The Boeing 737 MAX Debacle | DMA Current Affairs Discussion Paper

Synopsis

Boeing designed and developed an updated version of its popular 737 single-aisle aircraft, called the 737 MAX, and very successfully marketed the plane to many of its airline customers. Within two years of the plane's entry into service, two of them, flown by different foreign airlines, crashed shortly after take-off under very similar circumstances, resulting in the deaths of all onboard. The crashes were only five months apart. After the second crash, US and foreign aviation regulators grounded all 737 MAX planes. The following narrative briefly summarizes the salient points although the detailed story of what happened and why is highly complex.

Certification and Entry into Service. The 737 MAX is the 12th iteration of the 737 aircraft type, which was first certified by the FAA in 1967. According to our DMA colleague, Charles Salmans, the original version of the 737 was very low to the ground. When it was first designed, the idea was that it would serve small airports and luggage could be loaded into the hold without a conveyor belt. The diameter of the engines was constricted because they were close to the ground. Since its original design, the 737 has grown in size and its role in commercial aviation has expanded dramatically. As embodied in the MAX, the 737 is 61% heavier, 24% longer and 40% wider, and its engines are twice as powerful as those on the original. This is a very different airplane. The 737 MAX received FAA certification in March 2017 and the plane first entered revenue passenger service in May 2017.

The Two MAX Crashes. In late October 2018, Indonesian carrier Lion Air flight 610 crashed into the Java Sea 13 minutes after takeoff, killing all 189 passengers and crew. Less than five months later, in March 2019, in strikingly similar circumstances, Ethiopian Airlines flight 302 crashes 6 minutes after takeoff, killing all 157 passengers and crew. In each case, the pilots had difficulties controlling the plane shortly after liftoff in part because of the activation by a single faulty angle of attack sensor of a new software system that Boeing had developed to enhance the aircraft's aerodynamic stability. That system is known as the Maneuvering Characteristics Augmentation System (or MCAS). Upon activation, the MCAS repeatedly, and without pilot awareness or input, changed the position of the horizontal stabilizer trim in the tail section, thereby aggressively causing the nose of the aircraft to turn down. The pilots had precious little time to react and, faced with multiple and confusing signals and warnings in the cockpit, became unable to maintain altitude and the planes descended and crashed.

Distinct Aerodynamics of the 737 MAX. Airplanes fly because their wings greet the oncoming air at a positive angle, known as an angle of attack. The faster an airplane flies, the lower the angle of attack needs to be to generate the necessary lift. Conversely, the slower an airplane flies, the greater the angle of attack needs to be. But at some point, the angle of attack becomes too great for the oncoming air to negotiate smoothly. As the airplane approaches that critical angle, typically cockpit warnings direct the pilots to take the necessary actions to lower the

nose. If the pilot does not respond, the airflow starts to boil across the top of the wings, sometimes causing "buffets" that shake the airplane, before separating from the wings conclusively at the moment of the stall. At that point, the wings' effectiveness is hugely degraded, roll control becomes difficult and the nose drops unavoidably. The nose drop can be drastic. Fully stalled, the airplane enters into a precipitous descent that, if left unattended, will lead to a catastrophic impact with the ground. The event does not take long.

During stall testing, Boeing engineers determined that the Max, with its larger engines attached in a more forward position on the wings, had a higher tendency than earlier generation 737s to pitch up when the airplane is flown at certain high angles of attack. While pitching up into a stall is a characteristic of all jets with underslung engines, the tendency in the Max was stronger than in previous 737s. In addition, a new characteristic raised concern. Within the buffet zone as the airplane approached the stall, the flight behavior of the aircraft exhibited other erratic behavioral quirks.

The Fix: Development of the MCAS. Some at Boeing argued for an aerodynamic solution, but the modifications would have been slow and expensive, and Boeing was in a big hurry, given its intense competition with Airbus who had entered the market months earlier with a new more fuel-efficient single aisle plane known as the A320Neo. Boeing's decision was to create synthetic control forces by way of the MCAS, which was designed automatically to adjust the nose-down stabilizer trim at just the right moment, calculated largely by the angle of attack, so that the pilot will not inadvertently pull the airplane up too steeply causing a stall. The MCAS, when triggered, pushes the nose down without pilot input. The intent of the system was to enable the overall flight behavior of the MAX to mimic that of its immediate predecessor, the 737 NG. While the MCAS software was originally based on a prior version developed for Boeing's KC-46 fuel tanker, the MAX was much more aggressive in adjusting the horizontal stabilizer trim and, unlike the controls on the fuel tanker, MAX pilots could not override operation of the system by simply pulling back on the control column.

No Back-up System. Another major problem that became critical is that the MCAS was designed to be activated by only one angle of attack sensor, making this critical safety system vulnerable to a single point of failure (i.e., there was no back-up system). Boeing's 737 aircraft actually have two angle of attack sensors, one located on each side of the aircraft, but only one of the sensors was connected to the MCAS and, in most MAX aircraft, an angle of attack disagree alert, that might have warned pilots that one of the two sensors was faulty, was not operational.

In both the Lion Air and the Ethiopian Air accidents, it is clear from the flight data that the MCAS was triggered by falsely high angle of attack inputs from the faulty sensor that the aircraft had pitched up excessively. In both flights, the MCAS repeatedly activated the horizontal stabilizer trim motor to push the nose down so that the pilots struggled to gain altitude.

Mischaracterization. During the regulatory process leading up to the FAA's certification of the MAX, Boeing did not fully explain the operation of the MCAS, characterizing the system as a simple add-on to the plane's existing stability functions. In addition, in order to mitigate the

chances of enhanced regulatory scrutiny (and avoid delay), Boeing decided not to describe the MCAS in flight manuals or other training materials, based on the fundamental design philosophy of commonality with the 737 NG. Minimizing functional differences between the MAX and the NG would allow both variants to share the same regulatory rating – affording airline customers the opportunity to save money by employment of one pool of pilots to fly both interchangeably and eliminating the need for expensive additional flight simulation training.

Boeing had tremendous financial incentive to ensure that no regulatory determination required pilot simulator training for the MAX. This incentive included a Boeing contract with Southwest Airlines, its US launch customer, that would have cost Boeing more than $1 million per aircraft delivered to Southwest if pilot simulator training were required for pilots transitioning to the 737 MAX from the 737 NG. At the time of the Lion Air crash, Southwest had ordered or pre-ordered 280 MAX aircraft from Boeing.

The FAA Certification Process and the Important Role of Authorized Representatives. Boeing urged the FAA and its own engineering employees to move forward as quickly as possible to certify the MAX and used its clout to pressure FAA officials, company engineers and other employees to ignore potential safety issues. In this context, the company failed to identify the MCAS as a "safety critical system" which would likely have triggered a more thorough regulatory assessment.

Under a system known as the Organization Designation Authorization, the FAA delegated many important functional evaluations to Boeing, essentially allowing the company's employees who were designated "Authorized Representatives" to review its own product. Some have asserted that this delegation of authority, which presents a clear conflict of interest, extended beyond proper bounds, especially because Authorized Representatives attended to important safety-related issues, particularly the iterative changes to the MCAS that caused the system to operate more aggressively and under a broader range of circumstances than previously contemplated and disclosed to agency officials.

Even after the first crash, Boeing and the FAA failed fully to alert the airlines, pilots and the flying public about the unique characteristics of, and the significant risks posed by, the MCAS. In the immediate aftermath of the crash, the FAA conducted a separate risk assessment which calculated that, without a fix to the MCAS, during the lifetime of the MAX fleet there would be an estimated 15 additional fatal catastrophic accidents. However, the FAA permitted the MAX to continue flying anyway while Boeing and the FAA dithered on designing and validating a fix to the MAX software. That judgment proved to be tragically wrong, as the Ethiopian Airlines crash occurred less than five months after the Lion Air Crash.

Questionable Pilot Assumptions. In its safety analysis of the MCAS, Boeing included assumptions that pilots would be able to react satisfactorily ***within 4 seconds*** to circumstances where the MCAS was erroneously tripped, notwithstanding the likelihood of contradictory warnings and confusion in the cockpit at the very busy time immediately following takeoff. Moreover, up to the time of the initial crash, most pilots were not even aware of the system's existence, making it much more challenging for them to mitigate any malfunction.

One author, who extensively researched the circumstances of the MAX crashes, drew the following conclusions with reference to the airlines involved and their pilots. He asserted that Lion Air and Ethiopian Airlines were corrupt and poorly managed organizations, that their planes were not being properly serviced and that their aviation records were in many cases inaccurate or deliberately falsified. He also visited their flight schools and observed that, in his opinion, their pilots were trained to fly largely by way of rote checklists, were rigid in terms of their responses to the crisis after takeoff, and had little experience in terms of true airmanship. The circumstances in the cockpit (including confusing warnings that occurred upon activation of the MCAS) overwhelmed the pilots to such a degree that they could not, given their limited training and experience and the little time available, take actions that an experienced airman might have taken to save the aircraft from destruction.

The Grounding, Reassessment of the Airworthiness of the 737 MAX, and the Struggle for Return to Service. Within a few days of the second crash, the FAA and most foreign aviation agencies ordered the grounding of the 737 MAX, with the FAA being among the last to act. This affected all 387 MAX aircraft in service with 59 airlines. In addition, another 400 newly-manufactured aircraft await delivery to airlines pending the aircraft's return to service. And Boeing has now temporarily shut down further production of the MAX aircraft (with serious consequences for many companies, including GE, in the supply chain).

The certification process required to allow the airplane to fly again has been complicated by many factors, including the need for agreement on and testing of the updated MCAS software, resolution of other issues that have surfaced, including coordination of computers aboard the aircraft, concern over the close positioning of separate wiring bundles that could affect the stabilizers, and issues regarding lightning protection for other parts of the plane.

In addition, the return to service process has become attenuated as the FAA has clearly signaled that it won't be pressured into allowing the plane to fly again by any particular deadline, and major international aviation agencies, including those in Europe, Canada and India, have dropped their historical deference to the FAA and are now asserting their authority independently to review and assess the safety of the MAX. Finally, Boeing has now reversed its long-held position on the need for pilots to have simulator training on the MAX MCAS and have now agreed that all airline pilots expected to fly the MAX should have this training.

Beyond all the legal and regulatory issues, Boeing and the FAA will need to convince the airlines, pilots, flight attendants and the flying public that the plane is now safe to fly. This issue goes well beyond the types of concerns that arose with the lithium ion batteries housed in the 787 Dreamliner aircraft as it involves fundamental concerns about the airworthiness characteristics associated with the aerodynamics of the aircraft as well as the efficacy of its critical updated software in maintaining and controlling stable flight operations.

An Uncertain Future. Boeing right now is a wounded organization. It had the long-earned reputation of being a financially strong, high quality engineering organization that produced world-class aircraft. The two 737 MAX crashes, occurring within a period of five months, and Boeing's conduct, revealed through various investigations, disclosures of troubling internal employee communications, begrudging admissions regarding its lack of candor, and its

defensive and opaque responses to inquiries about the accidents, have changed all that. Many are now questioning the company's commitments to quality workmanship, professional engineering and the safety of the flight crews and the flying public. The company's senior executive at the time of the crash, Dennis Muilenburg, lost credibility and has left the company, another board member recently resigned, and further changes in the company's management and board membership may well ensue.

With the 737 MAX grounding and the halt in the production and deliveries of the 737 MAX, Boeing is bleeding cash. The grounding has reduced the company's revenues, operating margins and cash flows and will continue to do so until production and deliveries resume and production rates return to pre-grounding levels.

Over the last few months, Boeing has arranged for billions of dollars in new credit lines to enhance its cash position and is seeking massive financial assistance from the US government, in conjunction with the coronavirus crisis, not only for itself but also to provide financial lift for companies in its critical supply chain. Boeing has already recorded significant liabilities associated with the crashes and the financial penalties to be paid to MAX buyers on account of the delivery delays. Some financial analysts have projected the overall costs to the company could exceed $25 billion. The company is also cooperating with a number of US investigations related to the accidents and the 737 MAX, including those by the US Department of Justice and the Securities and Exchange Commission.

Moreover, the regulatory landscape is likely to change, with Congressional committees asserting serious flaws in the FAA's oversight of the certification process for the 737 MAX. Legislators may argue for changes in law and regulations that would strengthen the hand of the FAA in its oversight role for aircraft design and development and eliminate or modify the agency's historical delegation of authority to manufacturers in order to eliminate conflicts of interest and the potential for manufacturers to exert undue influence over critical decisions affecting airline safety.

Foreign aviation regulatory bodies, including Europe's EASA, Transport Canada, India's regulator and Australia's Civil Aviation Safety Authority have each expressed varying levels of regulatory independence from the FAA, including their intention to conduct their own flight tests in assessing whether to allow the 737 MAX to fly in their countries' airspace.

Finally, many have observed that it's time to rethink the basic assumptions regarding pilot capabilities and training that are embedded in today's aircraft design. Boeing, for much of its history, manufactured airplanes premised upon the ability of capable trained pilots to manage unanticipated flight challenges based on well-honed capabilities of airmanship. In response to repeated public criticisms that there was no safety back-up system in the event that a single faulty angle of attack sensor triggered a MACS crisis, one Boeing official retorted that the pilot was the safety back-up.

A reassessment of assumptions regarding ordinary pilot capabilities prevailing around the globe may be in order and could require plane manufacturers to modify cockpit design and functionality in order more fully to automate the entire flight process.

Postscript

Airmanship. "Airmanship" is an anachronistic word, but it is applied without prejudice to women as well as men. Its full meaning is difficult to convey. It includes a 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. Airplanes are living things. The best pilots do not sit in cockpits so much as strap them on. The United States Navy manages to instill a sense of this in its fledgling fighter pilots by ramming them through rigorous classroom instruction and then requiring them to fly at bank angles without limits, including upside down. The same cannot be expected of airline pilots who never fly solo and whose entire experience consists of catering to passengers who flinch in mild turbulence, refer to "air pockets" in cocktail conversation and think they are near death if bank angles exceed 30 degrees. The problem exists for many American and European pilots, too. Unless they make extraordinary efforts — for instance, going out to fly aerobatics, fly sailplanes or wander among the airstrips of backcountry Idaho — they may never develop true airmanship no matter the length of their careers. The worst of them are intimidated by their airplanes and remain so until they retire or die. It is unfortunate that those who die in cockpits tend to take their passengers with them.

William Langewiesche, 29 September 2019

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Selected Background Readings. The materials included in the URL links below and the attachments include the following:

1. Boeing's principles and vision, as articulated on its website
2. New York Times Magazine lengthy and provocative article entitled "What Really Caused the Deadly Crashes," by William Langewiesche
3. Detailed and well documented reports from Wikipedia covering (i) the 737 MAX groundings; (ii) the Lion Air crash; (iii) the Ethiopian Airlines crash; (iv) the design and purpose of the critical MCAS software and analysis of its flaws; and (v) the 737 MAX certification process
4. An article on the emerging friction between US and European aviation regulators
5. The recent preliminary report of the US House Committee on Transportation & Infrastructure
6. The preliminary accident investigation reports from the Indonesian NTSC and the Ethiopian ECAA on the two crashes
7. Boeing's recent Securities Exchange Act public filings covering (i) the company's major risk factors, (ii) Boeing's exposure to claims and customer payment demands and (iii) the company's liquidity challenges and new credit facilities

8. Sample articles in the financial press on the ultimate probable cost to Boeing and an assessment of whether the company has "lost its way"
9. Tom Igoe's correspondence with David Mace, a fellow DMA book group member, on the subject of causation, comparing the Chernobyl accident (as recounted in detail in the book, *Midnight in Chernobyl*) with the Boeing 737 crashes

Matters to be Discussed. At the Current Affairs Group meeting on April 16th, the following topics (among others) are expected to be vetted among the members of the group:

1. Has Boeing truly lost its way as a corporate and civil aviation engineering leader in the US, and will it be able to recover? If so, what does the company need to do to change?
2. Is there a global problem with pilot experience and training? Some people have suggested that the Indonesian and Ethiopian pilots involved in these crashes were part of organizations that were riven with systemic problems – inadequate pilot training and experience, poor aircraft maintenance and record keeping, and lax regulatory oversight
3. Boeing has long had a reputation for designing its commercial airplanes premised on the notion that they are to be "flown" by experienced pilots who possess "airmanship qualities" and have the ability to think and act independently in the moment like true aviators. Does Boeing need to rethink aircraft design to totally automate the flight process? Does Airbus maintain a different philosophy in its approach to aircraft design and software?
4. Does the current US system of aviation regulation make sense, or do we need to change the manner of regulation to eliminate conflicts and mitigate exposure to future regulatory lapses?
5. How do these crashes affect the standing of the US in the world of global commercial aviation and do we need to improve coordination and cooperation among foreign regulatory bodies on aircraft development, real time aviation and safety advisories, and analyses of the causes of crashes?

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Links to the Background Materials. Below are the URL links to relevant documents that will help to inform the discussions:

http://www.boeing.com/principles/vision.page

https://www.nytimes.com/2019/09/18/magazine/boeing-737-max-crashes.htmlhttps://en.wikipedia.org/wiki/Boeing_737_MAX_groundingshttps://en.wikipedia.org/wiki/Lion_Air_Flight_610

https://en.wikipedia.org/wiki/Ethiopian_Airlines_Flight_302

https://en.wikipedia.org/wiki/Maneuvering_Characteristics_Augmentation_System

https://en.wikipedia.org/wiki/Boeing_737_MAX_certification#Boeing_737_safety_analysis

https://www.wsj.com/articles/friction-between-u-s-european-regulators-could-delay-737-max-return-to-service-11570527001

https://transportation.house.gov/news/press-releases/nearly-one-year-after-launching-its-boeing-737-max-investigation-house-transportation-committee-issues-preliminary-investigative-findings-

https://transportation.house.gov/imo/media/doc/TI%20Preliminary%20Investigative%20Findings%20Boeing%20737%20MAX%20March%202020.pdf

http://knkt.dephub.go.id/knkt/ntsc_aviation/baru/pre/2018/2018%20-%20035%20-%20PK-LQP%20Preliminary%20Report.pdf

https://web.archive.org/web/20190404161640/http://www.ecaa.gov.et/documents/20435/0/Preliminary+Report+B737-800MAX+%2C%28ET-AVJ%29.pdf/4c65422d-5e4f-4689-9c58-d7af1ee17f3e

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Tom Igoe
9 April 2020