to occupants of aircraft (except operator) including injuries, major occupational illness and/or major environmental damage, and/or major property damage	10^{-5}
Minor	Does not significantly reduce system safety. Actions required by operators are well within their capabilities. Include: slight reduction in safety margin or functional capabilities, slight increase in workload such as routine flight plan changes, some physical discomfort to occupants or aircraft (except operators), minor occupational illness and/or minor environmental damage, and/or minor property damage	10^{-3}
No Safety Effect	Has no effect on safety	

4. Not a Single Point of Failure

Most system accidents, especially aviation accidents, do not occur in a vacuum, but are instead are a chain of events that eventually lead to the accident. However, as Professor Leveson stated, there is a need to break away from looking at traditional event-chain models to attempt to describe an accident. The entire socio-technical system must be analyzed to adequately describe an accident (Leveson, 2011, p.31). Systems thinking is a way to do this. When analyzing the Boeing 737 MAX 8 accidents, it is clear that the technical failures of the AoA sensors were not the sole reason the aircraft crashed. Instead it was a whole host of events that led to the unnecessary loss of life. These events include pressures from the market to produce a new, fuel efficient aircraft, the adaptation of the aircraft's schematics due to new engines, the design and implementation of MCAS, the hazard classification of MCAS, the awarding of the FAA amended certification, and the decision to leave MCAS out of the Boeing 737 MAX 8 Operations Manual. Notice that these are not all technical, engineering issues, but include issues form outside the technical realm of the aircraft design. Things that are social issues, certification issues, and management issues. This array of issues is why systems thinking must be implemented in the safety analysis of the Boeing 737 MAX 8 accidents. Some of the events and issues stated above will be discussed in detail in this section.

With regards to the technical failure of the AoA sensors, this is not the first time AoA sensors have caused issues in a passenger flight. There are at least 140 instances since the early 1990s of sensors on U.S. planes being damaged by jetways and other equipment on the ground, or striking birds in flight. In at least 25 cases in the U.S., Canada and Europe, the damage triggered cockpit alerts or emergencies (Beene, 2019). The high volume of instances of AoA sensor failures raises question as to why Boeing believed that MCAS could rely on one single AoA sensor. This speaks to the reliability of the AoA sensors. Reliability is defined as the "probability of a system or system element performing its intended function under stated conditions without failure for a given period of time" (ASQ, 2011). Neither Boeing nor UTC has released any reliability data regarding the specific model of sensor installed on the Boeing 737 MAX 8. If released, conducting reliability analysis on both MCAS and the AoA sensors may reveal the poor design of MCAS.

In the previous model of the 737 MAX 8, the 737 NG, there was a function of the AoA sensors, called the AoA Disagree function. The Primary Flight Display showed a message of "AoA DISAGREE" whenever the two AoA sensors, one on each side of the nose of the aircraft, were in disagreement of 10° for at least 10 seconds. This function was supposed to carry over to the 737 MAX 8. Following the Lion Air Flight 610 crash, Boeing released a statement stating that the design requirements for the 737 MAX line included the AoA Disagree alert as a standard, standalone feature, as it was in the 737 NG.

However, in 2017 Boeing stated the software linked the AoA Disagreement function to the AoA position indicator, not the sensor itself. Boeing then determined that the absence of the AoA Disagree alert did not adversely impact airplane safety or operation. Although this was Boeing's determination, the AoA Disagree alert is still an important piece to the systems thinking analysis of the 737 MAX 8. The AoA Disagree alert was present on the predecessor of the MAX 8, and because Boeing stated that the MAX 8 flew like the 737 NG, the pilots were accustomed to receiving an alert if the AoA sensors disagreed. If the aircraft had been equipped with the AoA Disagreement function, there is a chance that the pilots may have been more aware of the issues that they were experiencing in the cockpit. Additionally, the existence of this function, which by design is connected to both AoA sensors, makes it all the more surprising that MCAS was not designed to interface with both sensors.

Additionally, it is important to note that there is no scheduled maintenance for angle of attack sensors. Any maintenance that occurs is due to an annunciated fault or observed malfunction. The AoA sensor is the sole sensor MCAS is reliant on to be activated. This is an issue of functional allocation within MCAS. Functional allocation refers to allocating system functions to lower level elements (Lightsey, 2001). In this case, the functions of detecting stalled flight and activating MCAS were allocated to a single AoA sensor. Given the unreliable nature of these sensors, it is surprising that MCAS relied on a single AoA sensor when redundancy was available with the use of the second AoA sensor which every Boeing 737 MAX 8 is equipped with. Redundancy refers to the "process of adding extra instances of critical components to a system so that one can take over for another if something breaks" (McVagh, 2017). If MCAS had been designed using both AoA sensors with the functions stated above, MCAS may not have activated in Lion Air Flight 610, as the two AoA sensors were in such large disagreement with each other. Having a system as influential on flight as MCAS dependent on a single senor is surprising, especially due to the high volume of instances where the AoA sensor has caused issues in flight.

The development and testing phases also introduce issues with regards to MCAS implementation and absences in the Operations Manual. Boeing wanted to make the 737 MAX fly like its predecessor. In order to do this, they had to add a new system, MCAS, to the aircraft. Boeing believed that because of MCAS' background role, pilots did not need to be trained on the system. Boeing also assumed that the pilots could easily recognize the issue of the nose down pitching motion and could quickly resolve the issue. However, in both crashes, this was not the case. If Boeing had initially included MCAS in the operations manual and mandated that pilots be trained on the new system, these crashes could have been avoided. However, some pilots, namely ex-pilot and current New York Times columnist William Langewiesche, believe that pilots today generally overrely on the automation of the cockpit to fly. In turn, they have less experience and knowledge of flying without the aid and dependence on the automated cockpit (Langewiesche, 2019). Langewiesche believes that today's pilots lack airmanship. He believes airmanship includes "visceral sense of navigation, an operational understanding of weather and weather information, the ability to form mental maps of traffic flows, fluency in the nuance of radio communications and, especially, a deep appreciation for the interplay between energy, inertia and wings" (Langewiesche, 2019). Langewiesche believes that Lion Air is an aggressive airline who attempts to dominate the rapidly growing Indonesian low-cost airline market. Because of this, they are known for hiring pilots early in their career who, for the most part, are recent graduates of its own flight academy. Even though Langewiesche argues that they pilots should have been able to reconcile the MCAS activation in the cockpit, if Boeing had included MCAS in the Operations Manual forcing pilots to be trained on the system, it only would have helped the Lion Air and Ethiopian Airlines pilots in their cockpits.

However, Boeing did not want to force airlines to train their pilots on a new aircraft model. Instead, Boeing wanted to offer an aircraft that would ultimately save airlines training cost and times to ensure they could challenge Airbus in the new fuel efficient, single-aisle passenger aircraft market created by the A320neo. Ultimately, like most companies, Boeing was motivated by profit, and consequences of their design decisions can be seen throughout the development, testing, and implementation, and ultimately the crashes of the Boeing 737 MAX 8.

The Boeing 737 MAX 8 remains grounded today as the FAA, Boeing, the NTSB, and many other organizations conduct investigations and publish findings. It is important to view all reports released through a systems thinking lens. The more information that is released, the more connections can be made, and hopefully more lessons will be learned to prevent a tragic accident from occurring again.

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