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Ethics, Competition, Regulation - The Case of the Boeing 737 Max Failures

by

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Course Objectives:

1. To give engineers an understanding of their responsibilities, across different codes of engineering ethics, in situations where the health, safety, and welfare of the public is affected by engineering decisions.

2. To give engineers an understanding of how recent code of ethics changes have made the engineers' responsibility for the health, safety, and welfare of the public more explicit.

Course Summary:

After Lion Air flight 610 crashed into the Java Sea thirteen minutes after takeoff from Jakarta, Indonesia, on October 29, 2018, Boeing cited pilot error as a likely cause of the tragedy that killed all one 189 people on board its 737 Max aircraft. Post-flight analysis, however, showed an unusual trajectory for the crash. Shortly after takeoff, a series of twenty nosedives started to drive the plane downward, with the pilots recovering each time only to experience another rapid dive as the plane got lower and lower in the sky and crashed. On the recovered flight recorder, pilots could be heard furiously leafing through the technical manual of the airplane as it crashed into the sea. When another 737 Max, Ethiopia Airlines flight 302, crashed with a similar trajectory after taking off from Addis Ababa on March 10, 2018, killing all 149 people on board, the search for a cause beyond pilot error began in earnest. In both cases, an automatic system operating unbeknownst to the flight crews that they had no way of interacting with or turning off had taken control of the airplanes and driven them down, despite pilots' efforts to save the planes and, indeed, even determine what was happening. How could an autonomous system that pilots could not interact with during flight, nor turn off, come to be installed in widely used aircraft unbeknownst to pilots flying those aircraft—and why did that system fail? What roles did engineers play in the design and certification process? What consequences did engineers, and Boeing as a company, face after the crashes? What do different codes of ethics say about engineering decisions that affect the health, safety, and welfare of the public in such circumstances? Did the engineers involved act appropriately according to the different ethical codes?

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The first fundamental canon of engineering ethics from the National Society of Professional Engineers (NSPE) directs engineers to "hold paramount the health, safety, and welfare of the public." In engineering, keeping people safe from harm means doing sound engineering calculations and having a full understanding of the possible real-world scenarios that engineering designs will face. The third fundamental canon states that engineers shall "issue public statements only in an objective and truthful manner," while the fourth canon holds that the engineers shall "act for each employer or client as faithful agents or trustees." What happens when the charge to be a "faithful" employee comes into potential conflict with the first or third canons? The NSPE code does not give explicit guidance for such situations. Recent updates to the American Society for Civil Engineers (ASCE) code of ethics, however, give more guidance for the engineer in this regard and point to possible directions for other codes to follow. In the case of the Boeing 737 Max failures, questions can be asked of the engineers, managers, and regulators involved in the case. While both the Board of Aeronautical Engineers' (BAE) and the American Institute for Aeronautical and Aerospace Engineering's (AIAA) codes of ethics follow the NSPE code in refraining from offering explicit guidance regarding conflicts between different parts of the code, what kinds of expectations regarding the actions of those involved arise if guidance from the newly revised ASCE code is considered?

Mysterious Crashes

After Lion Air flight 610, a Boeing 737 Max aircraft, crashed into the Java Sea thirteen minutes after takeoff from Jakarta, Indonesia, on October 29, 2018, Boeing cited pilot error as a likely cause of the tragedy. Post-flight analysis, however, showed that shortly after takeoff, a series of twenty nosedives started to drive the plane downward, with the pilots recovering each time only to undergo another rapid dive as the plane was driven lower and lower in the sky. The twenty-first dive was not countered and the plane crashed into the water at a speed of 450 mph. When another 737 Max, Ethiopia Airlines flight 302, crashed in a similar manner after taking off from Addis Ababa on March 10, 2018, pilot error became harder to point to as a cause. Why would two different crews mistakenly perform the same series of nosedives and recoveries before finally crashing to the water or ground at high speed? It looked like a pattern with an underlying cause—and, indeed, it was. In both cases, an automatic system that was operating unbeknownst to the flight crews had taken over control of their airplanes and driven them down. In the case of the Lion Air crash, sounds from the black box recovered afterward gave indications that the flight crew was pouring through the technical manual of the plane to try to figure out what was happening during the crash. The manual could not help them, however, because it contained no information regarding the system that had asserted control of the airplane. The flight crew had even determined that there was an airplane engineer on board and had summoned them to the cockpit to help, but to no avail. Even if they had known about the system or somehow figured out that it was operating, there was no way for anyone on the plane to interact with the system and no way for them to turn it off. It operated fully autonomously, and its malfunction led to hundreds of deaths.

Why did the system fail, and how could an autonomous system that pilots could not interact with during flight, nor turn off, come to be installed in aircraft unbeknownst to pilots flying those aircraft without even be described in the technical manuals of the plane? The decisions that led to these circumstances, and these tragedies, began decades before in the design rooms and business meetings of Boeing.

A History of Dominance Challenged

From the 1960s through the 1980s, Boeing dominated the mid-size passenger jet market with its workhorse 737 model, the company's largest source of profits. By the mid-2000s, however, Boeing saw its market hold being challenged. Airbus had brought its alternative to the 737, the Airbus 320, into the market in 1987, and by 2002 it had surpassed the 737 in deliveries. The two planes had remained neck and neck in sales since that time, with the Airbus usually slightly ahead. A major selling point for the Airbus model was its fuel efficiency. It had a more "efficient burn" than the 737 by approximately 15%. By the mid-2010s, Boeing executives felt a sense of urgency to produce a new plane that could win back its lost market share. The company needed to offer a plane that was even more fuel efficient than the Airbus 320, and it needed to get it to market fast.

Due to the way that airline industry regulations are structured, it is a very different, and much longer, process to achieve certification of a newly designed aircraft than to gain regulatory approval for an upgrade to a design already in operation. Therefore, the clear path forward for Boeing was to alter the design of the already existing 737 to achieve its goal. Given that, in general, greater fuel efficiency in aviation is achieved through larger engines, the natural next step was to outfit larger engines onto the workhorse 737 that had been so successful for Boeing over the years. With this plan, however, there were engineering complications. It was Boeing's and the FAA's response to these complications that would lead to disaster.

For a plane to count as an upgrade to an existing aircraft, the basic dimensions of the aircraft must remain the same, including the height of the wings from the ground. A larger engine could be put on the 737 model, but it would have to be housed in a similar-sized space to that which currently held the smaller engine. The landing gear could be made a little longer, but only by so much. Thus, an important modification was needed that would affect the airflow over and under the wing when in flight. In the existing 737 configuration, the smaller engine hung down from the wing, held by a strut in such a way as to allow air to flow between the top of the engine and part of the bottom of the wing while in flight. To house a larger engine, this strut would have to be removed and the top of the engine would need to be secured flush against the underside of the wing. In this new configuration, air could not flow between the top of the engine and the bottom of the wing as that space was now blocked. The larger engine would also be cantilevered in front of the wing, rather than sitting directly beneath it. With this new, larger engine in this configuration, Boeing calculated that they could achieve a four percent more efficient burn than the Airbus 320, some fourteen percent better than the current Boeing 737.

Figure 1: The Boeing 737 wing and engine configuration (left) and the Boeing 737 Max engine and wing configuration (Right). The 737 Max engine is larger and is housed flush against the underside of the wing as well as being cantilevered forward.

Figure 2: The Boeing 737 Max engine and wing configuration showing the forward cantilevered engine design.

A Problem, an Autonomous Solution, and Another Problem

Since air could no longer pass above the engine but below the wing while in flight, the new planes, with the larger engines housed flush against the underside of the wing and cantilevered forward, would have more lift than the old 737 design. In fact, this added lift was significant enough that, according to Boeing engineers, the aircraft could possibly stall in high-speed conditions. This problem required a solution, and one was proposed that related to how the plane would be operated. An autonomous system to control flight trajectory, the Maneuvering Characteristics Augmentation System (MCAS), would be installed on the upgraded 737 Max planes. MCAS would continuously monitor the air speed and flight angle of the aircraft and automatically adjust the flaps of the wings to drive the nose of the plane down if the conditions for a stall were too closely approached. This solution, however, presented Boeing with another problem that could potentially undermine the whole project of regaining market share. When a new system is introduced into an airplane, even in an upgrade to an existing aircraft, pilots must be trained on that system before they can be certified to fly planes with that system installed on it. Pilot training takes time and money. A sales pitch that offered a four percent increase in fuel efficiency over a competitor, but would require retraining of an airline's flight crews, was not going to win back market share for Boeing.

In order to obviate any necessary pilot training on MCAS, Boeing's solution was to make the system fully autonomous, with no mechanism for interaction between the pilot and the system. If the pilots did not interact with the system in any way, then no training would be required. The logic of autonomy, when carried forward, led to important decisions that had direct bearing on the safety of the aircraft. For instance, if there is nothing a pilot could do with regard to MCAS, why would they even need to know about it at all? Thus, the decision to leave any mention of the new system out of the technical manual for the upgraded planes was made. In addition, common understandings of redundancy in engineering, long taught in engineering colleges and codified into law in many engineering fields as a prerequisite to safety, were inverted. In a human-controlled system, a strong case can generally be made that a redundant system is safer; in an autonomous system that long held principle of design becomes questionable. The input for the MCAS system was to be provided by sensors that would tell the system the air speed and flight angle of the plane. Would it be better for one sensor to provide each of those inputs or to have multiple sensors report to the system on each variable? At first glance, the usual redundancy would seem to make the system safer, except that the system would have to be able to handle the case where sensors disagree. If the system were to receive two different indications of the flight angle, for example, what would it do? In a non-autonomous configuration, a system with confusing inputs might "kick out" to human control in such a case. But with an autonomous system that was not an option. The system would never turn off, and pilots would have no interaction with it. Therefore, any choice by the system between conflicting inputs would be arbitrary, and possibly the wrong choice. Accordingly, the decision was made to use only one sensor each for the air speed and flight angle of the plane even though multiple sensors, whose use would conventionally be seen as redundant, were available on the aircraft.

Indeed, in both the Lion Air and Ethiopia Airlines crashes, a failed sensor made the system think that the planes were stalling when in fact they were not, and the actions of the system drove both planes down despite the pilots' efforts to keep the planes flying.

A Case of Self-Regulation?

Regulatory oversight is a common and common-sense aspect of many engineering projects. An engineering design that could endanger people should pass an independent review to check for aspects of the design that engineers might have missed. In the real, practical world, this idealized process faces many challenges. First is the matter of engineering expertise itself. After all, who can understand a complex engineering design better than the engineers who themselves produced the design and worked intimately with it? There are minimal incentives in the industry for an engineer to become a highly specialized expert, and then to work as a regulator in a reviewing capacity. Rather, most engineers work, at a higher salary, for the companies that produce the complex designs. In general, the companies designing and building projects that merit regulatory review are much better funded and staffed than the regulatory agencies tasked with overseeing their work. Given the discrepancy in resources and expertise between Boeing and the Federal Aviation Authority (FAA), it became a practical matter over the course of decades for the FAA to rely on the expertise Boeing engineers with regard to matters of safety and risk. In principle, such an arrangement could work effectively and the aviation industry, in general, has been very safe considering the very large numbers of air travelers and airplanes in service. With regard to the 737 Max, however, the arrangement broke down.

Prior to 2005, the FAA would choose which engineers from Boeing would participate in the regulatory process for particular projects. In 2005, however, in a regulatory change by the FAA, the privilege of choosing which engineers would participate in reviews was transferred from the FAA over to Boeing itself, although the FAA retained veto power over the choices. For each review, those selected engineers worked in a special section of the FAA whose name belied the central role that the company played in the aviation industry: The Boeing Aviation Safety Oversight Office. In 2013, the FAA had delegated twenty-eight of the ninety-one certification projects on the 737 upgrade to Boeing engineers. By 2015, that number was seventy-nine. And, by 2017, Boeing had delegated all of the certification projects to Boeing itself, of course subject to final FAA review.

As engineers, employed by Boeing but subject to FAA oversight, reviewed the system, an important consideration revolved around how aggressive, or not, the system would be. If the system were only capable of making very minor flight adjustments, then perhaps it could be seen as a "low level" stabilizing system that operates underneath the pilot control of the aircraft. But if the system could significantly alter the flight of the plane, then that might merit a different kind of regulatory consideration. In its post-crash analysis, the US Department of Justice (DOJ) focused on an important change that was made to the system in this regard, and how that change was not reported properly by Boeing to the FAA. At the start of the regulatory process, Boeing presented MCAS as a low-level system capable of only minor flight adjustments during high speeds, since that was the only time when stalling, it was thought, could occur. By 2016, however, Boeing engineers came to understand that stalling could actually occur at lower flight speeds also. This required a system could, and would, make significantly more aggressive interventions in order to account for low-speed stalls, rather than only countering stalls at high speed. With this new, more aggressive, capability, Boeing engineers determined that a pilot would need to respond to an incursion by the system within ten seconds or possibly lose control of the airplane. They thought that this would not be a problem, however, because they felt that pilots could readily respond in four seconds, leaving plenty of room to spare. FAA regulators who approved the 737 Max, including the approval for excluding mention of MCAS in technical manuals or training materials, stated to investigators afterward that they were not made aware of these significant changes to the MCAS system after 2016 and were not part of any assessments of expected pilot response time with respect to low-speed MCAS interventions.

Post-Crash Assessments and Determinations

As a result of an investigation by the DOJ, Boeing entered into a settlement whereby it paid out a total of $2.5 billion—a $243.6 million criminal monetary payment, $1.77 billion in compensation to 737 Max customers, and $500 million to compensate heirs, relatives and legal beneficiaries of the 346 crew members and passengers who perished. In touting the settlement, the DOJ noted that the agreement, "holds Boeing and its employees accountable for their lack of candor with the FAA regarding MCAS," and points out that, "the substantial penalties and compensation Boeing will pay demonstrate the consequences of failing to be fully transparent with government regulators. The public should be confident that government regulators are effectively doing their job, and those they regulate are being truthful and transparent." The DOJ report noted that during the investigation and lead up to the settlement, Boeing made several internal structural changes with regard to safety, including creating a committee of the Board of Directors to oversee Boeing's policies governing safety and the company's interactions with regulators, centralizing safety organizations within Boeing, requiring all Boeing engineers (as well as Boeing's Flight Technical Team) to report through Boeing's chief engineer rather than through the business units, and to increase the supervision and "professionalism" of Boeing's Flight Technical Pilots. These changes were likely taken into consideration by the DOJ as it, in the final analysis, did not see the need for an independent compliance monitor for Boeing, stating that, according to them, the misconduct at Boeing was "neither pervasive across the organization, nor undertaken by a large number of employees, nor facilitated by senior management." A survey, not associated with the 737 Max investigation, conducted by the DOJ itself in 2015 that reported that many Boeing engineers who were tapped by the company to work in the Boeing Aviation Oversight Safety Office of the FAA felt "undue pressure" from the corporation to certify Boeing projects could, however, could be seen as in conflict with this assessment.

Rather than general corporate pressure or culture, the DOJ focused on two particular Boeing employees who, in its view, shouldered the blame for the tragedies, asserting that:

"In and around November 2016, two of Boeing's 737 MAX Flight Technical Pilots, one whom was then the 737 MAX Chief Technical Pilot and another who would later become the 737 MAX Chief Technical Pilot, discovered information about an important change to MCAS. Rather than sharing information about this change with the FAA AEG, Boeing, through these two 737 MAX Flight Technical Pilots, concealed this information and deceived the FAA AEG about MCAS. Because of this deceit, the FAA AEG deleted all information about MCAS from the final version of the 737 MAX FSB Report published in July 2017. In turn, airplane manuals and pilot training materials for US based airlines lacked information about MCAS, and pilots flying the 737 MAX for Boeing's airline customers were not provided any information about MCAS in their manuals and training materials."

Criminal charges were brought against the Chief Technical Pilot, alleging that he knew about the changes to the MCAS that made the system more aggressive and capable of taking control of the aircraft at low-speed, but withheld this information from FAA regulators. While a Boeing manager, later promoted to Vice President, did testify at trial that he personally told the Chief Technical Pilot about the changes to the system, documents presented by the defense showed that the specifications provided to the Chief Technical Pilot by Boeing engineers did not describe any such changes. Facing charges that could have resulted in up to 20 years in prison, the Chief Technical Pilot was quickly acquitted. No other Boeing employees were criminally charged. Notably, the Inspector General of the DOJ conducted a separate survey in 2015, in the middle of the 737 Max certification process, where many Boeing engineers who worked on behalf of the FAA during certification processes in general reported that they felt "undue pressure" from Boeing managers during certifications.

Re-Certification of the MCAS System

From March 2019 to early 2021 the 737 Max was grounded worldwide. In order to achieve re-certification, Boeing made several changes to the MCAS system. The system now has a limit of one nose down maneuver during a single high angle event. A second angle of attack sensor is now used as input into the system. If the two angle of attack sensors disagree by more than 5.5 degrees, an alert appears on the pilot's controls, and pilots have the ability to override the system at any point in time. Finally, pilots will be extensively trained on the system before flying 737 Max planes. The grounding, redesign, and remanufacturing added approximately $4 Billion to production costs for the 737 Max (on top of the $2.5 Billion in fines and settlements). While many airlines cancelled orders during the grounding and investigation, orders picked up after re-certification and in 2022, 561 orders were placed (on par with Airbus 320 orders and approaching Boeing's high of 662 orders placed in 2018 before the crashes) at a price of around $120 Million per plane. The CEO of Boeing who presided over the development and subsequent crashes of the 737 Max did not outlast the scandal, however, and was fired in December 2019 just as the aircraft was about to be re-certified and after the internal changes regarding safety that had already been made at Boeing. After a career at Boeing where he started as an intern, he left the company with approximately $62 million in pension and stock benefits, with Boeing explicitly asserting that none of that compensation came from any kind of severance package or separation payment.

Ethics of the Engineer Reconsidered

In the 737 Max case, the breakdown of the regulatory process was pinned by the DOJ to two pilots who worked, through Boeing, with the FAA certification process. One pilot, the Chief Technical Officer of the MCAS, was brought to trial but acquitted of knowing about late, significant, changes to the MCAS system. No engineers were charged or held accountable by the FAA. According to the NSPE code of ethics, a fundamental responsibility of engineers is to the "health, safety, and welfare of the public." But the NSPE code also charges that engineers should be "faithful" employees and engineers are left to use their judgment as to how to manage such a conflict. This also holds true for the BAE and AIAA codes. This conflict of interest can be quite fraught given the serious consequences that can attend going against one's employer, be it a corporation or a regulatory agency, and it is understandable that engineers, while sanctioned by these codes to dissent as an engineer, would be served by more guidance in this regard. Recent changes to the ASCE code of ethics might serve as a template for such guidance. In the revised ASCE code, engineering decisions are seen to involve stakeholders, and the code provides a hierarchy of responsibility should an engineering decision result in a conflict between stakeholders. "Society" is identified as the primary stakeholder, followed by "the natural and built environment," the profession, the client and employer, and, finally, one's peers. Under "Society," the code further explains that engineers should "first and foremost protect the health, safety, and welfare of the public," "enhance the quality of life for humanity," and "express professional opinions truthfully and only when founded on adequate knowledge and honest conviction." This is in line with the NSEP, BAE, and AIAA codes, but the revised ASCE code also states explicitly that given any conflicts, protecting the health, safety, and welfare of the public "takes precedence over all other responsibilities." This is a stronger statement that engineers can refer to when facing the myriad of conflicts, large and small, that attend engineering practice and it gives a more foundational grounding for questioning whether and how engineers should have participated more vocally, perhaps dissenting from their employer, in the Boeing 737 Max case.

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