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AVIATION SAFETY AND THE FUTURE OF BOEING'S 737 MAX

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BEFORE THE

COMMITTEE ON COMMERCE,
SCIENCE, AND TRANSPORTATION
UNITED STATES SENATE

ONE HUNDRED SIXTEENTH CONGRESS

FIRST SESSION

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SENATE COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION

ONE HUNDRED SIXTEENTH CONGRESS

FIRST SESSION

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AVIATION SAFETY AND THE FUTURE OF BOEING'S 737 MAX

TUESDAY, OCTOBER 29, 2019

U.S. SENATE,
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION,
Washington, DC.

The Committee met, pursuant to notice, at 10:06 a.m., in room SH-216, Hart Senate Office Building, Hon. Roger Wicker, Chairman of the Committee, presiding.

Present: Senators Wicker [presiding], Thune, Blunt, Cruz, Fischer, Moran, Sullivan, Gardner, Blackburn, Capito, Johnson, Young, Scott, Cantwell, Klobuchar, Blumenthal, Markey, Udall, Peters, Baldwin, Duckworth, Tester, Sinema, and Rosen.

OPENING STATEMENT OF HON. ROGER WICKER, U.S. SENATOR FROM MISSISSIPPI

The CHAIRMAN. This hearing will come to order. Thank you all for being here today. One year ago, today, Lion Air Flight 610 crashed into the sea shortly after takeoff from Jakarta, Indonesia. All 189 people onboard perished. Five months later, Ethiopian Airlines Flight 302 departed Addis Ababa, Ethiopia. Just like Lion Air Flight 610, Ethiopian Airlines Flight 302 experienced problems shortly after takeoff and crashed. All 157 persons onboard died. Both of these accidents were entirely preventable.

We cannot fathom the pain experienced by the families of those 346 human beings who were lost. Many family members are here today, and we appreciate their attendance, and I appreciate many of them meeting with members of the Committee over time.

As Chairman of this Committee, I promise their loved ones that we are working to obtain a full answer as to how to prevent future tragedies. These families deserve answers, accountability, and action—and the public deserves to know this. The type of aircraft involved in both accidents is the 737 MAX 8 manufactured by Boeing. International aviation safety regulators began grounding the MAX the day after the Ethiopian crash.

On March 13, the Federal Aviation Administration formally grounded the aircraft in the United States. The MAX's return to service is contingent on Boeing's work with the FAA to test and certify fixes to the MCAS flight-control system, which activated during both crashes. In order for the MAX to return to service, international regulators also need to be satisfied that it is safe to fly. As the certification process continues, many questions remain about Boeing's actions and the FAA's actions during the design, de-

velopment, and certification processes, as well as the operation of the MAX.

Today's hearing is divided into two panels. Let me note for Senators that the Committee will follow regular order of recognition for both panels. The five-minute rule will be observed strictly because we have so many people who wish to participate. On the first panel, Dennis Muilenburg, President and CEO of Boeing, will testify on behalf of the aircraft manufacturer. He is accompanied by John Hamilton, Chief Engineer for Boeing Commercial Airplanes, who will provide technical expertise.

Our second panel will examine these issues from the Government's perspective. The witnesses today include National Transportation Safety Board Chairman Robert Sumwalt, and Chairman of the Joint Authorities Technical Review, or JATR, Chris Hart. Chairman Sumwalt oversees NTSB, which recently released a report and recommendations regarding the MAX certification. Chairman Hart led the JATR, an FAA-commissioned body that included the FAA, NASA, and nine foreign aviation safety authorities tasked with reviewing the MAX's flight control systems.

The JATR has submitted a broad range of recommendations to the FAA. Let me note that Chairman Hart has extensive past Government service in aviation safety, but he is a private citizen, today, who agreed to lead the JATR. We have many concerns that Boeing should address today. We need to know if Boeing and the FAA rushed to certify the MAX. In particular, critics have focused on the MCAS development and testing. The JATR criticized Boeing's communication with the FAA on MCAS's development, particularly after the system was modified to activate at lower airspeeds.

The JATR also criticized the FAA for relying on outdated regulations, guidance, and certification procedures, and failing to incorporate realistic human behavior factors into its assumptions. The NTSB also called into question Boeing and FAA's assumptions about pilot reaction during MCAS activation. These questions were especially important for stressful situations with multiple alerts going off in the cockpit.

Our witnesses should address the company and the safety regulators' actions regarding MAX certification in general and MCAS in particular. The process for certifying the MAX necessitated a close partnership between Boeing and the FAA. Under a decades-old system called Organization Designation Authorization, or ODA, the FAA has delegated certain certification activities to the ODA holder, in this case Boeing. While the ODA has been used to certify many aircraft over the years, some have criticized the system for permitting an inappropriately close relationship between companies and their safety regulator. Indeed, e-mail correspondence, dating from as early as 2015, between the MAX's former Chief Technical Pilot, Mark Forkner, and FAA personnel released on October 18 reflect a disturbing level of casualness and flippancy that seem to corroborate these criticisms.

I was disappointed to learn of a November 2016 instant messenger conversation between Mr. Forkner and a colleague, in which he acknowledged misinforming the FAA. Boeing should have notified the FAA about that conversation immediately upon its dis-

covery. Although the FAA is not testifying today, let me express my frustration with the agency's lack of responsiveness to my requests dating back to April of this year for documents relevant to the 737 MAX as part of the investigation that I opened, as Chairman, based on whistleblower disclosures.

The relationship between regulating agencies and organizations they regulate is important, but so are the internal reforms that Boeing is implementing. Witnesses should provide their views on the ODA system and whether or not reforms are needed. I invite Mr. Muilenburg to describe the steps Boeing is taking to improve aviation safety and to ensure that technical experts never experience undue pressure to put profits and relationships ahead of safety. The Committee's oversight is not limited to past actions. The reviews by both JATR and NTSB note that future aircraft systems are likely to be even more complex and interdependent than current models. Managing interfaces between humans and machines will become even more important as automation increases. At the same time, commercial aviation is set to continue expanding around the globe.

Many future pilots will fly in countries without the same training requirements and safety standards that we have in the United States. We welcome the witnesses' thoughts on how to improve design, development, and certification in the future to account for these major changes. This hearing will by no means be the end of our inquiry. Additional oversight hearings will be held. The Committee will carefully review the final Lion Air report, which was released on Friday, as well as the Ethiopian Airlines report, which is forthcoming.

The Committee also will consider the findings and recommendations from JATR, NTSB, and all other investigations and reviews. I now recognize the distinguished Ranking Member, Senator Cantwell, for her opening statement.

**STATEMENT OF HON. MARIA CANTWELL,
U.S. SENATOR FROM WASHINGTON**

Senator CANTWELL. Thank you, Mr. Chairman, and thank you for this important hearing. I too want to take a moment and recognize the families who have lost loved ones in both the Ethiopian Airlines and Lion Air tragedies, some of whom are here with us today. I cannot imagine the loss and the enduring pain that you must feel. I thank you for your vigilance on this issue, just as we have seen the families of the Colgan Air flight vigilance help us improve safety for the future.

Right now, Mr. Muilenburg, these families, millions of airline passengers, and over 150,000 aerospace workers want to know what we're doing to fix what went wrong and what did go wrong. To date, we have not gotten all those answers. Hopefully today's hearing will help provide some. But one thing is crystal clear, if you want to be the leader in aviation manufacturing, you have to be the leader in aviation safety. Aviation demand, especially for 737s and single-aisle planes is exploding to 101 percent growth over the next 10 years—something like 35,000 planes and \$3 trillion. I think that is actually 20 years. But we cannot have a race for commercial airplanes become a race to the bottom when it

comes to safety. The company, the Board, cannot prioritize profits over safety.

Safety always has to be job one. So, it is troubling to hear that Boeing may have skirted the FAA certification process over a desire by airlines to have more fuel-efficient planes but without pilot training. Now this issue of lowering standards is permeating through all of aviation. We are dealing with it here in the Committee. My Democratic colleagues have led the charge to try to stop companies coming here to say they do not want to have the same training for co-pilots on the regional jets because they do not have enough pilots. Or the issue my colleague has championed on rest requirements for cargo pilots having the same requirements for rest as passenger planes.

Thank God Captain Sullenberger, the hero of the Hudson, made it clear, when you are in an emergency, the pilot and co-pilot do not have time, a lot of time, to communicate. So that is why today we need answers to how the first 737 MAX certification process was done, and we especially need transparency on this process of review before the 737 MAX is put in the air again. The public needs to know and fully understand what testing, what review, what processes were conducted both by Boeing and the FAA before this plane is put back in the air.

We also want to know today about Boeing's safety culture, whether Boeing employees raised safety concerns that were not listened to, whether there was enough testing and complex system integration and information into a cockpit alert system that we now all know was flawed, and whether there was even enough data presented to the FAA. These are all questions that are important, including outsourcing of engineering and coding. There are many questions about software and cockpit automation and overload.

I guarantee you the FAA codes and laws are clear when it comes to the standards for certification. Yes, software and automation, flight training, better rest requirements for pilots have all led to 10 years between 2009 to 2018 as the safest 10 years in aviation history. But, more software and more automation without robust third-party testing and validation will lead us to where we are today. We should note that the last five aviation accidents have all involved this issue of automation and pilot response to automation. Whether it is Lion Air, Ethiopian, the Asiana, the French, or Qantas 330 accidents, they were all in response to an automation in a command and response from the pilot.

So that is why last week I introduced legislation with my colleagues Senator Duckworth and Senator Blumenthal to implement the recommendations of the NTSB safety board and the Inspector General report on better safety management systems, better cockpit prioritization, and a new FAA Center of Excellence on flight automation and human factors. The FAA needs the best engineers to understand the engineering challenges of the future and stay ahead on this human behavior response to new automation.

We are dealing—I see people here on the transportation, automobile side. It is the same issue in advanced vehicles, what automation exists and how do humans respond to it? So, I also look forward to hearing from Chairman Sumwalt and Chris Hart about their findings on improving the safety review process that we have

included in this legislation. I will just say again, our sorrows are nothing like the families who are with us today, but I do want to note that 737 MAX accidents have struck at the heart of everyone in the Northwest.

Soon after the Ethiopian crash, a Seattle firefighter approached me and asked if I thought he could get a job at Boeing. He said, I just want to go there and make sure we get the safety right. Everyone feels that way. Generations of workers in the Pacific Northwest have dedicated their lives to aviation excellence and safety, and that spirit lives on in Everett and Renton.

So, this is not a question about line workers, this is a question about the corporate view from Chicago, whether there is enough attention to manufacturing and certification. You should take, you know, offense to the fact that people say it is a great company not being run correctly.

So, for the 346 people who trusted Boeing without a second thought, we need to get this right. These families are counting on us. Thank you, Mr. Chairman.

The CHAIRMAN. Thank you, Senator Cantwell. Mr. Muilenburg, you have submitted an extensive written statement. It will be entered in full in the record at this point. You are now—and I understand Mr. Hamilton will not be making a formal statement. So, Mr. Muilenburg, you are recognized at this point to summarize your opening statement for five minutes. Thank you for being here.

**STATEMENT OF DENNIS MUILENBURG, PRESIDENT AND
CHIEF EXECUTIVE OFFICER, THE BOEING COMPANY;
ACCOMPANIED BY JOHN HAMILTON, VICE PRESIDENT AND
CHIEF ENGINEER, BOEING COMMERCIAL AIRPLANES**

Mr. MUILENBURG. Chairman Wicker, Ranking Member Cantwell, committee members, thank you for the opportunity to join you today and that we share your commitment to aviation safety. Before we start today, I would like to speak directly to the families of the victims that are here with us. On behalf of myself and the Boeing Company, we are sorry, deeply and truly sorry.

As a husband and father, myself, I am heartbroken by your losses. I think about you and your loved ones every day, and I know our entire Boeing team does as well. I know that probably does not offer much comfort and healing at this point, but I want you to know that we carry those memories with us every day, and every day that drives us to improve the safety of our airplanes and our industry and that will never stop.

I am grateful and humbled to be here today and to be able to say these words to the families directly, and I want to convey our absolute commitment to safety, our commitment to learning, our commitment to rebuilding the public's confidence in what we do, and to preventing accidents like this from ever ever happening again. We will never forget and that is our commitment going forward.

Mr. Chairman, I know this Committee has many questions about the MAX. We will do our best today to answer all of those questions. While one of the accidents is still under investigation, we know both accidents involve the repeated activation of a flight control system called MCAS, which responded to erroneous signals

from a sensor that measures the airplane's angle of attack. Based on that, we have enhanced MCAS in three ways. First, it will now compare information for both sensors instead of one before activating.

Second, MCAS will only activate a single time. And third, MCAS will never provide more input than a pilot can counteract using the control column alone. Pilots will also continue to have the ability to override MCAS at any time. We brought the best of Boeing to this effort. We spent over 100,000 engineering and test hours, we have flown more than 800 test flights, we conducted simulator sessions with 545 participants from 99 customers and 41 global regulators. I have flown on a couple of flights myself.

This has taken longer than expected but we are committed to getting it right. During this process, we worked closely with the FAA and other regulators, we provided them documentation, had them fly the simulators, answered their questions, and regulators around the world should rigorously scrutinize the MAX and only approve its return to flight when they are completely satisfied with its safety. The public deserves nothing less. Mr. Chairman, today and everyday over 5 million people will board a Boeing airplane and fly safely to their destination. Decades of cooperation and innovation by industry and regulators and the rigorous oversight of this Committee have reduced accidents by more than 95 percent over the last twenty years, but no number other than zero accidents is ever acceptable. We can and must do better.

We have been challenged and changed by these accidents. We have made mistakes and we got some things wrong. We are improving and we are learning, and we are continuing to learn. We established a permanent airspace safety committee of our Board. We stood up a new safety organization. We strengthened our engineering organization so that all engineers now report up through Boeing's Chief Engineer. We are also helping to rebuild the communities and families impacted by these accidents. We pledged \$100 million to this effort and have hired renowned experts in this area to ensure families can access these funds as quickly as possible. No amount of money can bring back what was lost but we can at least help the families meet their financial needs.

Mr. Chairman, I started at Boeing more than 30 years ago as a summer intern in Seattle. I was a junior at Iowa State University studying engineering having grown up on a family farm in Iowa. I was awestruck to work at the company that brought the jet age to the world and helped land a person on the moon. Today I am still inspired by what Boeing does and by the remarkable men and women who are committed to its outstanding legacy but these heartbreaking accidents and the memories of the 346 lives lost are now part of that legacy. It is our solemn duty to learn from them and we will.

Recently there has been much criticism of Boeing and our culture. We understand and deserve this scrutiny, but I know the people at Boeing. They are more than 150,000 of the most dedicated, honest, hard-working men and women in the world, and their commitment to safety, quality, and integrity is unparalleled and resolute.

We will stay true to those values because we know our work demands the utmost excellence. Mr. Chairman.
[The prepared statement of Mr. Muilenburg follows:]

PREPARED STATEMENT OF DENNIS MUILENBURG, PRESIDENT AND CHIEF EXECUTIVE OFFICER, THE BOEING COMPANY; ACCOMPANIED BY JOHN HAMILTON, VICE PRESIDENT AND CHIEF ENGINEER, BOEING COMMERCIAL AIRPLANES

Chairman Wicker, Ranking Member Cantwell, members of the Committee: good morning and thank you for inviting me to be here today.

I'd like to begin by expressing my deepest sympathies to the families and loved ones of those who were lost in the Lion Air Flight 610 and Ethiopian Airlines Flight 302 accidents, including those who are here in the room today. I wanted to let you know, on behalf of myself and all of the men and women of Boeing, how deeply sorry I am. As we observe today the solemn anniversary of the loss of Lion Air Flight 610, please know that we carry the memory of these accidents, and of your loved ones, with us every day. They will never be forgotten, and these tragedies will continue to drive us to do everything we can to make our airplanes and our industry safer.

Mr. Chairman, I know that you and your colleagues have many questions about the 737 MAX. My colleague John Hamilton, Chief Engineer for Boeing Commercial Airplanes, and I will do our best today to answer them. While the Ethiopian Airlines accident is still under investigation by authorities in Ethiopia, we know that both accidents involved the repeated activation of a flight control software function called MCAS, which responded to erroneous signals from a sensor that measures the airplane's angle of attack.

Based on that information, we have developed robust software improvements that will, among other things, ensure MCAS cannot be activated based on signals from a single sensor, and cannot be activated repeatedly. We are also making additional changes to the 737 MAX's flight control software to eliminate the possibility of even extremely unlikely risks that are unrelated to the accidents.

We have brought the very best of Boeing to this effort. We've dedicated all resources necessary to ensure that the improvements to the 737 MAX are comprehensive and thoroughly tested. That includes spending over 100,000 engineering and test hours on their development. We've also flown more than 814 test flights with the updated software and conducted numerous simulator sessions with 545 participants from 99 customers and 41 global regulators. This process has taken longer than we originally expected, but we're committed to getting it right, and return-to-service timing is completely dependent on answering each and every question from the FAA.

I have flown on two of the demonstration flights myself and seen first-hand the expertise and professionalism of our teams. Mr. Chairman, I could not be more confident in our solutions—and I could not be more grateful to the men and women who have worked so hard to develop and test these improvements always with safety at the forefront. When the 737 MAX returns to service, it will be one of the safest airplanes ever to fly.

During this process we have been working closely with the FAA and other regulators. We've provided documentation, had them fly the simulators, and helped them understand our logic and the design for the new software. All of their questions are being answered. Regulators around the world should approve the return of the MAX to the skies only after they have applied the most rigorous scrutiny, and are completely satisfied as to the plane's safety. The flying public deserves nothing less.

We know that it's not just regulators that need to be convinced. We know the grounding of the MAX is hurting our airline customers, their pilots and flight attendants, and most importantly, the people who fly on our airplanes. Our airline customers and their pilots have told us they don't believe we communicated enough about MCAS—and we've heard them. So we have partnered with customers and pilots from around the world as we've developed our solutions. We have welcomed and encouraged their questions and given them opportunities to test those solutions firsthand in simulators. And subject to regulatory approval, additional and enhanced training and educational materials will be available for pilots who fly the MAX.

We have learned and are still learning from these accidents, Mr. Chairman. We know we made mistakes and got some things wrong. We own that, and we are fixing them. We have developed improvements to the 737 MAX to ensure that accidents like these never happen again. We also are learning deeper lessons that will result in improvements in the design of future airplanes. As painful as it can be, the process of learning from failure, and even from tragedies like these, has been essential

to the advances in airplane safety since the industry began roughly a century ago. And it is one of the reasons that travel on a large commercial airplane is the safest form of transportation in human history.

Mr. Chairman, this is something we must not lose sight of. Today and every day, over 5 million people will board a Boeing airplane and fly safely to their destination. Whether it's their first flight or their millionth mile, we want it to be a great experience—and most importantly, a safe one. Decades of work and innovation throughout the industry, as well as the oversight of the FAA, this Committee, and regulators around the world have reduced the risks of air travel by more than 95 percent over the last twenty years. But no number, other than zero accidents, is ever acceptable.

For 103 years, Boeing has been dedicated to making the world a safer and better place. Our founder, Bill Boeing, established our first safety council in 1917, the first full year of the company's existence, beginning a commitment to safety that we have carried forward as a core value ever since. The engineers who design our airplanes, the machinists who work in our factories, and the many others who contribute to the extraordinarily complex work of building and maintaining commercial airplanes do so with pride and honor. Ensuring safe and reliable travel is core to who we are. Our customers and the traveling public, including our own families, friends, and loved ones, depend on us to keep them safe. That's our promise and our purpose.

But we also know we can and must do better. We have been challenged and changed by these accidents, and we are improving as a company because of them. We established a permanent aerospace safety committee of our Board of Directors; stood up a new Product and Services Safety organization that will review all aspects of product safety and provide streamlined reporting and elevation of safety concerns; and strengthened our Engineering organization by having all engineers in the company report up through Boeing's chief engineer. We also are investing in advanced research and development in new safety technologies and are exploring ways to strengthen not just the safety of our company but our industry as a whole. We have a shared bond of safety across the entire aerospace community.

We recognize it is not just our airplanes and our company that needs to be supported and strengthened. We also must help rebuild the communities and families affected by these accidents. Our first step was our pledge of \$100 million to them. We hired Ken Feinberg and Camille Biros, renowned experts in this area, to ensure families can access this money as quickly as possible. Of course, no amount of money can bring back what has been lost. But we can at least help families meet their financial needs. Our people also have donated more than \$750,000 of their own money to these funds—a tremendous example of the giving spirit our teams consistently display in the communities where they live and work across the globe.

Mr. Chairman, I've worked at Boeing my entire career. It started more than 30 years ago when Boeing offered me a job as a summer intern in Seattle. I was a junior at Iowa State University studying engineering, having grown up on our family farm in Iowa. It's beautiful land with rolling hills where my siblings and I milked cows and baled hay. Our parents taught us the value of hard work, integrity, and respect for others. Back then, I drove my 1982 Monte Carlo from Iowa to Boeing's operations in Seattle, crossing the Rocky Mountains for the first time. I was awestruck at the opportunities I had to work on projects that mattered at the company that brought the Jet Age to the world and helped land a person on the moon. I was amazed by the people of Boeing. Today, I'm still inspired every day by what Boeing does and by the remarkable men and women who are committed to continuing its legacy.

These heartbreaking accidents—and the memories of the 346 lives lost—are now part of that legacy as well. It's our solemn duty to learn from them and change our company for the better. I can assure you that we have learned from this and will continue learning. We have changed from this and will continue changing. The importance of our work demands it.

In the months since the accidents, there has been much criticism of Boeing and its culture. We understand and deserve this scrutiny. But I also know the people of Boeing, the passion we have for our mission, and what we stand for. There are over 150,000 dedicated men and women working for Boeing around the world—and their commitment to our values, including safety, quality, and integrity, is unparalleled and resolute. No matter what, we will stay true to those values because we know our work demands the utmost excellence.

Over the last few months, I've had the opportunity to visit many of our Boeing teams, talk about our safety culture, and gain ideas for how we can be better still. Last week, I saw our team in San Antonio—made up of 40 percent veterans—beaming with pride as they support the C-17 fleet for our men and women in uniform. Earlier, I talked with our people in Philadelphia building Chinook helicopters; in St. Louis testing F/A-18 Super Hornets; and in Charleston, South Carolina, and El

Segundo, California, connecting the world with the 787 Dreamliner and advanced satellites. I've also met with our people in Huntsville, Alabama, and New Orleans, Louisiana, who are building the rocket that will return humans to the moon and then travel on to Mars and those at Kennedy Space Center, Florida, who are preparing to launch the CST-100 Starliner that will commercialize space travel. I've spent time also with our teams in Everett, Washington, who are testing the new 777X long-range jet and in Renton, Washington, where 12,000 amazing people pour their hearts into building the 737 MAX. These are the people of Boeing. I wish you could all meet them. They change the world. They are Boeing.

I'm here today, honored to serve as the leader of this incredible team—talented engineers, machinists and all those who design, build and support our products. I want to answer all of your questions and convey to the world that we are doing everything in our power to make our airplanes and our industry safer and prevent an accident like this from ever happening again.

And, Mr. Chairman, you have my personal commitment that I will do everything I can to make sure we live up to that promise.

Thank you for listening, and I look forward to your questions.

Mr. CHAIRMAN. Thank you very much, Mr. Muilenburg. During my opening statement, I mentioned an instant message conversation and then a series of e-mails. This message conversation was between the 737 MAX Chief Technical Pilot and a colleague and it expresses concerns about the operation of the MCAS. Boeing knew about this instant message for months but failed to share it with the FAA until recently.

With regard to the e-mails, again, Mr. Forkner, the former MAX Chief Technical Pilot, calls for removing any mention of the MCAS flight control system from the flight crew operating manual. He talks about Jedi-mind tricking of regulators with at least one person who works for the FAA. So, with regard to the instant message conversation, when were you made aware of the existence of the November 2016 messages?

Mr. MUILENBURG. Mr. Chairman, as I recall, I was made aware of that message earlier this year. It was discovered as part of a document gathering process in response to a Government investigation.

The CHAIRMAN. So, it was after the crashes? You were made aware of it this year?

Mr. MUILENBURG. Sir, as I recall, I believe it was prior to the second crash earlier this year.

The CHAIRMAN. Prior to the second crash. Was it your decision to wait months before disclosing this to the FAA?

Mr. MUILENBURG. Mr. Chairman, at that point it had been identified as a document in response to an ongoing investigation and I relied on our counsel to provide that to the appropriate authorities.

The CHAIRMAN. OK, what did the counsel tell you? Did he say, I am going to supply it to the Justice Department, or did he say I am going to get it to the appropriate authorities?

Mr. MUILENBURG. Mr. Chairman, I do not recall having a specific conversation about which authorities. Just again as part of this investigative process, our intent to cooperate fully with your request and to provide that to the appropriate authorities. I think over this time period, we provided, on the order, half a million pages of documents in support of various requests.

The CHAIRMAN. Do you agree that this should have been provided to the FAA in retrospect?

Mr. MUILENBURG. Senator, as I became familiar with the details of the document over the last few weeks, as I expressed our disappointment and concern with the how this came to the FAA—I think you heard the same from Administrator Dickson—I called him and apologized for how this had come through the process. Again, I was not involved in the document production process, but I counted on our team to make sure all the right authorities were notified.

The CHAIRMAN. OK, so we should look to the team then. Can you ensure the Committee that Boeing has now turned over all such safety-related communications to the FAA and related to the 737 MAX?

Mr. MUILENBURG. Senator, our team continues to cooperate with all requests for documentation. I am sure that additional documents will be provided over time as they are discovered as would be normal to the process, and we will cooperate fully with the requests.

The CHAIRMAN. It seems to me that a request should not have to have been made with regard to that conversation, sir. Let me ask you, when did you become aware of the e-mails that I referred to in the second part of my question about Jedi-mind tricking regulators?

Mr. MUILENBURG. Senator, again just recently I have been informed of the details of those e-mails and instant messages—

The CHAIRMAN. Can you give us an idea of how recently?

Mr. MUILENBURG. Over the last couple of weeks when it became public news.

The CHAIRMAN. OK. And you did not know about it until then?

Mr. MUILENBURG. Sir, I do not recall being briefed on the details of those documents any time prior to that.

The CHAIRMAN. Can you see that this raises much concern about the level of coziness between Boeing personnel and FAA regulators?

Mr. MUILENBURG. Mr. Chairman, I understand the concern there, and again, we are doing our best to lean forward and provide information as part of this process. I can tell you that the comments, that the values, the approaches that are described in those e-mails are counter to our values, that in no way would meet any expectation I would have for our team or employees, so I understand the concern, share the concern, and am trying to convey it is not consistent with our values as a company at all.

The CHAIRMAN. And this series of e-mails has only in the last few weeks come to your attention, is that right, sir?

Mr. MUILENBURG. Senator, as I said, I was aware of the documents that were being produced as part of an investigation. That is what I recall from earlier this year. I do not recall getting briefed on the details of these documents. Those details are things that I learned of over the last few weeks.

The CHAIRMAN. Senator Cantwell.

Senator CANTWELL. Thank you, Mr. Chairman. And if you could help, I have a lot to go through, so we are going to try to move quickly through it. Was Boeing aware of the defects in the MCAS system which it failed to disclose to the FAA at the time the aircraft was in development and certification?

Mr. MUILENBURG. Senator, as you know the MCAS development occurred over a lengthy time period, about a six-year development program of the MAX. We have learned from both accidents and we have identified changes that need to be made to MCAS. We did, during the development process, follow our certification standards and long-standing industry standards behind the MCAS design but clearly, we have learned and there are things we need to improve on MCAS.

Senator CANTWELL. So are you saying—

The CHAIRMAN. Answer the question, Mr. Muilenburg.

Mr. MUILENBURG. Senator, could I ask you—

Senator CANTWELL. Was Boeing aware of defect in the MCAS system which it failed to disclose to the FAA at the time the aircraft was in development and certification?

Mr. MUILENBURG. Senator, I just have to question, I will say, the premise of the question. So, as part of our development process, we do identify hazards and failure modes—

Senator CANTWELL. And they were disclosed?

Mr. MUILENBURG. That was part of the failure mode analysis that we shared as part of the certification process during that time period.

Senator CANTWELL. So, you think everything that you were aware of was disclosed to the FAA as it relates to defects in the MCAS system?

Mr. MUILENBURG. Well Senator, as we get to defects—things we need to fix—we have identified three areas that we talked about that we need to address. One was the single sensor feed that was a piece of the architecture that was shared with the FAA. The fact that the system would operate more than once during a flight that was also part of the design description. And the control authority of the system at various parts of the flight—

Senator CANTWELL. Do you know what Mr. Forkner is referring to when he says, unknowingly lied to the FAA or Jedi-mind tricking?

Mr. MUILENBURG. Senator, I am not sure what he meant by that. We haven't been able to talk to him. He does not work for Boeing anymore. We have been trying to contact him.

Senator CANTWELL. Here is my concern, that if you do not know what he meant, then you also do not know what wasn't disclosed. And so, we do not know if there are things in the MCAS system that were defects that he or someone else knew about that were not disclosed. So, I hear what you are saying that there is a lot to discover in the process, but I would like to go over some of the very specifics about what was tested and did Boeing test the consequences of the MCAS reliance on a single AOA sensor? Did it test that?

Mr. MUILENBURG. Senator, we tested a broad array of different aspects of the MCAS system, a set of failure modes. We did thorough flight testing. You know, John, if you want to comment on the details there?

Mr. HAMILTON. Yes. Senator, the 737 NG is one of the safest airplane sets—

Senator CANTWELL. OK, look we are trying to understand what got tested. So did you test the reliability of the AOA sensors in gen-

eral? Did you test the reliability on a single sensor? Did you consult with the pilots on the lack of guidance on MCAS in the flight manuals? Did you test the AOA sensors' degree alert to ensure reliability? Did you test the human factor response? These are all things from the Lion Air report and my guess is you didn't test those and that is at the heart of this. But if you did and you have data on that and it was provided to the FAA, that is what we want to see.

Mr. HAMILTON. Senator, we did test the MCAS uncommanded inputs to the stabilizer system due to whatever causes was driving it, not specifically due to an AoA sensor. We assessed that hazard level. We talked about pilots—

Senator CANTWELL. Now do you think it is wrong?

Mr. HAMILTON. In hindsight, Senator, yes.

Senator CANTWELL. Thank you because I agree.

Mr. MUILENBURG. Senator, if I can just add a point to that because as John pointed out, we relied on these long-standing industry standards as part of our evaluation of response time behind MCAS, and that is one of the areas that we found shortfall.

Senator CANTWELL. Here is the thing I am very confused about which is just this larger issue, and look we want to get this right because we do want to go forward and we know there is going to be automation in many aspects of our lives, but this robust testing that must occur and third-party validation, there were just—I just do not understand how you have sensors on the outside of a plane and you are going to let that send a command to the inside of the plane that basically says turn the plane 2.5 degrees and then all of a sudden you are going to be yelled at from the cockpit from somebody saying pull up and then at the same time you are being forced down in your nose and you have seconds to respond because you are in takeoff.

That does not seem like a lot of robust testing was done to me because if it was then the Lion Air incident wouldn't have happened. OK, so I see my time, I have a few seconds left. I want to just bring up, look I think this whole issue of air speed is a major issue at large for all of us to get right in the sector. Those crashes about automation, even that Air France crash is related to a faulty pitot tube.

I do not know how much we should be trusting things on the outside of a plane to give commands to the inside of the plane when they can be damaged. But I do want to know that you are improving the safety culture, this issue of both reporting, people not being able to talk to FAA, oversight people, and this issue of some of the machinist Boeing quality inspectors, their work being taken over. I want to understand that a safety culture is going to exist.

Mr. MUILENBURG. Senator, if anything I can leave with you today, I want to reinforce the culture of safety at Boeing, and we know we can improve, we encourage our employees to speak up when there are issues and some of those have been public recently.

We respect and accept those inputs. We take action following on those. We have recently made a number of improvements that includes restructuring our safety review boards, elevating them to increase transparency and focus on safety. We have moved all 50,000

Boeing engineers to now report directly to our Chief Engineer, separating them from——

Senator CANTWELL. OK, I am going to ask you to come back on the SPIA and Boeing quality inspectors, two different issues, with a written response. Thank you, Mr. Chairman. I know I went over my time.

The CHAIRMAN. Thank you. Now I have the duty of telling the distinguished Whip that he is limited to five minutes.

[Laughter.]

**STATEMENT OF HON. JOHN THUNE,
U.S. SENATOR FROM SOUTH DAKOTA**

Senator THUNE. Thank you, Mr. Chairman. Mr. Muilenburg, it is my understanding that the MCAS has been substantially redesigned to include several redundancies that will better prevent erroneous activation. Could you speak to why some of the changes being made in the reconfiguration of the MCAS were not considered in the initial development of the system?

Mr. MUILENBURG. Yes, Senator. I think you raise a very important point. And as John began to allude to earlier, the original concept for the MCAS design was an extension of what we call the speed trim system on the 737 NG, the previous version of the 737, that is a single sensor system that has been proven safe in flight—more than 200 million flight hours.

So, one of our safety principles is to minimize change from model to model. That is a good standard safety process that was the concept behind the original MCAS design. And what we have learned from both accidents is that we made some mistakes. There are some things we can improve. One of them is this idea of going to a dual sensor feed instead of single as well as limiting MCAS with a single action or activation during a flight.

Those are improvements that we have identified. We take responsibility for that. We feel responsible for our airplanes and we know that there are some fixes that we need to make, we own that, and we are implementing those fixes going forward.

Senator THUNE. As we discuss possible improvements to the certification of an aircraft, it would be helpful for you to explain how safety supposed to be integrated into the certification process from the initial conception of the aircraft all the way to flying at 30,000 feet filled with passengers. Since these crashes, we have heard concerns about whether Boeing's relationship with the FAA is too cozy and we want a certification process that is efficient and that promotes U.S. competitiveness but one that always prioritizes safety. So, what would you say to address the concerns that have been raised about regulatory capture?

Mr. MUILENBURG. Senator, I agree with the focus in that area. I would say that over the last couple of decades the improvements that have been made in aviation safety are because of strong Government oversight, that includes the work of this Committee, it includes the other oversight of the FAA. The delegated authority process as it is structured, we do think has contributed to safety of the industry. I mentioned in my comments that it is about a 95 percent improvement in safety over the last two decades, some of

that I believe is associated with the delegated authority, but we have to get the balance right.

And I think it is very important that we have strong Government oversight, strong FAA oversight, but we also tap the technical depth that our industry teams can bring to the table. That is the concept. But if we need to rebalance it—I fully support evaluating that concept, looking at the details, and making sure we have got the balance right.

Senator THUNE. Could you briefly explain, very briefly if you could, how Boeing and the FAA work together to certify aircraft?

Mr. MUILENBURG. Yes, Senator, I could but I think Mr. Hamilton here is a deeper expert on that, if I could ask him to take that question?

Mr. HAMILTON. Certainly. Senator, the FAA is actually in control of the certification process the whole time. Let me just kind of walk you through the process very quickly. It starts out by identifying the requirements to certify the airplane. That is the sole authority of the FAA. It establishes the certification basis of the airplane. The second step is identifying the methods of compliance to those requirements. So, this is how you are going to show that the airplane design actually meets those requirements.

Again, the FAA is the sole authority on that. That is their action. The third step is doing the testing, the analysis, and the documentation that demonstrates the airplane meets those requirements. And that is done by Boeing in our case or the applicant. And then there is a review of those documents to validate that they actually met the requirements, and that can be done by the FAA, or the ODA who acts as a designee of the FAA, or it can be a combination.

And finally, there is oversight. The FAA does oversight of the actual unit members. They do oversight of the ODA and are you following the processes. They do oversight of did you find compliance as they expected with the methods of compliance. And then they do systemic oversight of the entire system.

Senator THUNE. And Mr. Muilenburg, how are you working to ensure, coming back to this issue of safety, that employees who raised concerns even if they inhibit your ability to get a product to the market quickly are taken seriously and then importantly those concerns are raised to the top and not brushed aside?

Mr. MUILENBURG. Senator, in my role as the CEO of this company I take that responsibility very seriously. We have a number of ethics hotline avenues that our employees can use. When it comes to delegated authority, in particular we also have additional survey tools that we deploy, and we openly share that data with the FAA and make improvements.

That said, again, we know we can improve, and one of the areas that I have taken recent action on is to restructure our safety organization. So, we have now created a new safety organization. Vice President Beth Pasztor reports to my Chief Engineer who reports directly to me. That safety organization has responsibility for all safety related accident investigations, our ODA process, and also responding to any employee concerns.

Senator THUNE. Thank you, Mr. Chairman.

The CHAIRMAN. Senator Klobuchar.

**STATEMENT OF HON. AMY KLOBUCHAR,
U.S. SENATOR FROM MINNESOTA**

Senator KLOBUCHAR. Thank you, Mr. Chairman, and thank you to Senator Cantwell. I also want to give my sincere thanks to the people who are here who lost their loved ones in these two crashes. I think you know you are here not only for them, and it must be hard to hear all this technical issues when you think of your brother or sister or father or mother or son or daughter, but I want you to know that we want to get to the bottom of this and we want to change this.

So, I will start where Senator Thune was going with the FAA and Boeing, and this relationship. Our recent Inspector General report found that only 4 percent of airline manufacturer employees responsible for conducting the certification were certified by the FAA that conducted oversight. The same report found that one manufacturer approved about 95 percent of certifications for their own aircraft. What can you tell us about the percentage of certifications that Boeing conducts on its own aircraft?

Mr. MUILENBURG. Senator, I cannot answer that number off the top of my head. I do not know—John if you have a—

Mr. HAMILTON. No, I would have to follow up.

Senator KLOBUCHAR. OK. How many Boeing engineers both design systems for the company and then certify those same systems for the FAA? I am just trying to get at a safety check from the outside.

Mr. HAMILTON. So, we have approximately 1,000 engineering unit members that work not just in systems—

Senator KLOBUCHAR. But what percentage of them then certify the safety as opposed to having the FAA certify the safety?

Mr. HAMILTON. Those are roughly 1,000 unit members that are acting on behalf of the FAA to find the compliance, but that is beyond just systems. This includes structures and propulsion, so it is across the whole airplane.

Mr. MUILENBURG. Senator just to clarify, we have about 50,000 engineers at Boeing. About 1,000 of them are what we call, operate in this area that John's referring to, unit members. So, these are members who have the authority and the training.

Senator KLOBUCHAR. OK. We will follow up. I am trying to get at when the FAA steps in and when you certify it yourself, and we will get that later. Two months after Mr. Forkner sent these messages expressing safety concerns, he asked the FAA to remove mention of the MCAS automated flight control feature from the 737 Max pilots' flight manual and training course, a change that the FAA approved in 2017.

Notably Indonesia's National Transportation Safety Committee report on the Lion Air crash confirms that the pilot's lack of knowledge of MCAS was one of the key reasons for the plane crash. How frequently are new automated systems left out of the manual and training that you give to pilots?

Mr. MUILENBURG. Senator, first of all of one of the things we have learned from both of these accidents is that we need to provide additional information on MCAS to pilots. Just to give you context, as we develop our training manuals, our idea is to provide training to pilots so they can respond to the effects of failures as

opposed to trying to diagnose failures and that is a very important distinction.

And so more information in the training manuals is not necessarily safer but as we understand from both of these accidents, we need to provide more information on MCAS to enhance safety. But we do try to include information in the training manuals—

Senator KLOBUCHAR. But do you think it is acceptable that pilots are flying planes without knowing about these key automated flight systems?

Mr. MUILENBURG. Senator, again our approach is to train pilots on the effects of a failure mode. So, in this case, the MCAS automation system, when it fails it fails in what we call a runway stabilizer, uncommanded movement of the horizontal tail. That is what is in the training manual and we try to train pilots to respond to the effect of the failure as opposed to diagnose it.

Senator KLOBUCHAR. OK, let me move on to two more questions. After these terrible crashes have claimed 346 lives, do you think it makes sense for these aircraft to be allowed to fly in some countries and not others because the FAA says each country can make its own decision?

Mr. MUILENBURG. Well, Senator, we respect the jurisdiction of the regulatory authorities around the world—

Senator KLOBUCHAR. So, you think it is acceptable? Just say yes or no.

Mr. MUILENBURG. Senator, that is up to the regulatory authorities. That is not a decision that we can make. We respect the authority of the regulators.

Senator KLOBUCHAR. OK. You are saying the same thing again, so I am going to go with a yes. While there have been several factors that contributed to the plane crashes, one that is particularly troubling was highlighted in a recent article in the Washington Post, which found that the Lion Air had a faulty angle-of-attack sensor which gave pilots and airplanes systems unreliable information the day before it crashed. Do you think that is a problem and what steps can be taken to change that?

Mr. MUILENBURG. Senator, in the case of the angle of attack disagree alert we got the implementation wrong. I mentioned in my comments up front that we made some mistakes, we made a mistake in that implementation. Once we discovered it, our engineering teams quickly convened a safety review board.

They confirmed that it wasn't an operational safety issue and the FAA subsequently concurred with that but nonetheless, we got the implementation wrong and we have addressed the faults in the process. We have fixed that. And angle of attack disagree alert will be standard implementation on all MAXs going forward.

The CHAIRMAN. Thank you, Senator Klobuchar. Senator Fischer.

**STATEMENT OF HON. DEB FISCHER,
U.S. SENATOR FROM NEBRASKA**

Senator FISCHER. Thank you, Mr. Chairman. I too would like to recognize and offer my sympathies to the people that are here today and the people who are at home who have lost loved ones in these crashes. I hope that we can get answers at this hearing and

also in the future so that these issues, these mistakes will not happen again and cause future loss of life.

Mr. Muilenburg, the Joint Authorities Technical Review notes that Boeing made several other changes to the 737 MAX that differ from the earlier model, such as structural changes that would accommodate the new engines that were planned on the plane and other advanced technologies. Senator Thune touched on this with the delegated authority. Was Boeing delegated authority over the certification of those changes as well?

Mr. MUILENBURG. Senator, I cannot answer that question completely because as you pointed out to there were a number of changes. Again, those are done and evaluated jointly with the FAA. I don't know, John, if you want to comment on any specifics there?

Mr. HAMILTON. There were approximately 92 certification plans associated with the MAX which encompass all the different changes to the airplane. The FAA reviewed approximately 8 of those initially and—

Senator FISCHER. Are you looking into those certification processes as part of your review of the 737 MAX?

Mr. MUILENBURG. Senator, yes, we are. I asked my Board to set up an independent review committee headed by Admiral Giambastiani about 5 months ago, and that committee did its work, provided inputs that we are acting on. And with the other authorities, we are continuing to take a hard look at that, and we look forward to taking an action on those reports.

Senator FISCHER. OK. Also, the Joint Authorities Technical Review included a recommendation that states, "if any flight control service is used in a novel manner, the FAA should be directly involved." This is based on the observation that the FAA was not, "completely unaware of MCAS," but, "because information and discussions about MCAS were so fragmented and they were delivered to disconnected groups within the process, it was difficult to recognize the impacts and the implications of this system."

Do you agree that the communication between Boeing and the FAA is fragmented to the point that relevant information on MCAS was not provided to the agency? Is this what you were referring to when you talked about getting the balance right?

Mr. MUILENBURG. Senator, I think you raise some very good points there. I do think one of the areas we can improve, and we have seen it in the JATR report and others is system-wide integration, cross system integration amongst the different technical expertise areas and improvements in documentation and communication. And again, we found some areas where we could have, should have, done better.

Senator FISCHER. Do you think those steps will improve your communication with the FAA?

Mr. MUILENBURG. Senator, I do.

Senator FISCHER. Do you think the FAA has a responsibility to also change its process to improve communication?

Mr. MUILENBURG. Senator, I believe the FAA does, but I would not say that is only the FAA's responsibility. We at Boeing need to make some improvements in communication and we own that, and we are committed to doing that.

Senator FISCHER. The Boeing 737 airplanes are based on a type certificate that was originally provided in 1967, I believe, and it has been amended to address the different 737 model since then. The Technical Review notes that, "some elements of the design and certification remain rooted in the original 1967 certification of the Boeing 737-100." Does Boeing or the FAA review the elements of the 737 that are based in the 1967 certification for continued safety when new models of the airplane are produced?

Mr. MUILENBURG. Senator, if I could ask John to field that question?

Mr. HAMILTON. Senator, as you note there is a single type certificate for the 737 but as the design has evolved with each new generation of airplanes, the safety standards on which the airplane is designed to have also evolved. Yes, there are some amendments that the designs might reference back to an earlier amendment level but those are likely changes that have not changed in the family of airplanes since the original design.

An example might be some of the structural elements. However, we have stepped up in many areas voluntarily to later amendment levels to demonstrate that it still meets the latest standards in compliance.

The CHAIRMAN. Thank you, Senator Fischer.
Senator Blumenthal.

**STATEMENT OF HON. RICHARD BLUMENTHAL,
U.S. SENATOR FROM CONNECTICUT**

Senator BLUMENTHAL. Thank you, Mr. Chairman. Thank you to both our witnesses for being here today and thank you most importantly to the relatives who have lost loved ones. If you could please stand so we could thank you all. Thank you for being here. If you could just stand. Thank you.

The CHAIRMAN. Go ahead and hold up the photographs that you brought.

Senator BLUMENTHAL. I was going to ask that you hold up those photographs because I understand that for security purposes you cannot during the hearing but just for this short period of time. Mr. Muilenburg—

The CHAIRMAN. So, thank you, and if the timekeeper could start Senator Blumenthal's time over. Thank you very much to the family members. Senator Blumenthal.

Senator BLUMENTHAL. Thank you very much, Mr. Chairman. Mr. Muilenburg, as I watched those loved ones stand and frankly as I reviewed this file over the past week or so again and as I sit here today my anger has only grown. These loved ones lost lives because of an accident that was not only preventable as the Chairman said at the very start but was the result of a pattern of deliberate concealment.

Boeing came to my office shortly after these crashes and said they were the result of pilot error. Those pilots never had a chance. These loved ones never had a chance. They were in flying coffins as a result of Boeing deciding that it was going to conceal MCAS from the pilot. And the best evidence is this message from Mark Forkner saying in effect we are going to conceal MCAS, delete it from the manual used in training. When did you become aware of

the fact that MCAS was not going to be included in the flying manual?

Mr. MUILENBURG. Senator, first if I could express my deepest sympathies for——

Senator BLUMENTHAL. You have done that, and my time is limited. I apologize for interrupting you, but I want to know specifically when you became aware of this effort?

Mr. MUILENBURG. Senator, I cannot reference that e-mail and I am not——

Senator BLUMENTHAL. I am not asking about the e-mail. You have been asked about the e-mail already. I am asking you about Boeing policy as reflected in this e-mail, its chief test pilot deciding he was going to mislead pilots who were then going to take passengers into the air, these loved ones, and turn those planes into flying coffins.

Mr. MUILENBURG. Senator, I am not sure what Mr. Forkner meant by that e-mail. I can tell you that certification and training materials are not determined by one individual.

Senator BLUMENTHAL. In fact, let me just interrupt you again. In the over 1,600 page original flight manual of Boeing 737 MAX, the aircraft's new MCAS computer system was mentioned only once, once in 1,600 pages in the glossary of abbreviated terms. So, when Boeing came to us and they said it is the pilot, inexperienced pilots, you were lying to us as well.

Mr. MUILENBURG. Senator, if I could try to respond to your question. First of all, the premise that we would lie or conceal is just not consistent with our values.

Senator BLUMENTHAL. Well I know it is not consistent with the values that you are articulating here but let me just, since my time is limited, move on. Would you agree that this system of certification and oversight is absolutely broken? That is the lesson here, isn't it? That Boeing lobbied the Congress for more delegation and now we have to reverse that delegation of authority. Would you support those legislative efforts?

Mr. MUILENBURG. Senator, again I support taking a hard look at the delegated——

Senator BLUMENTHAL. I am not asking you for a hard look, I am asking you for a commitment here because you have the opportunity to make things right?

Mr. MUILENBURG. Senator, I am not familiar with particular legislation, but I am committed to working and supporting it.

Senator BLUMENTHAL. Boeing asked for legislation that exists right now. Will you commit to supporting reform efforts such as many of us on this Committee are advocating?

Mr. MUILENBURG. Senator, we will commit to participating in those reform efforts and providing our inputs.

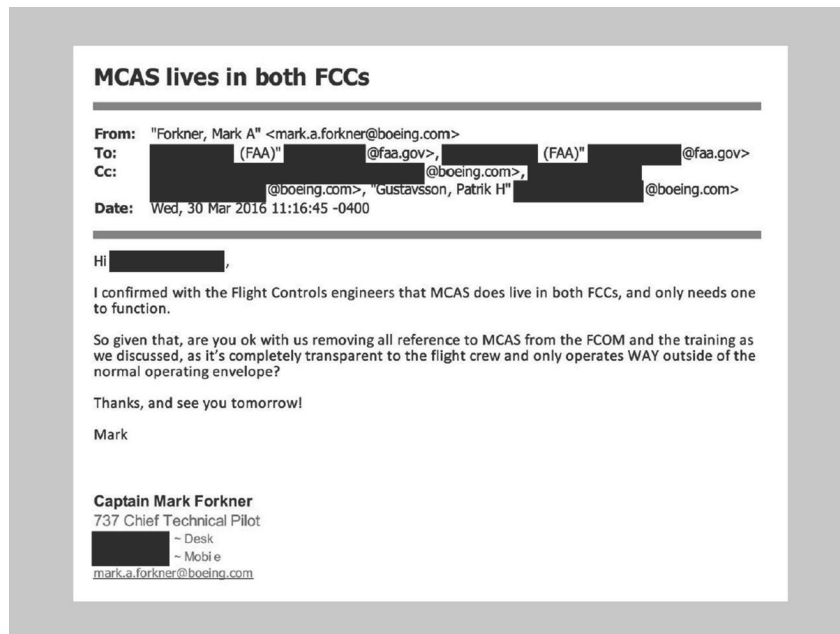
Senator BLUMENTHAL. Well, I agree that your input would be valuable. I am looking for input in support of reform that will stop outsourcing by the FAA, and I might just add, the FAA has been really disappointing and its disclosure to us is an example, the kind of disclosure the FAA has given us, total redaction. I have asked for full disclosure of documents. The FAA has failed to provide them.

I have asked for the FAA to return my phone calls. It has failed to do so and I think the FAA is part of this problem as well, and it is the result at the end of the day of Boeing rushing this process, I am using the Chairman's terms, putting profits over safety, rushing the certification process with you in charge of that certification and prioritizing speed and cost over safety.

And my time has expired but the folks who really deserve time here are the people who lost loved ones.

The CHAIRMAN. Thank you, Senator Blumenthal. Let us do this; this poster is entitled, "MCAS lives in both FCC." If you can provide a copy of that, we will admit it into the record at this point without objection.

[The information referred to follows:]



The CHAIRMAN. Thank you. And Mr. Hamilton, let me just ask you, when it says MCAS does live in both FCCs, what does that mean? Briefly.

Mr. HAMILTON. Certainly. So, the MCAS function is replicated in the two flight control computers that are onboard the airplane. And so, each flight control computer previously received its input from one AOA sensor on the left or right side. In the software changes we are making going forward, now both flight control computers will receive the data from both sensors, compare it, and only if they agree they will activate.

The CHAIRMAN. OK. Thank you. Senator Moran.

**STATEMENT OF HON. JERRY MORAN,
U.S. SENATOR FROM KANSAS**

Senator MORAN. Mr. Chairman, thank you. Mr. Muilenburg, did you determine that the failures that resulted in the tragic consequences, were they failures in the policies and protocols that Boeing had in place or was it a failure to comply with those protocols and policies that resulted in these consequences?

Mr. MUILENBURG. Senator, in some cases we relied on these long-standing industry-standards, policies, and certified to those, and we are now raising questions around those. That gets back to this pilot response time discussion that we had earlier. And in some cases, we missed on implementation as I mentioned earlier with the angle of attack sensor but overall, we did follow the certification process and steps. But nonetheless, we have learned from both of these accidents. And the fixes that we need to make are clear.

Senator MORAN. So, the fixes are both in policy and then making certain that the policies are followed once the new policies are in place?

Mr. MUILENBURG. Senator, I believe both are true, yes.

Senator MORAN. Thank you. And I assume there is other certification and just developments at Boeing that are always ongoing. Have you changed your behavior and or policies for the certification and development process for other pieces of equipment, other aircraft that Boeing is now proceeding toward certification?

Mr. MUILENBURG. Senator, we have, and we are going to continue to change. As I said we have learned, but we are still learning. I mentioned earlier that we changed our safety review board structure. That is a big, substantive change, the stand-up of our new safety organization. The realignment of our engineering team, those 50,000 engineers. We are also taking a look at some of those long-standing assumptions behind how we design as we look at next generation products like the 777-X as an example. So, we are taking a comprehensive approach to those updates.

Senator MORAN. As this Committee looks certainly at certification, as we look at the FAA, what suggestions does Boeing have for this Committee when you look at any policies or failures at the FAA? So, the way I would view this is we have two major organizations involved in this process: one is the manufacturer Boeing, the other is the Federal agency that is there to certify. My assumption is that neither one did things right. And what have you learned about the FAA that we should know as we look at the FAA now and in the future?

Mr. MUILENBURG. Senator, we have a great deal of respect for the FAA. I have personally worked with the FAA for many years, have a great deal of respect for them and their professionals. I know the FAA is also taking a hard look at all of the reports and inputs and investigations and is committed to making changes. I think you heard that from Administrator Dickson.

Senator MORAN. Do you have suggestions on what changes the FAA should make?

Mr. MUILENBURG. Senator, I do not have specific recommendations for you, but we would be glad to follow up on that if it would be useful.

Senator MORAN. Thank you. Where are we now in the 737 MAX? It seems like every week there is a report that an airline is going to believe they are going to have that plane flying again or certification is nearby. What is the status?

Mr. MUILENBURG. Senator, we are in the final stages of the process, so we are currently testing the final software updates. When ready and with the FAA's approval, we will proceed to a certification flight in the near-term. Subsequent to that it would be the FAA's responsibility to evaluate and issue an airworthiness directive. That is all work that we are proceeding on over the next few weeks and months, but I think it is important again that the airplane will return to service when it is safe. This is not going to be timeline driven. We are committed to answering every question the regulators have and the airplane will fly when everyone is convinced it is safe. That is the most important thing here.

Senator MORAN. It troubles me that to get to that point is certainly not that it is taking so long, I want the result that you just described but with the right circumstance before we're flying again, but it would suggest to me that there was much more significant problems with the MAX 737 if it was previously certified and yet now it takes so long. It is something more than just a glitch, it is something more than just a minor change. That makes me concerned about the process that allowed it to be certified in the first place. What am I missing?

Mr. MUILENBURG. Senator, I think you raise a very good point. Our initial effort early this year was focused on the MCAS updates that we have already talked about. Around the middle of the year, as we were evaluating all of the other inputs and data, we identified some additional safety enhancements that we can make. Not something that was required for certification but something that we thought while the airplane was grounded was the right thing to do and a safety enhancement, and rather than waiting to do that later after return to service, we as a company and with the FAA decided that we would take the extra time for those additional software updates.

And that is the work we have been doing through the summer and into the fall. That is designed to add additional software redundancies throughout the flight control computers and that is the final software we are testing. What I want to convey here is this is really the culture of Boeing. And I understand the questions that are being raised but when our teams find opportunity to improve safety, that goes to the top of the list. That is the top priority.

And if it takes time, if it takes money to do that, that is where we are focused and that is why it is taking longer than I think some anticipate.

Senator MORAN. I request your follow up on your thoughts about the FAA. Thank you.

The CHAIRMAN. Thank you, Senator Moran. Senator Markey. Senator Udall. Senator Peters.

**STATEMENT OF HON. GARY PETERS,
U.S. SENATOR FROM MICHIGAN**

Senator PETERS. Thank you, Mr. Chairman. Let me begin also by expressing my sympathies to those who lost loved ones in the two 737 MAX crashes and I would like to thank the families that are here today for your continued attention to safety and for working to prevent future tragedies like we saw here.

Over the years our aviation system has become the safest in the world, but these tragedies certainly remind us so that we cannot rest, safety cannot be taken for granted. There is no doubt from what we have been hearing in the testimony here today that many mistakes were made, and the consequences were unfortunately tragic. The reports from technical experts underscore that technology becomes increasingly complex. The debate about how to move forward cannot be simply about a one-size-fits-all regulatory regime versus a let the free market just police itself type of approach.

We have a new paradigm and they need to be developed to address the regulatory challenges associated with very complex technology and that is something this Committee needs to weigh in very heavily into as we move forward. Mr. Muilenburg, as you know, the BP oil disaster in the Gulf of Mexico killed 11 workers, lasted 87 days, and cost upwards of \$65 billion.

And in the wake of that disaster, it was revealed that the oil and gas industry have lobbied for the reduced safety precautions that could have prevented that disaster. We often hear in Congress about how much our regulations cost industry however thoughtful regulation plays an incredibly important role in protecting the public.

So, I am curious if Boeing's view on oversight has changed in the wake of this tremendous human tragedy as well as the cost that this company is facing right now. Has your view changed? You have talked in response to an earlier question about having a balance. Clearly something is wrong with that balance. Please let me know if your thoughts have changed recently?

Mr. MUILENBURG. Senator, my thoughts have changed. We have learned lessons from these two accidents and the families that are here with us today, the pictures we saw, they are heartbreaking. They remind us of the importance of the work we do and the paramount importance on safety. That is what makes this industry great, and strong oversight is part of the fabric of our industry, always has been, and I think this should give us pause to take a hard look at that.

Senator PETERS. Well, the hard look. You said we need to look at the balance. Has the balance gone too far to allowing the industry to police itself?

Mr. MUILENBURG. Senator, I do not know if I can characterize it that way. My sense is that we all have the same objective here. We all want the safest industry possible. That is our objective and my sense is that we could look at the balance. There are refinements that would be worthy. I think, you know, technology—

Senator PETERS. Do you think it is out of balance now based on what happened here? Do you think we have not just taken a look at it, but seriously understand that the balance may be out of

whack if we delegate too much to industry and do not have impartial eyes and make sure the regulatory regime is sufficient. That you truly have impartial eyes looking at these factors. It is going to save lives and you won't put a company through the cost that you have when you balance those regulations. Is it out of balance right now, yes or no?

Mr. MUILENBURG. Senator, again, I think it can be improved. I completely agree with you on the importance of strong oversight. I have worked in this industry for more than three decades from airplanes to spacecraft. People's lives depend on what we do and strong oversight from the Government is a key to the safety of our industry. So, I think we have a shared objective there and we will work with you on examining any improvements we can make. We have a mutual interest.

Senator PETERS. Mr. Muilenburg, the NTSB report indicated that the FAA and industry have historically used highly trained test pilots to verify the safety of new aircraft models rather than average pilots who typically have less experience. Does Boeing use pilots with average training and experience?

Mr. MUILENBURG. Senator, our Boeing test pilots are experienced, highly qualified pilots. We work with airlines, the FAA, and the regulators to bring other pilots in from around the world as part of the evaluation, but I think as you are pointing out as we look to the future again, we want to make sure that the testing we are doing is representative of that future pilot population.

Senator PETERS. Thank you.

The CHAIRMAN. Thank you, Senator Peters. Senator Capito.

**STATEMENT OF HON. SHELLEY MOORE CAPITO,
U.S. SENATOR FROM WEST VIRGINIA**

Senator CAPITO. Thank you, Mr. Chairman. I thank the Ranking Member as well. I want to say first of all to the families who are here, extending my sympathies but also my gratitude for you coming forward through your pain to bring to us to Congress, which is not an easy thing to do, your frustrations and probably stronger feelings in the loss of your loved ones. I will say that when Colgan flight 3407 went down in Buffalo in early 2009, the families that came forward to us, I was on Transportation committee on the House side, made such an incredible impact and it made flying on our regional airlines much, much safer because of that.

So hopefully that will be what the result of this is for you today and for all of us. Mr. Muilenburg, particular attention has been called to the fact that Boeing later in the development process of the MAX revised the range of flight conditions that could lead to activation of the MCAS, but that Boeing did not notify the FAA of these changes at the time. This is troubling if in fact this is true. Was Boeing not obligated by the FAA to report changes like the ones I just described?

Mr. MUILENBURG. Senator, I believe you are referring to the low-speed extension of MCAS and I have seen those same reports, but they do not reflect the facts. The extension of MCAS low speeds was done in a rigorous way. It was done in a very visible way. There was testing done on that from the mid-2016 time-frame to the early 2017 time-frame including flight test with the FAA on-

board. The FAA was aware of the low-speed extension and ultimately certified that, and I believe FAA leadership has publicly stated——

Senator CAPITO. So that is a false report then?

Mr. MUILENBURG. I believe it is a false report. I believe the low-speed extension was fully certified with the FAA.

Senator CAPITO. OK. Another report that has been out in the media and among is that after the second flight went down that Boeing actually actively lobbied the FAA to keep the planes in the air. Can you respond to that?

Mr. MUILENBURG. Senator, could you just clarify your question for me?

Senator CAPITO. Yes, after the second plane with Ethiopian Air went down that there was quite—several countries had limited the flight of that plane. We have not done that yet in the United States. There are media reports that Boeing was actively lobbying the FAA to keep the planes in the air at that time in this country. Is that true?

Mr. MUILENBURG. Senator, let me, let me clarify what was happening in that timeframe.

Senator CAPITO. Could you make it brief, please?

Mr. MUILENBURG. Yes. We immediately after that accident reached out to the FAA and other regulatory authorities to understand what happened in the accident. What has made aviation safe is that we make decisions based on data. At that point we didn't have data and so we with the FAA were looking to understand what happened. There were early reports that the airplane had some kind of low speed, low altitude problem that turned out to be incorrect.

So, we, with the FAA, were pursuing data to make a good safety based decision. That was our position with the FAA. When data became available, satellite data that was referred to in the media, again with the FAA we came to a conclusion that there could be similarities between the two accidents and that led very quickly to a decision to ground the fleet.

Senator CAPITO. Well, I think, you know, in retrospect I think it was pretty obvious and I do not want to say conclusively so but there is a problem and a consistent problem. The other thing that has really bothered me about this whole thing and I questioned this in the last Committee hearing that we had. Between the Lion Air crash and the Ethiopian Air crash, it defies logic to me that some of these folks who wrote e-mails or sent text messages did not come to you and to the expertise of the engineering of these engines and of these planes and say this is what we were talking about.

Why was there any reaction at all like that within your company after the Lion Air crash? And do not tell me because you did not have the official report, that would have maybe saved those people in that Ethiopian Air flight.

Mr. MUILENBURG. Senator, I think about that decision over and over every day. And if we knew everything back then that we know now, we would have made a different——

Senator CAPITO. OK, the question then, did people come to you at the highest levels, at any level, and say wait a minute, this is sounding familiar? Yes or no?

Mr. MUILENBURG. Senator, after the first accident we convened our broad technical team across Boeing. It wasn't any single individual or small team. It was a broad team. We brought all those experts to bear trying to assemble data from the accident, understanding what occurred. We quickly with the FAA issued an operational bulletin to remind everyone of the training and the emergency scenario that—

Senator CAPITO. Around that particular system?

Mr. MUILENBURG. Around what we call runaway stabilizer, which again is the effect of that system, and at the same time we began work on an MCAS software update in that timeframe.

Senator CAPITO. So, the answer is yes. Thank you.

Senator CANTWELL. Mr. Chairman, just one point of clarification. Are you saying Mr. Muilenburg the FAA did know about the 2.5 trim not 0.6 but 2.5? The FAA knew about that?

Mr. MUILENBURG. Yes, Senator. You are referring to that low-speed extension which is the 2.5 degree trim?

Senator CANTWELL. Yes.

Mr. MUILENBURG. That is the low-speed extension. The FAA did know about that and participated.

Senator CANTWELL. Thank you.

The CHAIRMAN. Senator Udall.

**STATEMENT OF HON. TOM UDALL,
U.S. SENATOR FROM NEW MEXICO**

Senator UDALL. Thank you, Mr. Chairman, and thank you to the Ranking Member for having this hearing. And Mr. Muilenburg, you know, I first want to say to all the people that stood up, that I am very moved by you being here and that your losses are very, very I think heartfelt across the Committee here. And, you know, the thing that really bothers me is knowing that it is preventable. It makes it even more outrageous that we haven't made the kind of dramatic changes that I want to talk to the CEO here about. Mr. Muilenburg, you showed some emotion when these folks stood up and everything.

What should come from that emotion is some action to do something to really make a difference, and for this Committee to coalesce around the solution that is really going to move us forward would require you to step forward and specifically say what you support. And I haven't seen you do that in all the questioning you have been asked over and over again. What would you support? I mean, it is absolutely clear that it is too cozy a relationship with the FAA and your airline. And so, what is it you are going to commit to specifically in terms of reform? That is why you are up here.

And that is what we want to see you do is to weigh in with us, this is what would make a difference, this is what would make it safer, this is what would make sure that we do not lose passengers like this in the future or the crew.

Mr. MUILENBURG. Senator, while I respectfully do not agree with the characterization of coziness with the FAA, we respect the independent oversight of the FAA and that is very important to us from

a safety principle standpoint. We have taken a number of internal actions that we think are meaningful as they relate to our own internal reforms on safety.

We are engaged in the legislative process, and Senator, I appreciate your invitation for us to be involved in that. I know there are many stakeholders. As you heard from me earlier, we are committed to strong oversight in the aerospace industry. It is part of what makes this system safe. We have a shared objective and if there are things we can do to make it better we will. I do not know John if you have any specific—

Mr. HAMILTON. Thank you. Senator, you know, I would say that, you know, one of the big issues was we made use of an industry standard assumption on pilots and how they would react and that proved incorrect in these two accidents. So, in terms of things that I think we need to change with the FAA, we need to go revisit some of these regulatory guidances and make sure they are up to date.

I would even tell you that there are probably some regulations that we advocate as part of the FAA reauthorization bill, 10 regulations, that FAA should work with industry to update based on technology that is out there today. But in terms of opposing this, I used to be the lead administrator for the ODA, and I can tell you that we have a respectful relationship with the FAA, but we do have our differences of opinion sometimes.

But we discuss those, we work it out on how we are going to comply, and it is not a cozy relationship. It is a professional relationship.

Senator UDALL. It is a relationship that didn't work for the consumers and for your employees that went down in those flights. You and others in your company blamed the deceased pilots and the culture of the countries where the crashes occurred for the accidents. But from what we have seen in the last year since the first crash, it appears that Boeing's own culture is more blameworthy for installing a faulty system that resulted in too many deaths and could have caused more.

This culture starts at the top and that is why I have been asking you for the specifics of what you support, and I hope after this hearing you will come forward and when there is legislation out there say this is going to make it better and come up here and spend some time to build the consensus to get this done.

Because I think the large, powerful interests that are a part of this do not want any reform. They want you to tinker around like you are talking about it, but they do not want to see any reform. If Boeing could not guarantee that pilots were prepared to fly these jets, your company should not have sold them. Did anyone at Boeing question, hesitate, or raise any issues prior to selling the 737 MAX 8 with this software to Lion Air or Ethiopian Air?

Mr. MUILENBURG. Senator, first we look forward to responding to your request there and providing inputs on the reforms. To your question, we do rely on the airlines and the regulatory authorities around the world as part of this integrated system to make sure we are fielding airplanes and crews that can fly safely. I do think it is important for me to clarify a point that you made earlier. We

have not blamed the pilots and I know that has been reported but that is not our company position and it never will be.

We are responsible for our airplanes. We are responsible and we own that. Regardless of cause, any accident with one of our airplanes is unacceptable.

Senator UDALL. That change is welcomed but that about the culture went out from your company early on. Thank you, Mr. Chairman.

The CHAIRMAN. Thank you, Senator Udall. Let's do this at this point. Mr. Muilenburg, the JATR published 12 main recommendations. Will both of you get back to us on the record and tell us Boeing's position with regard to these 12 recommendations?

Mr. MUILENBURG. Senator, we will.

The CHAIRMAN. Thank you. Senator Markey is next.

**STATEMENT OF HON. EDWARD MARKEY,
U.S. SENATOR FROM MASSACHUSETTS**

Senator MARKEY. Thank you, Mr. Chairman. Let me begin by recognizing the families who lost so much on these flights. Many of you are here today including Michael Stumo and Nadia Milleron, the parents of Samya Stumo, a University of Massachusetts Amherst graduate and a resident of Sheffield, Massachusetts who was tragically killed on the Ethiopian flight. The losses that the Stumo family and all of the families suffered is absolutely inexcusable and we will remember that as we are moving forward in the drafting of legislation. We will do it in the memory of your families.

One thing is clear to make sure that safety is our top priority is to guarantee that every aviation safety measure is built into every plane and that it is never for sale. Unfortunately, our current laws only prevent aircraft manufacturers like Boeing from selling critical safety elements for an additional price. Existing rules allow companies to charge extra for non-critical safety enhancing features. And Boeing actually does charge more for those technologies.

The 737 MAX aircraft involved in the Indonesian and Ethiopian crashes lacked two, two safety enhancing features, an angle of attack indicator and a disagree light. Both of these technologies would have helped the pilots recognize the faulty sensor readings were causing the plane's automated flight control system to push the aircraft nose down toward the ground. With that knowledge the pilots may have been able to take more effective action to prevent these crashes. In fact, the Indonesian crash report released last week specifically cited the lack of a disagree light on the 737 MAX as contributing to the Lion Air tragedy.

Shamefully, the law allows Boeing to treat these safety technologies as a la carte add-ons that airlines can obtain only by paying an extra fee. A la carte add-ons, safety. Not like XM radio, all leather seats on a plane, safety is a la carte. Safety is an added on feature. These tragic crashes have made it all too clear that there should not be any distinction between critical and non-critical safety enhancing features and that is why I have introduced my Safety is not for Sale legislation.

My bill will require aircraft manufacturers like Boeing to offer or provide any technology that measurably enhances safety without an additional charge to airline carriers. If you believe that safety

should never be for sale, the question is why was it? Now you seem to now recognize that the disagree light should be standard, but you have yet to say the same thing about the angle of attack indicator and whether or not that should be offered for free or whether or not each airline should be given the option of not building it into the plane for free.

So, I think you have to make a decision here in terms of where you want to go because otherwise your disagree light is still oncoming from Boeing toward the safety features. So, I want first of all to have you answer whether or not according to the *Wall Street Journal* you agree that Boeing did not originally include the disagree light on the 737 even though the same technology was standard on prior models of the airplanes, is that correct?

Mr. MUILENBURG. Senator, I feel I need to respond to your earlier point about selling safety. We do not sell safety. That is not our business model. And I do want to clarify your points on the angle of attack indicator. That is a system that we have offered as an option to airlines. Some airlines do not want it. It is not necessarily a safety improvement. It actually takes up space on the flight deck displays and more information on the displays is not necessarily safer. So that is not a safety feature. On the angle of attack disagree—

Senator MARKEY. All I am saying is you should not offer it for a price. You should give the option to the airline without any price attachment. Do you agree to do that?

Mr. MUILENBURG. Senator, yes. And in fact, we have already announced that the angle of attack disagree alert will be on all MAX airplanes going forward, standard, and the angle of attack indicator will be available as an option to all airlines at no cost.

Senator MARKEY. So, given your stated support for the principle behind my legislation, will you support my legislation that ensures that you offer to provide any technology that measurably enhances safety without an additional fee to airlines? Would you agree to support that legislation?

Mr. MUILENBURG. Senator, I haven't seen the specific legislation. I think the principle around focusing on safety is a top priority. I agree with that and it is a worthy principle, and I ask if we could take a look at the legislation.

Senator MARKEY. The key is just—the word is free to an airline for anything that measurably impacts safety. Do you agree?

Mr. MUILENBURG. Yes, we do not sell safety and that is not our business model.

The CHAIRMAN. Thank you. Thank you, Senator Markey.
Senator Duckworth.

**STATEMENT OF HON. TAMMY DUCKWORTH,
U.S. SENATOR FROM ILLINOIS**

Senator DUCKWORTH. Thank you, Mr. Chairman. So, I am going to try to put some of the issues here into layman's terms. I want to first of course share my sincere condolences to the families who are here, but also to the families in Ethiopia and in Indonesia who are watching this hearing, who will be watching this hearing. I do not speak Amharic, but for the Indonesians—

[Speaking in a foreign language.]

Senator DUCKWORTH. And what I just said was we will as Senators get to the bottom of this tragedy and we will continue to investigate this. We will not stop because you see Boeing sells its aircraft to the world and we in America have well-earned reputation as leaders in aviation in the world and I want us to reach that shining example once again.

Pilots know that tragedies do not occur in a vacuum. Catastrophic outcomes result in long succession of failures that often overwhelm the pilots at the control of the aircraft. We call it an aviation the accident chain and there are many links in an accident chain that must happen that would eventually overwhelm the pilots and results in the crash. Many of these links in the accident chain happened with Boeing and your decisions in the development of the 737 MAX. So, let me talk about what has happened here. You put a sensor on the outside of the aircraft, which is standard, but you allowed that sensor to override the pilot's input in this system.

So, in every other 737 aircraft, there is the function of the, you can pull back the pilot, the cutout, and that will override that uncommanded nose-down altitude. That is standard. That is the basic assumption. As you said you use an industry standard on how a pilot would react to a malfunction like that.

Uncommanded nose down, every pilot including helicopter pilots, you pull back. But what you did was you put an MCAS system into an aircraft, you didn't tell the pilots that this MCAS system was in there, and you put in a function in order for the MCAS to work the way you wanted it to work after the pilot does to uncommanded—reaction to the uncommanded nose down, in every other 737, cutout, that is the end of it.

In the 737 MAX, after five seconds, the system resets and it pushes the nose right back down. The pilots had exactly three seconds to pull, nose down, pull up. Now we got to do a new procedure that did not exist in previous 737 models, which is the electronic cutout switch because you have now put in a system that overrides the pilot in command of that aircraft.

So, you have been telling this Committee that, yes, you use basic pilot reactions. That is true. But you have not been telling this Committee the whole truth. Time and again, this is my frustration, Boeing has not told the whole truth to this Committee and to the families and to the people looking at this. Yes, the pilots did exactly what they were supposed to do but five seconds later, especially if that sensor is still stuck, it overrides what the pilot does, and it pushes the nose right back down again. Three seconds.

A pilot's best friend is time and altitude. And on takeoff there is no altitude and he has got no time. You set those pilots up for failure. And when I sent you a letter asking you to answer several questions, it took Boeing over five months to respond to my question. I only got the answers the day before you and I met. And one of the questions I asked was, what date did Boeing discover that a stuck angle of attack vane would result in MCAS issuing persistent commands with unlimited authority to trim the airplane nose down?

In layman's terms, if this vane is stuck, MCAS will continue to provide faulty directions and will keep pushing that nose down

over and over and over again no matter how many times an experienced 737 pilot pulls back on the yoke, five seconds later, reset, nose back down. You knew in 2016 that this was happening and your team at Boeing decided we didn't need to fix that because of well-understood piloting techniques and procedures.

But the problem is that the well-understood piloting techniques and procedures are to pull back and that is it. But you added something else. You put in a system you didn't tell pilots about and then you put in an override by resetting the system 5 seconds later.

Boeing is the company that built the Flying Fortress that saved Europe. I remember watching B-17s fly above—it is a storied aircraft that has rescued the free world and yet you knew about these problems and you continued to put the system into place. And when we asked you to answer these questions, you have told this Committee and you have told me half-truths over and over again, including in that meeting. This is why I am so upset. You have not told us the whole truth and these families are suffering because of it.

The CHAIRMAN. Thank you, Senator Duckworth. Members of the Committee, at this point Senator Scott is deferring his time to the Chairman of the Subcommittee, Senator Cruz. You're recognized, sir, for five minutes.

**STATEMENT OF HON. TED CRUZ,
U.S. SENATOR FROM TEXAS**

Senator CRUZ. Thank you, Mr. Chairman. Mr. Muilenburg, I have to say the testimony here today has been quite dismaying. I want to focus on the text exchange that has been referred to and has been publicly reported on. This was a text exchange between Mark Forkner who was then Boeing's technical pilot for the MAX, chief technical pilot for the MAX, and Mr. Gustavsson who in 2018 was promoted to being Boeing's 737 chief technical pilot. Is that right?

Mr. MUILENBURG. We believe that is the case, Senator.

Senator CRUZ. So, this exchange is stunning. Mr. Forkner, "oh, shocker alert. MCAS is now active down to M2. It is running rampant in the sim on me. At least that is what Vince thinks is happening." Gustavsson responds, "oh great, that means we have to update the speed trim description in volume 2." Mr. Forkner, "so basically I lied to the regulators unknowingly." Gustavsson, "it was not a lie. No one told us that was the case." Forkner, "I am leveling off at like 4,000 feet, 230 knots, and the plane is trimming itself like crazy. I am like what?" Gustavsson, "that is what I saw in sim 1 but on approach I think that is wrong." Forkner, "granted I suck at flying but even this was egregious."

That exchange describes what happened in Lion Air and Ethiopian Air. The men and women who are gathered here with the photos of your loved ones, 346 people are dead because what these chief pilots described as egregious and crazy—that is their language, that is Boeing's internal language in this exchange. Now what I find truly stunning, Boeing handed this exchange over to the Department of Justice in February.

In March, I chaired a hearing of the Aviation subcommittee on these two crashes. Boeing did not see fit to give this Committee

that exchange, nor did Boeing give it to the FAA or the Department of Transportation. But what I find most stunning is your testimony here today that you said you first learned of this exchange a couple of weeks ago.

These are senior leaders at Boeing in an exchange saying and I will quote again, “so I basically lied to the regulators.” Look, I have practiced law for a lot of years. You had your lawyers look over this document and they read a senior leader, after these crashes occurred, saying they lied to the regulators. Mr. Muilenburg, how in the hell did nobody bring this to your attention in February when you produced this to the Department of Justice? How did you just read this a couple of weeks ago?

Mr. MUILENBURG. Senator, again to clarify my earlier comments. I was made aware of the existence of this kind of document, this issue, as part of that discovery process in the investigation early in the year as you pointed out. At that point I counted on my Counsel to handle that appropriately.

Senator CRUZ. Did you read this exchange? Look, I was made aware documents were being produced. Whether that is passive voice and disclaiming responsibility—you are the CEO, the buck stops with you. Did you read this document? And how did your team not put it in front of you, run in with their hair on fire saying we got a real problem here? How did that not happen and what does that say about the culture at Boeing if they didn’t give it to you and you didn’t read it? If you didn’t say, I want to read it and see what happened?

Your testimony here earlier today is well we are not sure what they were talking about because he is not at Boeing anymore. How did you not in February set out a 9 alarm fire to say, we need to figure out exactly what happened, not after all the hearings, not after the pressure but because 346 people have died, and we do not want another person to die?

Mr. MUILENBURG. Senator, as you mentioned, I didn’t see the details of this exchange until recently and we are not quite sure what Mr. Forkner meant by that exchange. His lawyer has suggested he was talking about a simulator that was in development in that time period. That is where he was working. That could be the case. We do not know. I fully support diving deep into this and understanding what he said and what he meant but I can also tell you that in that same time-frame where his original message was made—

Senator CRUZ. Mr. Gustavsson still works at Boeing?

Mr. MUILENBURG. Senator, yes, he does.

Senator CRUZ. Have you had that conversation with him?

Mr. MUILENBURG. Senator, my team has talked with Patrick as well.

Senator CRUZ. Have you had that conversation?

Mr. MUILENBURG. Senator, I have not.

Senator CRUZ. My time has expired.

The CHAIRMAN. Thank you. Thank you, Senator Cruz. Senator Tester. Let’s do this. The entire poster—Senator Cruz if you can have that reduced in size and we will enter into the record without objection at this point. So ordered.

[The information referred to follows:]

Mark Forkner 6:50 PM:
 Oh shocker alert!
 MCAS is now active down to M .2
 It's running rampant in the sim on me
 at least that's what Vince thinks is happening

Gustavsson, Patrik H 6:51 PM:
 Oh great, that means we have to update the speed trim description in vol 2

Mark Forkner 6:51 PM:
 so I basically lied to the regulators (unknowingly)

Gustavsson, Patrik H 6:51 PM:
 it wasn't a lie, no one told us that was the case

Mark Forkner 6:51 PM:
 I'm levelling off at like 4000 ft, 230 knots and the plane is trimming itself like crazy
 I'm like, WHAT?

Gustavsson, Patrik H 6:52 PM:
 that's what I saw on sim one, but on approach
 I think that's wrong

Mark Forkner 6:52 PM:
 granted, I suck at flying, but even this was egregious

Gustavsson, Patrik H 6:52 PM:
 No, I think we need aero to confirm what it's supposed to be doing

Mark Forkner 6:53 PM:
 Vince is going to get me some spreadsheet table that shows when it's supposed to kick in.
 why are we just now hearing about this?

Gustavsson, Patrik H 6:53 PM:
 I don't know, the test pilots have kept us out of the loop
 It's really only Christine that is trying to work with us, but she has been too busy

Mark Forkner 6:54 PM:
 they're all so damn busy, and getting pressure from the program

Gustavsson, Patrik H 6:54 PM:
 That is true, I wouldn't want to be them

The CHAIRMAN. Senator Tester.

**STATEMENT OF HON. JON TESTER,
 U.S. SENATOR FROM MONTANA**

Senator TESTER. Thank you, Mr. Chairman. I want to thank you and the Ranking Member for having this hearing and I know for the two folks on the panel this morning it is probably a painful morning for you. But the fact is it is infinitely more painful for the folks that are sitting a couple rows behind you. You have said many times, Mr. Mulenburgh, that mistakes were made and obviously they were.

Unfortunately that admission was made after 346 people died. And there are a lot of reasons an airplane can go down whether it is pilot error, whether there is an equipment malfunction, or birds, but safety should not be one of them. And in a previous question you said you guys do not sell safety and I will be honest with you I didn't listen to the whole thing. But you damn well better sell safety.

I fly four legs a week and there is a lot—if not for the grace of God it could have been me on one of those airplanes and we expect there to be safety. Obviously, something went wrong, and it is not the first time. There is the MCAS situation here that was pointed

out as several people on this Committee have already pointed out to you and nothing was done or to your leadership team.

There was a South Carolina whistleblower that talked about debris being left in the planes or those technicians were removed. There is a KC-46 finding, wrench bolts and trash inside the new airplanes. That was in June of this year. There was a cargo 777. You get the deal. It goes on.

And so the question is the one that Senator Udall brought up that you didn't answer, and I think other people on this Committee also brought it up and that is, what do we do? What do you do? So I will be a little more specific. I do believe there is a cozy relationship and I do not believe that quite frankly time and money are no object because there is also plenty of examples.

For example in 2014, FAA made regulatory changes to safety standards that would have required changes to the MAX to add new crew alerts. Boeing appealed it to the FAA and sought to seek an exemption arguing it would cost too much money, \$10 billion, which is a lot of money, but the truth is that it wouldn't happen if FAA would have been doing their job and it also wouldn't have happened if you would have known what the hell was going on.

So my question is, and I know there was a push a number of decades ago about privatization of the Federal Government, and I think that is how we got here is privatization of Government. But why do we not just turn over the certification back to the FAA and let them do it and then they would be the ones sitting at this desk and not you. Why not do that?

Mr. MUILENBURG. Well Senator, we share your focus on safety and I can confidently say that is our number one priority.

Senator TESTER. OK, cool, but we failed in this case and there is a whole bunch of people back there that are going through incredible anguish because we failed.

Mr. MUILENBURG. Senator, I agree, and we feel—

Senator TESTER. So let's get to the question and look there is—I can pivot with the best of them. I know how to pivot, I know when people are pivoting. You are pivoting. Tell me if you would support having the FAA do the certification?

Mr. MUILENBURG. Senator, we believe that delegated authority process that we have today has contributed to improve safety over the last two decades. As I mentioned earlier, we are open to improving it but the idea that we can tap the deep technical expertise for companies across the aerospace industry is a valuable part of the certification process. But the FAA is the certification authority and should be and should continue to be.

Senator TESTER. Well, but they really aren't. The truth is you can say that they have the ultimate responsibility, but the truth is if the issues aren't flagged by the ODA, by your people doing the certification, the FAA never does it because quite frankly it would cost them more money to have the FAA do the certification.

And by the way, it is costing you money so we could charge you for that certification to help pay for it so it would have no reflection on the taxpayers. So the question becomes—I am going to tell you what, when the FAA says you need to do this and you come in and say no, you do not need to do this, it is fine if nothing happens, but when 350 people die, we got a problem.

And to bring up the point that Senator Cruz brought up that there was plenty of information out there on this and nothing was done. And so the whole thing about it, you know, when it comes to safety, time and money are no object is not—the record certainly does not show that.

Mr. MUILENBURG. Senator, I understand your points and criticism and I think it is true that we operate in a very competitive world and we are the only large airplane, commercial airplane maker left in the United States. We do have competitive pressures around the world, but I can also tell you that it never takes precedence over safety. Our business model is safe airplanes.

Senator TESTER. Think it absolutely could be argued that it did in this case, and I heard Senator Duckworth questions. And Boeing has had an incredibly valuable name, but I have got to tell you and I think I told you guys this an office some time ago, I would walk before I would get on the 737 MAX. I would walk. There is no way and the question becomes when issues like this happen, it costs your company huge. And so you shouldn't be cutting corners and I see corners being cut and this Committee is going to have to do something to stop that from happening. Thank you, Mr. Chairman.

The CHAIRMAN. Thank you, Senator Tester. I am going to ask that Mr. Muilenburg answer on the record his opinion of the current ODA system, whether it should be modified. Answer Senator Tester's question.

Senator Johnson.

**STATEMENT OF HON. RON JOHNSON,
U.S. SENATOR FROM WISCONSIN**

Senator JOHNSON. Thank you, Mr. Chairman. Let me add my condolences to the surviving family members and friends of the victims of these tragedies.

And Mr. Muilenburg, among many failures it strikes me there are two primary failures. First and foremost in the original design and certification process, and then second in the reaction after the first crash. So let's concentrate on those two things. Tell me if I am getting this right, the 737, a very successful airframe. New, more fuel-efficient engines were available and so you wanted to include that and upgrade of that airframe, correct?

Mr. MUILENBURG. New fuel-efficient engines and some other enhancements.

Senator JOHNSON. And those fuel-efficient engines created different aerodynamics for that aircraft, correct?

Mr. MUILENBURG. That is correct.

Senator JOHNSON. Is the MCAS system, is that a standard type of automatic pilot type of software system on planes? Is that pretty standard to have something like that?

Mr. MUILENBURG. Senator, the MCAS system that we have on the MAX is unique to that airplane.

Senator JOHNSON. So it was put in there specifically because you added a different type of engine to a known, successful airframe which made that less stable and required some kind of, as you called it, a runaway stabilizing system?

Mr. MUILENBURG. Senator, if I can clarify that, the 737 family has a system called the speed trim system and the MCAS is an extension of that system that is unique for the MAX.

Senator JOHNSON. Unique because of that added engine design?

Mr. MUILENBURG. We tailor the software of each one of our airplanes so that they optimize the handling qualities for the unique airplane configuration.

Senator JOHNSON. But again going into the introduction of this 737 MAX, you realize that that airframe was changed because those engines required this MCAS system for stabilization?

Mr. MUILENBURG. That was one of the additions we made to create the handling qualities we wanted for the pilots. We also made some changes to things like the vortex generators on the wing. So it is an integrated solution to creating—

Senator JOHNSON. You are well aware that this design change created something that required an MCAS system. So now fast forward, you have the Lion Air tragedy. According to Senator Cruz, the message that he set up there which I believe was written on November 15, 2016 just a couple years before that Lion Air crash, there are people or it sure appears some in Boeing that knew exactly or suspected what went wrong because the integrated design, you had an MCAS system to take care of this eventuality in the flight characteristics, correct?

Mr. MUILENBURG. Senator again, I am not exactly sure what was meant by that traffic, that e-mail traffic, but I can tell you in that timeframe—

Senator JOHNSON. It seems pretty obvious, does it not? I mean it does not seem pretty obvious to you? I mean again you are engineers, you understand how this was designed, you understood you needed an MCAS system to make up for that instability, and then something happened. I would think you would diagnose pretty fast.

I mean again, I am reading these things. I am not a pilot. I am not an aerospace engineer and yet I am scratching my head going, whoa, something really wrong happened. You know a whole lot. Why didn't you react faster?

Mr. MUILENBURG. Well Senator, completely separate from that e-mail traffic and what it might mean, our team very quickly after the Lion Air accident assembled with the regulators. We evaluated the data from the accident. We saw that MCAS was involved and so we began to take quick action immediately. It does not have to do with that e-mail. That is not relevant to that discussion. Our team was immediately identifying—

Senator JOHNSON. Which is exactly my point. The fact that it took another tragedy to actually ground the airplanes so you could actually have a true—a fix that worked is I think really what is on the table here. And the diagnosis is why didn't we react? Why didn't we ground that aircraft a lot sooner so that another tragedy wouldn't happen?

Mr. MUILENBURG. And Senator, we have asked that question over and over. And you know, if we knew everything back then that we know now, we would have made a different decision. The decision that was made on that at that point with the data we had, we quickly convened a safety review board, the FAA coming out of

that confirmed the continuing airworthiness of the airplane and issued that officially.

That was the safety case that was built. But Senator as you pointed out we have learned from the second accident and if we could go back, we would have made a different decision. And we have learned. We are making those improvements to MCAS and that is where our focus is going forward.

Senator JOHNSON. Boeing is an important company. It is important for our economy. I want to see you get this right, but you have to properly diagnose this. You have to accept responsibility for what happened so we actually can make those changes both within Boeing and also within the FAA. Thank you, Mr. Chairman.

The CHAIRMAN. Thank you, Senator Johnson. Senator Rosen.

**STATEMENT OF HON. JACKY ROSEN,
U.S. SENATOR FROM NEVADA**

Senator ROSEN. Thank you. And I want to thank all the families that are here today who have lost their most precious loved ones. Their death should not be in vain and we all have to do every bit of our part together to make sure that we prevent future tragedies from happening. And in order to honor the memories of these 346 souls and the empty chairs that they will leave behind this Thanksgiving and Christmas and on and on and on.

And so you said additional information wasn't available. I want to touch a little bit on MCAS and Brazil. According to news reports, when the Brazilian National Civil Aviation Agency came to the U.S. in 2017 to test out the MAX 8, they determined the changes made to the old 737 were significant enough that they needed much more information from Boeing and were going to provide it for their pilots.

When they eventually published their pilot training requirements, they were therefore able to flag the MCAS as one of the changes the pilots needed to take into consideration when flying the MAX 8. And yet for United States pilots, MCAS wasn't mentioned in their manual.

So, Mr. Muilenburg, why was this information not flagged for your other customers who had 737 MAXs in their fleet? And to prevent your company from sharing these differences to other regulatory bodies or operators, I have here the Brazilian manual. They decided their pilot should learn this and why wouldn't you provide it to the United States pilots?

Mr. MUILENBURG. Senator, I cannot comment on the details of the Brazilian document. John may be able to but let me more broadly make the point that that is exactly how the process is supposed to work. We provide information, we evaluate with the regulators in the various jurisdictions what should be included in the training. We have no desire to hide features of the airplane that pilots need to know.

Senator ROSEN. But they reported back to you and it was significant enough for them to put this in their manual then why wouldn't you consider that it was a significant change?

Mr. MUILENBURG. Senator, I understand your point and that was a decision that was made in Brazil. Again, I am not familiar with the details of that one. But the discussion—

Senator ROSEN. So let me just ask you this question then, moving forward will you commit to making it a practice when other countries are clearly paying attention enough to make significant changes to their pilot manuals based on major operational changes, that Boeing will send these notifications of changes to the other users of these aircraft so at least they have the opportunity to train their pilots? You denied them the opportunity, sir.

Mr. MUILENBURG. Senator, we are committed to sharing that information and that is part of our international collaboration. But I also want to note again that the discussion around MCAS training and whether it would be included in the training manuals that was an active, iterative discussion with the FAA, and it was a decision made based on safety.

Again, we try to put information in the training manuals that focuses on the effects of failures and things that will be valuable to the pilots and it is not always the case that more information adds to safety. Although in this case, we understand this, and this is one of the additions going forward.

Senator ROSEN. Brazil thought it added to their safety. But I want to touch a little bit on Senator Fischer, the question that she raised earlier. All these changes have taken place, of course, over the years and this plane is still working off its original certification from 1967. This is despite the fact that pilots have told me that the MAX 8 is in no way functionally similar to the original 737s that took to the skies 52 years ago.

I said in the last hearing that we had, seems to me like there have been so many significant modifications. It is almost as if you took a canoe and turned it into a cruise ship. So Mr. Hamilton, can you tell us how many derivative certificates Boeing has received for the 737 since initially being certified over 50 years ago?

Mr. HAMILTON. Senator, I do not have the exact number in my head, but it is approximately 14.

Senator ROSEN. Fourteen or 814?

Mr. HAMILTON. Fourteen derivatives. But I will—let me take the action to follow up with you on that.

Senator ROSEN. Thank you. I appreciate that. And the last thing I am going to ask. Do you believe that the 737 MAX is functionally the same plane that was certified in 1967?

Mr. HAMILTON. Senator, as I mentioned to you earlier, Senator, the safety standards have evolved as the airplane has evolved, and one of the important things I think to understand is what is really important also is for the pilots as they transition from an earlier version of the 737 to the newer version, that the airplane behaves and handles in the same way. That was important from a handling characteristics standpoint—

Senator ROSEN. And important enough for Brazil to mention but not for us?

Mr. HAMILTON. With respect to that Senator, so there is a joint operation evaluation board that determines the training, but other regulators can determine what training they want to do above and beyond based on the information. I do not know the specifics of the Brazilian document you are referencing. We can follow up on that.

The CHAIRMAN. Thank you. Thank you, Senator Rosen. Senator Blunt.

**STATEMENT OF HON. ROY BLUNT,
U.S. SENATOR FROM MISSOURI**

Senator BLUNT. Thank you, Mr. Chairman. So Mr. Muilenburg, I do not want to absolve you from both the opportunity and responsibility to go back and look at that long question from Senator Tester and answer it for the record. But for now one of the sources, one of the central thoughts in that question was, why shouldn't we change this process and go back to where it is no longer cooperative, or the FAA takes full responsibility?

Give me the answer to that. Should this process be changed where the Federal Government is fully responsible with employees only hired by the Federal Government? What impact would that have on safety?

Mr. MUILENBURG. Senator, I believe the data clearly shows that creation of the delegated authority process and its implementation has enhanced safety over the last couple of decades. I mentioned earlier about a 95 percent improvement in aviation safety over the last couple of decades. I think a portion of that at least can be attributed to the delegated authority process.

That does not mean we should not refine it, reform it over time, but the fundamental process of strong Government oversight combined with deep industry technical knowledge in the right balance is a strong safety process. And I firmly believe that is one of the things that has contributed to aviation safety. And that process demands oversight and we are fully supportive of strong oversight, but we also fully support the idea of tapping deep industry technical expertise. And that combination is the safest combination.

Senator BLUNT. And what do you think the view of the industry technicians is of their responsibilities there? Do you think they feel the right level of both responsibility and liability of providing the information that they need to provide?

Mr. MUILENBURG. Senator, they do, and I can tell you that is the culture of our company. And I respect the comments that were made today, and the questions have been raised about our culture. We deserve the scrutiny, but I have been at this company for 34 years. I know the people of Boeing. You all know the people of Boeing. These are 150,000 people that every day come to work because they have an important mission. They are honest, they are resolute in their efforts, they are committed to safety. That is our culture and every employee at Boeing—that is just how we think about the work we do.

And we are going to continue to improve as a company. I am not saying we have done everything right. As I have noted today, we have gotten some things wrong. But this is a great company with a great legacy that is committed to excellence and where we can improve, we will, where we can learn we will, but our culture is about safety. That is at the very core of Boeing. It has been that way for 103 years.

Senator BLUNT. Alright. Mr. Hamilton, I had two or three questions that actually Senator Rosen just asked pursuing that further. But you have got a 1967 certification that has had 14 variants since 1967. You have a significantly different plane that is based on the 14th variant of the original plane.

What difference do you think would have made if the certification process would have gone back to the we are certifying a new plane? Would that have made a difference in the MCAS system? Or you have been doing this a long time, what difference would it have made if we hadn't built on the previous half-century of this plane's history and just had started with a new plane. Would that have been better or worse?

Mr. HAMILTON. You know, in part 21 of the Federal Regulations, it spells out the change product rule which is how you assess for a derivative type certification. And it is a process that is in the USFAA's regulations. It is also in European and other countries regulations. And it requires you to look at all significant changes and step up. I think there is an assumption here that derivative type certification is less robust than the new type certification.

I think when you look at new types of certifications, or you often-times have some exceptions or equivalent levels of safety very similar to what you see on a derivative. So I am not sure it would have necessarily resulted in a safer airplane. It might have driven some different design decisions though, but fundamentally one of the things that happened in these two accidents was this assumption around how we expected crews to respond under certain situations, which proved to be—it did not happen.

And I think you know, that is a fundamental issue that we have to address in the industry.

Senator BLUNT. Thank you, Mr. Chairman.

The CHAIRMAN. Thank you, Senator Blunt.

Senator Blackburn.

**STATEMENT OF HON. MARSHA BLACKBURN,
U.S. SENATOR FROM TENNESSEE**

Senator BLACKBURN. Thank you, Mr. Chairman. Thank you for being here today and for taking our questions. I will tell you this is you have responded you have addressed Senator, Senator, Senator. I think you should be addressing victims because they are the ones who we are asking questions on behalf of and they are the ones who have come today on behalf of their family members.

And another thing I want to ask you, you have mentioned a couple of times a lack of awareness of e-mails or documents or communications and you know, Mr. Muilenburg, we have something around here, before we vote, we say we read the bill so that we know what is in it. And if we need to ask questions, we ask questions, and we develop that awareness that is so necessary to make good decisions and to have a full view of the situation that is in front of us.

And it is disconcerting to hear someone who is to be the leader of a company to say I wasn't aware, or I didn't know, or I haven't read that, nobody made me aware of that, I depended on that. You know, we call that passing the buck and it is your responsibility if you are going to lead the company to have that awareness.

So have you at this point read each and every page of every document that is relative to the situation in this case?

Mr. MUILENBURG. Senator, I cannot say I have read every document, every page. I know we have provided more than half a million pages of documents as part of the production process over the

last year. I accept your input and your criticism. I am accountable, our company is accountable. Accountability starts——

Senator BLACKBURN. I appreciate that, but I think that it is unsettling to hear you say I haven't read that. Let me move on. I do believe that you are in the business of safety as a priority and even though you say you do not sell safety, let us talk a little bit about the simulators because you had pilots that were training in the simulators as well as training in flight, correct?

Mr. MUILENBURG. You are referring during the MAX development?

Senator BLACKBURN. Yes.

Mr. MUILENBURG. Yes, Senator.

Senator BLACKBURN. OK. So the simulators that were being used for training, were they built by the same engineers with the same components, the same sensors, the same systems as the MAX system?

Mr. MUILENBURG. Senator, we have a wide variety of simulators, some of which are what we call conformed simulators which represent the actual hardware and software of the airplane. We have others that are engineering simulators.

Senator BLACKBURN. So it is conceivable that some of the pilots were not training on this specific simulator? And then you also—you know, Mr. Peters had started down a line of questioning with you about the pilots and the pilots that were trained. And you only had highly experienced pilots and simulators before flying the new MAX system, correct?

Mr. MUILENBURG. Senator, I was referring to our Boeing test pilots. We also have pilots from a number of other organizations, regulators, and airlines.

Senator BLACKBURN. Why would you not use pilots with a variety of experience, a wide range of experience? Because there are pilots with the wide range of experience that are going to be in that cockpit flying that plane in real time.

Mr. MUILENBURG. Senator, I agree with your view on the necessity of having a variety of pilot experiences involved in the testing process, but again our Boeing pilots are not the only testers in the process.

Senator BLACKBURN. OK. Well, then let's take it this way. What changes are you going to make in the simulators and in the training that is going to bring to account for human factor?

Mr. MUILENBURG. Senator, we have made several changes and have more to come but to start the baseline training program for the MAX is a roughly a 24 day training program which includes heavy use of simulators, advanced simulators. We have also modified the computer-based training for the incremental training between the NG and the MAX. We have added visibility to the training materials for the MCAS system that we have talked about.

That new training is all currently being evaluated and will be ultimately certified by the regulators to make it a baseline in the program. We are also investing R&D significantly in advance——

Senator BLACKBURN. Let me ask you this, I appreciate all of that and I appreciate your answer. Prior to these occurrences, did you feel that your training was not sufficient?

Mr. MUILENBURG. Senator, no, we implemented the training that was planned and certified for the airplane.

Senator BLACKBURN. I yield back.

The CHAIRMAN. Thank you, Senator Blackburn.
Senator Scott.

**STATEMENT OF HON. RICK SCOTT,
U.S. SENATOR FROM FLORIDA**

Senator SCOTT. Thank you, Mr. Chairman. First off, my heart goes out to all the families. I mean, I just cannot imagine, you know, the impact on these families after these tragic accidents. I come from Florida, so air travel is a pretty big deal for us. 126 million people traveled to Florida as tourists last year and a lined share of them came by aircraft. So the safety of everybody is really important. Mr. Muilenburg, the President and CEO of your commercial airlines was let go after this. So what is your process to hold people accountable to make sure this does not happen again?

Mr. MUILENBURG. Senator, first of all my company and I are accountable. I believe that accountability starts with me. My Board took some recent actions regarding my position, which I fully support and will allow me to focus even more on safety. So every action we take strives to focus on safety. I have also taken some management actions. Again, those are focused on operational excellence and safety going forward. As other reviews are completed, if we see additional actions that need to be taken, we won't hesitate.

But in some cases, accountability also includes improvements to our processes and our organization structure, and that gets to some of the changes we announced on our safety review boards, our new safety organization, our new board safety committee, and the realignment of all 50,000 of our engineers to our chief engineer in terms of reporting structure. All of those accountability actions are important and all of them are focused on safety.

Senator SCOTT. So if anybody, if any of your—whether it is engineers or nonengineers, if somebody has a concern in the future about safety, what is the process you have created to make sure that it gets to you and you can react to it because ultimately as a CEO the buck stops with you?

Mr. MUILENBURG. Senator, that has been one of the key learnings from this whole process is we need to elevate the visibility on safety issues that might come up the at the ground floor level. Make sure they get the right visibility and action. So a couple of things we have done there. One is again restructuring our safety review boards. So I now get a weekly update on safety review boards from across the Boeing enterprise at a detailed level, which I found to be very helpful.

We have also with the start of our new safety organization under Beth Pasztor, instead of having those safety teams underneath our businesses, they are now separated and report up through our chief engineer. Any safety concerns that employees have will come through that organization.

We set up a new anonymous reporting system for those employees that want might want to make anonymous reports to facilitate that, and we continue to have a full range of ethics hotlines across our enterprise that encourage employees to make their inputs. And

we have a culture of asking our employees to speak up. We want them to speak up. We want to make sure they are heard and that we take action.

Senator SCOTT. Have you made any changes at the Board level to increase the accountability for all employees?

Mr. MUILENBURG. Senator, our Board has been very engaged in this entire process. One of the things we did is a now about six months ago I asked our Board to set up an independent review led by Admiral Giambastiani. He has a tremendous safety background. That Committee came forward with a number of recommendations, some of which I mentioned in things that we have implemented.

Our Board will continue to be engaged in that process. And this new this new safety organization that I talked about, in addition to reporting to the Chief Engineer and to me, it also provides independent audit, if you will, back into our Board.

And our Board has set up a new aerospace safety committee that is now permanent headed up by Admiral Giambastiani. You might have seen on Friday we added another Board member, Admiral Richardson, who also has deep experience in safety. He will also be a member of that committee and so our safety organization will have an independent reporting line to them as well, which I think is a good discipline process.

Senator SCOTT. I had to go to preside, so I didn't get to hear all the testimony. But have you made any recommendations to this Committee on things that at the Federal level we ought to be doing differently, you know, to make sure whether Boeing, Airbus, or anybody else, this does not happen again?

Mr. MUILENBURG. Senator, we have discussed a number of options there. Again, we have learned and there are some things that we need to fix that are related to the airplane design and training and communications. We also think there are some opportunities to reform our processes and how we work together as a Government and industry. And we are very supportive of any actions there that would enhance safety.

Senator SCOTT. Thank you.

The CHAIRMAN. Thank you, Senator Scott.

Senator Sullivan.

**STATEMENT OF HON. DAN SULLIVAN,
U.S. SENATOR FROM ALASKA**

Senator SULLIVAN. Thank you, Mr. Chairman. And I also want to express my sympathies and condolences to the family members here. We have a safe commercial aviation industry in America, but I think we always have to look at ways to improve the industry, the airlines, FAA, Congress. So I am sure it is difficult for the family members to be here, but it is important that you are here. So I want to thank you for that. I am going to start with just a bit of a kind of a parochial question.

Mr. Muilenburg, Mr. Hamilton, Alaska Airlines is my state's airline, it is a very good airline, certainly critically important to my state. I know it is to the Ranking Member's state as well. They fly almost all 737 Boeings. We Alaskans travel a lot. I have had many constituents in the aftermath of these MAX crashes that have asked me, are the 737s that we are flying on all the time in Alaska,

to and from Seattle and other places, safe? So can both of you assure my constituents that these 737s are safe that are such an important component of the Alaskan air travel?

Mr. MUILENBURG. Yes, Senator. The 737 NG fleet that Alaska operates is a safe fleet, it is a safe airplane and it has got about 200 million hours of air safety track record behind it.

Senator SULLIVAN. Mr. Hamilton?

Mr. HAMILTON. I agree with Mr. Muilenburg's comments. I also just want to say that we have a weekly meeting that we review all the reports that are coming in from the fleet on whether or not there are potential safety issues or not.

Senator SULLIVAN. So the MAX issues that we are focused on here with regard to 737s are not issues that exist with your other line of 737s, 800s, and 900s?

Mr. HAMILTON. No.

Mr. MUILENBURG. That is correct.

Senator SULLIVAN. Let me ask—and I know the House side was looking at this issue. As we focus as this Committee on the tragic lessons learned from the MAX 737 accidents, should we also take the time to ensure that the other 737 models that are receiving less attention now nevertheless continue to be safe and to take the opportunity to look at the FAA certification process on those to make sure that that is not bedeviled with some of the challenges that we are discussing here with regard to the MAX? Would you agree that that is an opportunity to not just focus on the MAX but the overall process to reboot the focus both at your company, but also in the FAA on safety?

Mr. MUILENBURG. Yes, Senator, I believe there are a number of independent reviews underway right now looking at that broader certification process, some of which have begun to report out. We support that broader look.

Senator SULLIVAN. So models that aren't just the MAX?

Mr. MUILENBURG. All models. So we are taking an end-to-end comprehensive look at the certification process and I believe there are a number of Government independent reviews that are focused on that.

Senator SULLIVAN. Let me ask for both of you. I keep hearing from safety experts about the importance of what they refer to as functional safety and that is the way the different systems work together with the operator as opposed to looking at each system as it is added to a new model in a vacuum. And it seems to me that this issue of functional safety is a core issue as it relates to the MAX given what has happened.

Can you tell the Committee about what your company's approach to this issue of functional safety is when adding new systems to an existing aircraft like the 737? Obviously, there was a failure here on that issue. How are you working to improve that and does the FAA do enough to focus on this idea of functional safety not just the individual additions to existing and older models?

Mr. MUILENBURG. I will ask John to take that question.

Mr. HAMILTON. Yes. So Senator, I think it starts with our requirements breakdown of what is our airplane level requirements, system level requirements, component level requirements and then validating at the component level, the system level, and the air-

plane level how any change met the requirements and interacted across at the system or airplane level. You also talked about regulatory requirements.

Senator SULLIVAN. Yes. Does the FAA focus enough do you think on functional safety?

Mr. HAMILTON. So there has been some rather recent changes in what we call development assurance that I think has continued to mature and again this looks at the functional safety and some of the things that you really focused at is the breakdown of requirements and how different systems interact with that. So, I think we as Mr. Muilenburg pointed out, some of the recent industry committee reports have discussed this and I think we will support those recommendations and the FAA's actions going forward.

Senator SULLIVAN. Thank you. Thank you, Mr. Chairman.

The CHAIRMAN. Thank you, Senator Sullivan. And thank you to the panel. We appreciate you being with us and I am sure we will be questioning you further as we continue to get more reports. Our second panel of witnesses will be escorted in now. We thank you two gentlemen for being with us.

The second panel, as I said before, is Mr. Robert Sumwalt, Chairman of the National Transportation Safety Board, and the Honorable Christopher Hart. Mr. Hart is the team Chair of the Joint Authorities Technical Review, which we use the shorthand of JATR for, and I have referred to that a number of times during this hearing. Mr. Hart is a former Chairman of the National Transportation Safety Board.

They have been waiting patiently during these two and a half hours. Gentlemen, we appreciate you being here. We ask each of you to summarize your submitted testimony in five minutes. And Mr. Sumwalt, we will begin with you. You are recognized.

**STATEMENT OF HON. ROBERT L. SUMWALT III, CHAIRMAN,
NATIONAL TRANSPORTATION SAFETY BOARD**

Mr. SUMWALT. Thank you, Mr. Chairman. Good afternoon Chairman Wicker, Ranking Member Cantwell, and members of the Committee. Thank you for the opportunity to testify before you today. This afternoon I will address the NTSB's recent recommendation report regarding the 737 MAX certification processes. This recommendation report issued last month contained seven recommendations to the FAA.

These recommendations are the result of the NTSB's involvement as an accredited representative to the Indonesian government's investigation into last year's Lion Air crash and to the Ethiopian government's investigation into this year's crash involving the Ethiopian Airlines Boeing 737 MAX. The NTSB participates in foreign investigations in accordance with ICAO Annex 13, which details the standards and recommended practices of international aviation accident investigations.

Under Annex 13, the state of occurrence leads the investigation and the U.S. has the right to participate in the investigation when it involves a U.S. manufacturer or U.S. registered or designed aircraft such as the 737 MAX 8. This is so that any design or manufacturing issues can promptly be addressed by the FAA and the manufacturer.

As an accredited representative to these crash investigations, the NTSB initiated an in-depth examination of the U.S. design certification processes used to certify the MAX. The issues we identified revolve around three basic areas and our safety recommendations are centered on them.

First, the system safety assumptions used by Boeing for the MCAS and ultimately accepted by the FAA did not use realistic pilot recognition and corrective actions in response to uncommanded flight control inputs. Quite simply, the assumptions that Boeing used did not consider or account for the impact that multiple flight deck alerts or indications could have on pilots' responses to uncommanded MCAS activation.

Next, we identified the need for manufacturers to validate their pilot response assumptions using scientific methods and application of human factors principles to improve cockpit design, procedures, and training. We believe that the use of validated methods and tools to assess pilot performance in dealing with failure conditions in emergencies would result in more effective requirements for flight deck interface design, pilot procedures, and training strategies.

And finally, we believe that manufacturers should develop and incorporate in airline cockpits mechanisms that would allow pilots to better diagnose, prioritize, and react to multiple alerts and alarms. The pilots in the Lion Air and Ethiopian crashes were faced with multiple oral and visual alerts.

Research demonstrates that emergency situations increase workload and require additional effort to manage effectively because of the stress involved and possible confusion regarding which actions are necessary to resolve the problem. Each of our seven recommendations are detailed in my written testimony.

In closing, it should be noted that the NTSB investigators continue to examine the design certification process, and we may issue additional recommendations in this area if warranted. Thank you again for the opportunity to testify and I look forward to your questions.

[The prepared statement of Mr. Sumwalt follows:]

PREPARED STATEMENT OF HON. ROBERT L. SUMWALT III, CHAIRMAN,
NATIONAL TRANSPORTATION SAFETY BOARD

Good afternoon, Chairman Wicker, Ranking Member Cantwell, and Members of the Committee. Thank you for inviting the National Transportation Safety Board (NTSB) to testify before you today.

The NTSB is an independent Federal agency charged by Congress with investigating every civil aviation accident in the United States and significant accidents in other modes of transportation—highway, rail, marine, and pipeline. We determine the probable cause of the accidents we investigate, and we issue safety recommendations aimed at preventing future accidents. In addition, we conduct special transportation safety studies and special investigations and coordinate the resources of the Federal government and other organizations to assist victims and their family members who have been impacted by major transportation disasters. The NTSB is not a regulatory agency—we do not promulgate operating standards, nor do we certify organizations, individuals, or equipment. The goal of our work is to foster safety improvements, through safety recommendations, for the traveling public.

Today I will address NTSB's recent recommendation report, "Assumptions Used in the Safety Assessment Process and the Effects of Multiple Alerts and Indications on Pilot Performance," issued on September 26, 2019, which contained seven recommendations to the Federal Aviation Administration (FAA). These recommenda-

tions resulted from our examination of relevant factors in the U.S. design certification process following two crashes of Boeing 737 MAX 8 aircraft.

NTSB's Role in Boeing 737-MAX 8 Crashes

On October 29, 2018, a Boeing 737 MAX 8, operated by Lion Air, crashed into the Java Sea shortly after takeoff from Soekarno-Hatta International Airport, in Jakarta, Indonesia, killing all 189 passengers and crew on board. The Komite Nasional Keselamatan Transportasi (KNKT) of Indonesia, investigated the accident and released the final report on October 25, 2019.¹ On March 10, 2019, a Boeing 737 MAX 8, operated by Ethiopian Airlines, crashed after takeoff from Addis Ababa Bole International Airport in Ethiopia, killing all 157 passengers and crew, including 8 American citizens. The investigation is being led by the Ethiopia Accident Investigation Bureau (EAIB), which released a preliminary report on April 4, 2019.²

The NTSB participated in these foreign investigations in accordance with the Chicago Convention of the International Civil Aviation Organization (ICAO) and the Standards and Recommended Practices provided in Annex 13 to the Convention because these accidents involved the Boeing 737 MAX 8, a US-designed, certified and manufactured airplane.³ Because both Indonesia and Ethiopia are signatories to the ICAO Convention, they are each responsible for the investigation in their state and control the release of all information regarding the investigation.

Following the Lion Air crash, the NTSB appointed a U.S. accredited representative and immediately dispatched investigators to Indonesia to participate in the KNKT investigation. NTSB investigators had access to all investigative data and participated in all aspects of the investigation, including: download and analysis of the flight data recorder (FDR) and cockpit voice recorder (CVR); teardown and examination of airplane components such as the angle of attack sensor that was removed prior to the accident flight; airplane performance analysis and simulation sessions; airplane system and certification analysis; interviews of airline and maintenance personnel; and review of the KNKT draft final report. The final report released by the KNKT on October 25, 2019, reiterated the seven NTSB recommendations and also included an additional 25 recommendations to seven organizations, including Lion Air, Boeing, Indonesian Directorate General of Civil Aviation, and the FAA.

In response to the Ethiopian Airlines crash, the NTSB also appointed an accredited representative, who we dispatched to Ethiopia with a team of investigators. NTSB investigators continue to take part in this ongoing investigation and have had access to all investigative data, including taking part in the download and analysis of the CVR and FDR.

In accordance with ICAO Annex 13, technical advisors from the FAA, Boeing, and General Electric have accompanied NTSB investigators to the Lion Air and Ethiopian Airlines accident sites to provide their specialized technical knowledge regarding the aircraft and its systems.

ICAO Annex 13 provides for other involved states to gain timely access to investigative information for the purposes of continued operational safety. As a result, NTSB participation in the foreign accident investigations enabled safety deficiencies to be promptly addressed by the FAA and the manufacturer and through NTSB safety recommendations. Because the United States is the state of design and manufacturer of the aircraft involved in these accidents, we examined relevant factors in the U.S. design certification process to ensure deficiencies were identified and addressed.

Design Certification of the 737 MAX 8 and Safety Assessment of the Maneuvering Characteristics Augmentation System (MCAS)

The 737 MAX 8 is a derivative of the 737-800 Next Generation (NG) model and is part of the 737 MAX family (737 MAX 7, 8, and 9).⁴ The 737 MAX incorporated a new engine (CFM LEAP-1B) and nacelle, which produced an airplane-nose-up pitching moment when the airplane was operating at high angle of attack (AOA) and mid-Mach numbers. After studying various options for addressing this issue, Boeing implemented aerodynamic changes as well as a stability augmentation function, Maneuvering Characteristics Augmentation System (MCAS), as an extension of the existing speed trim system to improve aircraft handling characteristics and

¹ Komite Nasional Keselamatan Transportasi, *Final Report No. KNKT.18.10.35.04*.

² Ethiopia Accident Investigation Bureau, *Report No. AI-01/19*.

³ ICAO is a UN specialized agency that manages the administration and governance of the Convention on International Civil Aviation (Chicago Convention), (<https://www.icao.int/about-icao/Pages/default.aspx>).

⁴ Boeing, *737 MAX Family*, (<https://www.boeing.com/commercial/737max/>).

decrease pitch-up tendency at elevated AOA. As the development of the 737 MAX progressed, the MCAS function was expanded to low Mach numbers.

As originally delivered, the MCAS became active during manual flight (autopilot not engaged) when the flaps were fully retracted and the airplane's AOA value (as measured by either AOA sensor) exceeded a threshold based on Mach number. When activated, the MCAS provided automatic trim commands to move the stabilizer airplane nose down. Once the AOA fell below the threshold, the MCAS would move the stabilizer to the original position. At any time, the stabilizer inputs could be stopped or reversed by the pilots using their stabilizer trim switches. If the stabilizer trim switches were used by the pilots and the elevated AOA condition persisted, the MCAS would command another stabilizer airplane nose down trim input after 5 seconds.

In each of the accident flights, the MCAS activated in response to erroneous AOA inputs, resulting in continuous command of airplane nose down stabilizer trim input as well as other alerts and indications. Multiple alerts and indications can increase pilots' workload, and the combination of the alerts and indications did not trigger the accident pilots to immediately perform the runaway stabilizer trim procedure during the MCAS-activated airplane-nose-down stabilizer trim input. The pilots' responses did not match the assumptions of the pilot responses to unintended MCAS operation on which Boeing based its hazard classifications within the safety assessment and that the FAA approved and used to ensure the design safely accommodates failures. Thus, the NTSB concluded that Boeing's functional hazard assessment of uncommanded MCAS function for the 737 MAX did not adequately consider and account for the impact that multiple flight deck alerts and indications could have on pilots' responses to the hazard.

We further concluded that a standardized methodology and/or tools for manufacturers' use in evaluating and validating assumptions about pilot recognition and response to failure condition(s), would help ensure that system designs adequately and consistently minimize the potential for pilot actions that are inconsistent with manufacturer assumptions. Lastly, because the pilots were uncertain how to prioritize and respond to the multiple alerts and indications that they received, we concluded that aircraft systems that can more clearly and concisely inform pilots of the highest priority actions when multiple flight deck alerts and indications are present would minimize confusion and help pilots respond most effectively.

Since the Lion Air accident in October 2018, Boeing has developed a software update to provide additional layers of protection to the MCAS and is working on updated procedures and training. However, we are concerned that the process used to evaluate the original design needs improvement because that process is still in use to certify current and future aircraft and system designs. Therefore, in accordance with our responsibilities as the accredited representative of the state of design and manufacture of the 737, we felt it necessary to issue safety recommendations.

NTSB Recommendations

On September 19, 2019, the NTSB issued seven safety recommendations to the FAA as a result of our examination of the U.S. design certification process used to approve the original design of the MCAS system on the Boeing 737 MAX.

The NTSB found that the accident pilots' responses to the unintended MCAS operation were not consistent with the underlying assumptions about pilot recognition and response that Boeing used, based on FAA guidance, for flight control system functional hazard assessments, including for MCAS, as part of the 737 MAX design. We issued these recommendations to address assumptions about pilot recognition and response to failure conditions used during the design certification process as well as diagnostic tools to improve the prioritization and clarity of failure indications presented to pilots.

As a result of the NTSB's in-depth examination of the U.S. design certification process and assumptions used to approve the original design of the MCAS system on the Boeing 737 MAX, the NTSB issued the following seven recommendations to the FAA:

1. Require that Boeing (1) ensure that system safety assessments for the 737 MAX in which it assumed immediate and appropriate pilot corrective actions in response to uncommanded flight control inputs, from systems such as the Maneuvering Characteristics Augmentation System, consider the effect of all possible flight deck alerts and indications on pilot recognition and response; and (2) incorporate design enhancements (including flight deck alerts and indications), pilot procedures, and/or training requirements, where needed, to minimize the potential for and safety impact of pilot actions that are inconsistent with manufacturer assumptions. (A-19-10)

2. Require that for all other U.S. type-certificated transport-category airplanes, manufacturers (1) ensure that system safety assessments for which they assumed immediate and appropriate pilot corrective actions in response to uncommanded flight control inputs consider the effect of all possible flight deck alerts and indications on pilot recognition and response; and (2) incorporate design enhancements (including flight deck alerts and indications), pilot procedures, and/or training requirements, where needed, to minimize the potential for and safety impact of pilot actions that are inconsistent with manufacturer assumptions. (A-19-11)
3. Notify other international regulators that certify transport-category airplane type designs (for example, the European Union Aviation Safety Agency, Transport Canada, the National Civil Aviation Agency-Brazil, the Civil Aviation Administration of China, and the Russian Federal Air Transport Agency) of Recommendation A-19-11 and encourage them to evaluate its relevance to their processes and address any changes, if applicable. (A-19-12)
4. Develop robust tools and methods, with the input of industry and human factors experts, for use in validating assumptions about pilot recognition and response to safety-significant failure conditions as part of the design certification process. (A-19-13)
5. Once the tools and methods have been developed as recommended in Recommendation A-19-13, revise existing Federal Aviation Administration (FAA) regulations and guidance to incorporate their use and documentation as part of the design certification process, including re-examining the validity of pilot recognition and response assumptions permitted in existing FAA guidance. (A-19-14)
6. Develop design standards, with the input of industry and human factors experts, for aircraft system diagnostic tools that improve the prioritization and clarity of failure indications (direct and indirect) presented to pilots to improve the timeliness and effectiveness of their response. (A-19-15)
7. Once the design standards have been developed as recommended in Recommendation A-19-15, require implementation of system diagnostic tools on transport-category aircraft to improve the timeliness and effectiveness of pilots' response when multiple flight deck alerts and indications are present. (A-19-16)

The complete safety recommendation report is attached to this testimony.

Finally, it should be noted that NTSB investigators continue to examine the design certification process and the NTSB may issue additional recommendations in this area in the future if such recommendations are warranted.

Conclusion

Thank you again for the opportunity to be here today to discuss the NTSB's role in these important international aviation accident investigations and to highlight our recent recommendations to FAA regarding the safety assessment process. I will be happy to answer any questions.

National Transportation Safety Board

WASHINGTON, DC 20594

Safety Recommendation Report

Assumptions Used in the Safety Assessment Process and the Effects of Multiple Alerts and Indications on Pilot Performance

Accident Number:	DCA19RA017/DCA19RA101
Operator:	PT Lion Mentari Airlines/Ethiopian Airlines
Aircraft:	Boeing 737 MAX 8/Boeing 737 MAX 8
Location:	Java Sea, Indonesia/Ejere, Ethiopia
Date:	October 29, 2018/March 10, 2019

The National Transportation Safety Board (NTSB) is providing the following information to urge the Federal Aviation Administration (FAA) to take action on the safety recommendations in this report. They are derived from our participation in the ongoing investigations of two fatal accidents under the provisions of Annex 13

of the International Civil Aviation Organization. As the accident investigation authority for the state of design and manufacture of the airplane in these accidents, the NTSB has been examining the U.S. design certification process used to approve the original design of the Maneuvering Characteristics Augmentation System (MCAS) on the Boeing Company (Boeing) 737 MAX. We note that, since the PT Lion Mentari Airlines (Lion Air) accident on October 29, 2018, Boeing has developed an MCAS software update to provide additional layers of protection and is working on updated procedures and training. However, we are concerned that the process used to evaluate the original design needs improvement because that process is still in use to certify current and future aircraft and system designs.

Although the NTSB's work in this area is ongoing, based on preliminary information, we are concerned that the accident pilot responses to the unintended MCAS operation were not consistent with the underlying assumptions about pilot recognition and response that Boeing used, based on FAA guidance, for flight control system functional hazard assessments, including for MCAS, as part of the 737 MAX design.¹ We are making these recommendations to address assumptions about pilot recognition and response to failure conditions used during the design certification process as well as diagnostic tools to improve the prioritization and clarity of failure indications presented to pilots.

FACTUAL INFORMATION

Accidents

On October 29, 2018, Lion Air flight 610, a Boeing 737 MAX 8, PK-LQP, crashed in the Java Sea shortly after takeoff from Soekarno-Hatta International Airport, Jakarta, Indonesia. The flight crew had communicated with air traffic control and indicated that they were having flight control and altitude issues before the airplane disappeared from radar. The flight was a scheduled domestic flight from Jakarta to Depati Amir Airport, Pangkal Pinang City, Bangka Belitung Islands Province, Indonesia. All 189 passengers and crew on board died, and the airplane was destroyed. The National Transportation Safety Committee of Indonesia is leading the investigation.²

The airplane's digital flight data recorder (DFDR) recorded a difference between the left and right angle of attack (AOA) sensors that was present during the entire accident flight; the left AOA sensor was indicating about 20° higher than the right AOA sensor. During rotation, the left (captain's) stick shaker activated, and DFDR data showed that the left airspeed and altitude values disagreed with, and were lower than, the corresponding values from the right. The first officer asked a controller to confirm the altitude of the airplane and later also asked the speed as shown on the controller radar display. After the flaps were fully retracted, a 10-second automatic aircraft nose-down (AND) stabilizer trim input occurred. After the automatic AND stabilizer trim input, the flight crew used the stabilizer trim switches (located on the outboard side of each control wheel) and applied aircraft nose-up (ANU) electric trim. According to DFDR data, about 5 seconds after the completion of the pilot trim input, another automatic AND stabilizer trim input occurred. The crew applied ANU electric trim again. DFDR data then showed that the flaps were extended for almost 2 minutes. However, the flaps were then fully retracted, and automatic AND stabilizer trim inputs occurred more than 20 times over the next 6 minutes; the crew countered each input during this time using ANU electric trim. The last few automatic AND stabilizer trim inputs were not fully countered by the crew.

During the preceding Lion Air flight on the accident airplane with a different flight crew, the DFDR recorded the same difference between left and right AOA of about 20° that continued until the end of the recording. During rotation, the left control column stick shaker activated and continued for the entire flight, and DFDR data showed that the left airspeed and altitude values disagreed with, and were lower than, the corresponding values from the right. After the flaps were fully retracted, a 10-second automatic AND stabilizer trim input occurred, and the crew countered the input with an ANU electric trim input. After several automatic AND stabilizer trim inputs that were countered by pilot-commanded ANU electric trim

¹(a) We based our preliminary findings on information from the publicly released preliminary accident reports. (b) While Boeing uses the term "uncommanded MCAS function" in its assessment documents, in this report, we are using the term "unintended MCAS operation" as it relates to our review of the accident events.

²Information in this section is taken from the preliminary report on this accident, which can be found at https://reports.aviation-safety.net/2018/20181029-0_B38M_PK-LQP_PRELIMINARY.pdf.

inputs, the crew noticed that the airplane was automatically trimming AND. The captain moved the stabilizer trim cutout (STAB TRIM CUTOUT) switches to CUTOUT.³ He then moved them back to NORMAL, and the problem almost immediately reappeared. He moved the switches back to CUTOUT. He stated that the crew performed three non-normal checklists: Airspeed Unreliable, ALT DISAGREE (altitude disagree), and Runaway Stabilizer. The pilots continued the flight using manual trim until the end of the flight. Upon landing, the captain informed an engineer of IAS DISAGREE (indicated airspeed disagree) and ALT DISAGREE alerts, in addition to FEEL DIFF PRESS (feel differential pressure) light problems on the airplane.

On March 10, 2019, Ethiopian Airlines flight 302, a Boeing 737 MAX 8, Ethiopian registration ET-AVJ, crashed near Ejere, Ethiopia, shortly after takeoff from Addis Ababa Bole International Airport, Ethiopia. The flight was a scheduled international passenger flight from Addis Ababa to Jomo Kenyatta International Airport, Nairobi, Kenya. All 157 passengers and crew on board died, and the airplane was destroyed. The investigation is being led by the Ethiopia Accident Investigation Bureau.⁴

The airplane's DFDR data indicated that shortly after liftoff, the left (captain's) AOA sensor data increased rapidly to 74.5° and was 59.2° higher than the right AOA sensor; the captain's stick shaker activated. Concurrently, the airspeed and altitude values on the left side disagreed with, and were lower than, the corresponding values on the right side; in addition, DFDR data indicated a Master Caution alert. Similar to the Lion Air accident flight, a 9-second automatic AND stabilizer trim input occurred after flaps were retracted and while in manual flight (no autopilot). About 3 seconds after the AND stabilizer motion ended, using the stabilizer trim switches, the captain, who was the pilot flying, partially countered the AND stabilizer input by applying ANU electric trim. About 5 seconds after the completion of pilot trim input, another automatic AND stabilizer trim input occurred. The captain applied ANU electric trim and fully countered the second automatic AND stabilizer input; however, the airplane was not returned to a fully trimmed condition. Cockpit voice recorder data indicated that the flight crew then discussed the STAB TRIM CUTOUT switches, and shortly thereafter DFDR data were consistent with the STAB TRIM CUTOUT switches being moved to CUTOUT.

However, because the airplane remained in a nose-down out-of-trim condition, the crew was required to continue applying nose-up force to the control column to maintain level flight. About 32 seconds before impact, two momentary pilot-commanded electric ANU trim inputs and corresponding stabilizer movement were recorded, consistent with the STAB TRIM CUTOUT switches no longer being in CUTOUT. Five seconds after these short electric trim inputs, another automatic AND stabilizer trim input occurred, and the airplane began pitching nose down.

Design Certification of the 737 MAX 8 and Safety Assessment of the MCAS

The 737 MAX 8 is a derivative of the 737-800 Next Generation (NG) model and is part of the 737 MAX family (737 MAX 7, 8, and 9).⁵ The 737 MAX incorporated the CFM LEAP-1B engine, which has a larger fan diameter and redesigned engine nacelle compared to engines installed on the 737 NG family. During the preliminary design stage of the 737 MAX, Boeing testing and analysis revealed that the addition of the LEAP-1B engine and associated nacelle changes produced an ANU pitching moment when the airplane was operating at high AOA and mid Mach numbers. After studying various options for addressing this issue, Boeing implemented aerodynamic changes as well as a stability augmentation function, MCAS, as an extension of the existing speed trim system to improve aircraft handling characteristics and decrease pitch-up tendency at elevated AOA. As the development of the 737 MAX progressed, the MCAS function was expanded to low Mach numbers.

As originally delivered, the MCAS became active during manual flight (autopilot not engaged) when the flaps were fully retracted and the airplane's AOA value (as measured by either AOA sensor) exceeded a threshold based on Mach number. When activated, the MCAS provided automatic trim commands to move the stabilizer AND. Once the AOA fell below the threshold, the MCAS would move the stabilizer ANU to the original position. At any time, the stabilizer inputs could be

³Two STAB TRIM CUTOUT switches on the control stand can be used to stop the flight crew electric and autopilot trim inputs to the stabilizer trim actuator. The switches can be set to NORMAL or CUTOUT. If the switches are moved to CUTOUT, both the electric and autopilot trim inputs are disconnected from the stabilizer trim motor. NORMAL is the default position to enable operation of the electric and autopilot trim.

⁴Information in this section is taken from the preliminary report on this accident, which can be found at <http://www.ecaa.gov.et/Home/wp-content/uploads/2019/07/Preliminary-Report-737-800MAX-ET-AVJ.pdf>.

⁵The 737-600, -700, and -800 airplanes are part of the 737 NG family.

stopped or reversed by the pilots using their stabilizer trim switches. If the stabilizer trim switches were used by the pilots and the elevated AOA condition persisted, the MCAS would command another stabilizer AND trim input after 5 seconds.

The FAA's procedures for aircraft type certification require an aircraft manufacturer ("applicant") to demonstrate that its design complies with all applicable FAA regulations and requirements.⁶ For transport-category airplanes, as part of this process, applicants must demonstrate through analysis, test, or both that their design meets the applicable requirements under Title 14 *Code of Federal Regulations* (CFR) Part 25. Specifically, 14 CFR 25.671 and 25.672 define the requirements for control systems in general and stability augmentation and automatic and power-operated systems, respectively. Title 14 CFR 25.1322 addresses flight crew alerting and states, in part, that flight crew alerts must

- (1) Provide the flightcrew with the information needed to:
 - (i) Identify non-normal operation or airplane system conditions, and
 - (ii) Determine the appropriate actions, if any.
- (2) Be readily and easily detectable and intelligible by the flightcrew under all foreseeable operating conditions, including conditions where multiple alerts are provided.

Advisory Circular (AC) 25.1322-1, "Flightcrew Alerting," provides guidance for showing compliance with requirements for the design approval of flight crew alerting functions and indicates that "Appropriate flightcrew corrective actions are normally defined by airplane procedures (for example, in checklists) and are part of a flightcrew training curriculum or considered basic airmanship." Title 14 CFR 25.1309 relates to aircraft equipment, systems, and installations, and the primary means of compliance with this section for systems that are critical to safe flight and operations is through safety assessments or through rational analyses; AC 25.1309-1A, "System Design and Analysis," provides guidance for showing compliance with Title 14 CFR 25.1309(b), (c), and (d).⁷ AC 25.1309-1A explains the FAA's fail-safe design concept, which "considers the effects of failures and combinations of failures in defining a safe design." As part of demonstrating 737 MAX 8 compliance with the requirements in 14 CFR 25.1309, Boeing conducted a number of airplane-and system-level safety assessments, consistent with the guidance provided in AC 25.1309-1A.⁸

The NTSB reviewed sections of Boeing's system safety analysis for stabilizer trim control that pertained to MCAS on the 737 MAX. Boeing's analysis included a summary of the functional hazard assessment findings for the 737 MAX stabilizer trim control system. For the normal flight envelope, Boeing identified and classified two hazards associated with "uncommanded MCAS" activation as "major."⁹ One of these hazards, applicable to the MCAS function seen in these accidents, included uncommanded MCAS operation to maximum authority.¹⁰ Boeing indicated that, as part of the functional hazard assessment development, pilot assessments of MCAS-related hazards were conducted in an engineering flight simulator, including the

⁶Title 14 *Code of Federal Regulations* Part 21 defines the procedures for certification.

⁷Safety assessments are performed by the manufacturer and its suppliers and are reviewed and accepted by the FAA. Safety assessments proceed in a stepwise, data-driven manner to ensure that all significant single-failure conditions have been identified and all combinations of failures that could lead to hazardous or catastrophic airplane-level effects have been considered and appropriately mitigated. When a safety assessment cannot be performed on a new or complex system, a rational analysis may be performed to estimate quantitative probabilities and supplement qualitative analyses and tests. The safety assessment process outlined in AC 25.1309-1A is not mandatory, but manufacturers that do not conduct safety assessments must demonstrate compliance in another manner, such as ground or flight tests.

⁸Safety assessments can include the development of airplane-and system-level functional hazard assessments (to identify and classify potentially hazardous failure conditions), failure modes and effects analyses (a structured bottom-up analysis that evaluates the effects of each possible failure), and fault tree analyses (a structured top-down analysis to identify the conditions, failures, and events that would cause a failure condition).

⁹The "major" classification used by Boeing indicated a remote probability of this hazard occurring and that it could result in reduced control capability, reduced system redundancy, or increased crew workload. Other classification categories included "minor," "hazardous," and "catastrophic."

¹⁰In March 2016, Boeing determined that MCAS should be revised to improve flaps up, low Mach stall characteristics and identification. The preliminary hazard assessments of MCAS were re-evaluated after this change by pilot evaluation in the motion simulator and determined to have not changed the hazard classification.

uncommanded MCAS operation (stabilizer runaway) to the MCAS maximum authority.

To perform these simulator tests, Boeing induced a stabilizer trim input that would simulate the stabilizer moving at a rate and duration consistent with the MCAS function. Using this method to induce the hazard resulted in the following: motion of the stabilizer trim wheel, increased column forces, and indication that the airplane was moving nose down. Boeing indicated to the NTSB that this evaluation was focused on the pilot response to uncommanded MCAS operation, regardless of underlying cause. Thus, the specific failure modes that could lead to uncommanded MCAS activation (such as an erroneous high AOA input to the MCAS) were not simulated as part of these functional hazard assessment validation tests. As a result, additional flight deck effects (such as IAS DISAGREE and ALT DISAGREE alerts and stick shaker activation) resulting from the same underlying failure (for example, erroneous AOA) were not simulated and were not in the stabilizer trim safety assessment report reviewed by the NTSB.

Boeing indicated to the NTSB that, based on FAA guidance, it used assumptions during its safety assessment of MCAS hazards in the engineering flight simulator. Four of these assumptions were the following:

- Uncommanded system inputs are readily recognizable and can be counteracted by overriding the failure by movement of the flight controls “in the normal sense” by the flight crew and do not require specific procedures.¹¹
- Action to counter the failure shall not require exceptional piloting skill or strength.
- The pilot will take immediate action to reduce or eliminate increased control forces by re-trimming or changing configuration or flight conditions.
- Trained flight crew memory procedures shall be followed to address and eliminate or mitigate the failure.

Boeing advised that these assumptions are used across all Boeing models when performing functional hazard assessments of flight control systems. These assumptions were consistent with requirements in 14 *CFR* 25.671 and 25.672 and guidance in AC 25-7C, “Flight Test Guide for Certification of Transport Category Airplanes.”¹² AC 25-7C stated that short-term forces are the initial stabilized control forces that result from maintaining the intended flightpath after configuration changes and normal transitions from one flight condition to another, “*or from regaining control following a failure. It is assumed that the pilot will take immediate action to reduce or eliminate such forces by re-trimming or changing configuration or flight conditions, and consequently short-term forces are not considered to exist for any significant duration* [emphasis added].” In a 2019 presentation to the NTSB, Boeing indicated that the MCAS hazard classification of “major” for uncommanded MCAS function in the normal flight envelope was based on the following conclusions:

- Unintended stabilizer trim inputs are readily recognized by movement of the stabilizer trim wheel, flightpath change, or increased column forces.
- Aircraft can be returned to steady level flight using available column (elevator) alone or stabilizer trim.
- Continuous unintended nose-down stabilizer trim inputs would be recognized as a stabilizer trim or stabilizer runaway failure and the procedure for stabilizer runaway would be followed.¹³

¹¹Title 14 *CFR* 25.672 states the following: “The design of the stability augmentation system or of any other automatic or power-operated system must permit initial counteraction of failures of the type specified in § 25.671(c) without requiring exceptional pilot skill or strength, by either the deactivation of the system, or a failed portion thereof, or by overriding the failure by movement of the flight controls in the normal sense.”

¹²On October 16, 2012, the FAA released AC 25-7C, which revised version B to reduce the number of differences from the European Aviation Safety Agency’s Flight Test Guide; provide acceptable means of compliance for the regulatory changes associated with amendments 107, 109, 113, 115, 119, and 123 to 14 *CFR* Part 25; respond to NTSB recommendations; and provide a general update to reflect current FAA and industry practices and policies. AC 25-7C was in effect at the time of Boeing’s safety assessments of the 737 MAX. On May 4, 2018, the FAA released AC 25-7D to clarify several paragraphs, revise an appendix, and improve usability with formatting changes.

¹³The runaway stabilizer procedure includes holding the control column firmly, disengaging the autopilot and autothrottles (if engaged), setting the STAB TRIM CUTOFF switches to CUTOFF, and trimming the airplane manually.

Assumptions about Pilot Recognition and Response in the Safety Assessment

Functional hazard assessments at the aircraft and systems levels are a critical part of the design certification process because the resulting hazard classifications (severity level) drive the safety requirements for equipment design, flight crew procedures, and training to ensure the hazard effects are sufficiently mitigated. On the basis of Boeing's functional hazard assessment for the MCAS, which assumed timely pilot response to uncommanded MCAS-generated trim input, uncommanded MCAS activation was classified as "major." Boeing was then required to verify that each system that supported MCAS complied with the quantitative and qualitative safety requirements for a "major" hazard, as provided in AC 25.1309-1A, and demonstrate this to the FAA in its aircraft and system safety assessments.

On the Lion Air flight immediately before the accident flight and the Lion Air and Ethiopian Airlines accident flights, the DFDR recorded higher AOA sensor data on the left side than on the right (about 20° higher on the previous Lion Air flight and the Lion Air accident flight and about 59° higher on the Ethiopian Airlines accident flight). As previously stated, the MCAS becomes active when the airplane's AOA exceeds a certain threshold. Thus, these erroneous AOA sensor inputs resulted in the MCAS activating on the accident flights and providing the automatic AND stabilizer trim inputs. The erroneous high AOA sensor input that caused the MCAS activation also caused several other alerts and indications for the flight crews. The stick shaker activated on both accident flights and the previous Lion Air flight. In addition, IAS DISAGREE and ALT DISAGREE alerts occurred on all three flights. Also, the Ethiopian Airlines flight crew received a Master Caution alert. Further, after the flaps were fully retracted, the unintended AND stabilizer inputs required the pilots to apply additional force to the columns to maintain the airplane's climb attitude.

Multiple alerts and indications can increase pilots' workload, and the combination of the alerts and indications did not trigger the accident pilots to immediately perform the runaway stabilizer procedure during the initial automatic AND stabilizer trim input. In all three flights, the pilot responses differed and did not match the assumptions of pilot responses to unintended MCAS operation on which Boeing based its hazard classifications within the safety assessment and that the FAA approved and used to ensure the design safely accommodates failures. Although a number of factors, including system design, training, operation, and the pilots' previous experiences, can affect a human's ability to recognize and take immediate, appropriate corrective actions for failure conditions, industry experts generally recognize that an aircraft system should be designed such that the consequences of any human error are limited.¹⁴ Further, a report on a joint FAA-industry study published in 2002, *Commercial Airplane Certification Process Study: An Evaluation of Selected Aircraft Certification, Operations, and Maintenance Processes*, noted that human performance was still the dominant factor in accidents and highlighted that the industry challenge is to develop airplanes and procedures that are less likely to result in operator error and that are more tolerant of operator errors when they do occur, in particular errors involving incorrect response after a malfunction.¹⁵

Consistent with this philosophy, the NTSB notes that FAA certification guidance in AC 25.1309-1A that allows manufacturers to assume pilots will respond to failure conditions appropriately is based, in part, upon the applicant showing that the systems, controls, and associated monitoring and warnings are designed to minimize crew errors, which could create additional hazards.¹⁶ While Boeing considered the possibility of uncommanded MCAS operation as part of its functional hazard assessment, it did not evaluate all the potential alerts and indications that could accom-

¹⁴(a) Yeh, Michelle, Cathy Swider, Young Jin Jo, and Colleen Donovan. 2016. *Human Factors Considerations in the Design and Evaluation of Flight Deck Displays and Controls*. Version 2.0, Final Report—December 2016, DOT/FAA/TC-16/56. pp. 248–249. (b) The FAA's *Pilot's Handbook of Aeronautical Knowledge*, FAA-H-8083-25B, Chapter 2, page 2–12, states, "Historically, the term 'pilot error' has been used to describe an accident in which an action or decision made by the pilot was the cause or a contributing factor that led to the accident. This definition also includes the pilot's failure to make a correct decision or take proper action."

¹⁵The industry study team included representatives from manufacturers, airlines, pilot labor organizations, and other aviation stakeholders. See *Commercial Airplane Certification Process Study: An Evaluation of Selected Aircraft Certification, Operations, and Maintenance Processes*. March 2002. The Report of the FAA Associate Administrator for Regulation and Certification's Study on the Commercial Airplane Certification Process.

¹⁶Title 14 *CFR* 25.1309(c) states, "Warning information must be provided to alert the crew to unsafe system operating conditions, and to enable them to take appropriate corrective action. Systems, controls, and associated monitoring and warning means must be designed to minimize crew errors which could create additional hazards."

pany a failure that also resulted in uncommanded MCAS operation. Therefore, neither Boeing's system safety assessment nor its simulator tests evaluated how the combined effect of alerts and indications might impact pilots' recognition of which procedure(s) to prioritize in responding to an unintended MCAS operation caused by an erroneous AOA input.¹⁷ The NTSB is concerned that, if manufacturers assume correct pilot response without comprehensively examining all possible flight deck alerts and indications that may occur for system and component failures that contribute to a given hazard, the hazard classification and resulting system design (including alerts and indications), procedural, and/or training mitigations may not adequately consider and account for the potential for pilots to take actions that are inconsistent with manufacturer assumptions.

Thus, the NTSB concludes that the assumptions that Boeing used in its functional hazard assessment of uncommanded MCAS function for the 737 MAX did not adequately consider and account for the impact that multiple flight deck alerts and indications could have on pilots' responses to the hazard. Therefore, the NTSB recommends that the FAA require that Boeing (1) ensure that system safety assessments for the 737 MAX in which it assumed immediate and appropriate pilot corrective actions in response to uncommanded flight control inputs, from systems such as MCAS, consider the effect of all possible flight deck alerts and indications on pilot recognition and response; and (2) incorporate design enhancements (including flight deck alerts and indications), pilot procedures, and/or training requirements, where needed, to minimize the potential for and safety impact of pilot actions that are inconsistent with manufacturer assumptions.

Further, because FAA guidance allows such assumptions to be made in transport-category airplane certification analyses without providing applicants with clear direction concerning the consideration of multiple flight deck alerts and indications in evaluating pilot recognition and response, the NTSB is concerned that similar assumptions and procedures for their validation may have also been used in the development of flight control system safety assessments for other airplanes. Therefore, the NTSB recommends that the FAA require that for all other U.S. type-certificated transport-category airplanes, manufacturers (1) ensure that system safety assessments for which they assumed immediate and appropriate pilot corrective actions in response to uncommanded flight control inputs consider the effect of all possible flight deck alerts and indications on pilot recognition and response; and (2) incorporate design enhancements (including flight deck alerts and indications), pilot procedures, and/or training requirements, where needed, to minimize the potential for and safety impact of pilot actions that are inconsistent with manufacturer assumptions.

Because the FAA routinely harmonizes related standards and guidance with other international regulators who type certificate transport-category airplanes, the NTSB notes that those airplanes may have been designed using similar standards and therefore may also be impacted by this vulnerability. Therefore, the NTSB also recommends that the FAA notify other international regulators that certify transport-category airplane type designs (for example, the European Union Aviation Safety Agency [EASA], Transport Canada, the National Civil Aviation Agency-Brazil, the Civil Aviation Administration of China, and the Russian Federal Air Transport Agency) of Recommendation A-19-11 and encourage them to evaluate its relevance to their processes and address any changes, if applicable.

As early as 2002, the joint FAA-industry study recognized that, while excellent guidance existed for manufacturers on various topics salient to the development of system safety assessments, there were no methods available to evaluate the probability of human error in the operation of a particular system design and that existing qualitative methods for assessing human error were not "very satisfactory." The 2002 study went on to state that the processes used to determine and validate human responses to failure and methods to include human responses in safety assessments needed to be improved.¹⁸ The NTSB notes that a number of human performance research studies have been conducted in the years since the certification guidance contained in AC 25.1309-1A was put in place (in 1988) and this study was conducted and it is likely that more rigorous, validated methodologies exist today to assess error tolerance with regard to pilot recognition and response to failure con-

¹⁷Per Title 14 *CFR* 25.1309(d)(4), compliance demonstration as part of aircraft certification must include analysis that considers the crew warning cues, corrective action required, and the capability of detecting faults.

¹⁸*Commercial Airplane Certification Process Study: An Evaluation of Selected Aircraft Certification, Operations, and Maintenance Processes*. March 2002. The Report of the FAA Associate Administrator for Regulation and Certification's Study on the Commercial Airplane Certification Process.

ditions. The NTSB also believes that the use of validated methods and tools to assess pilot performance in dealing with failure conditions and emergencies would result in more effective requirements for flight deck interface design, pilot procedures, and training strategies. However, we are concerned that such tools and methods are still not commonplace or required as part of the design certification process for functions such as MCAS on newly certified type designs.

Thus, the NTSB concludes that a standardized methodology and/or tools for manufacturers' use in evaluating and validating assumptions about pilot recognition and response to failure condition(s), particularly those conditions that result in multiple flight deck alerts and indications, would help ensure that system designs adequately and consistently minimize the potential for pilot actions that are inconsistent with manufacturer assumptions. Therefore, the NTSB recommends that the FAA develop robust tools and methods, with the input of industry and human factors experts, for use in validating assumptions about pilot recognition and response to safety-significant failure conditions as part of the design certification process. Further, the NTSB recommends that once the tools and methods have been developed as recommended in Recommendation A-19-13, the FAA revise existing FAA regulations and guidance to incorporate their use and documentation as part of the design certification process, including re-examining the validity of pilot recognition and response assumptions permitted in existing FAA guidance.

System Diagnostic Tools

As previously discussed, Title 14 *CFR* 25.1322 addresses flight crew alerting and states, in part, that flight crew alerts must

- (1) Provide the flightcrew with the information needed to:
 - (i) Identify non-normal operation or airplane system conditions, and
 - (ii) Determine the appropriate actions, if any.
- (2) Be readily and easily detectable and intelligible by the flightcrew under all foreseeable operating conditions, including conditions where multiple alerts are provided.

Multiple alerts and indications in the cockpit can increase pilots' workload and can also make it more difficult to identify which procedure the pilots should conduct. The NTSB notes that the Lion Air and Ethiopian Airlines accident pilots' responses to multiple alerts and indications are similar to the circumstances of a 2009 accident involving Air France flight 447, an Airbus A330, which was traveling from Rio de Janeiro to Paris when it crashed in the Atlantic Ocean.¹⁹ In its accident report, the Bureau d'Enquêtes et d'Analyses Pour la Sécurité de L'aviation Civile (BEA) concluded that failure messages successively displayed on the electronic centralized aircraft monitoring system did not allow the crew to rapidly and effectively diagnose the issue (the blockage of the pitot probes) or make the connection between the messages that appeared and the procedure to use. Accordingly, the BEA recommended that EASA "study the relevance of having a dedicated warning provided to the crew when specific monitoring is triggered, in order to facilitate comprehension of the situation."²⁰

Human factors research has identified that, for non-normal conditions, such as those involving a system failure with multiple alerts, where there may be multiple flight crew actions required, providing pilots with understanding as to which actions must take priority is a critical need.²¹ This is particularly true in the case of functions implemented across multiple airplane systems because a failure in one system within highly integrated system architectures can present multiple alerts and indications to the flight crew as each interfacing system registers the failure. For example, the erroneous AOA output experienced during the two accident flights resulted in multiple alerts and indications to the flight crews, yet the crews lacked tools to identify the most effective response.²² Thus, it is important that system interactions

¹⁹Bureau d'Enquêtes et d'Analyses Pour la Sécurité de L'aviation Civile. 2012. Final Report, *On the accident on 1st June 2009 to the Airbus A330-203, registered F-GZCP, operated by Air France, flight AF 447, Rio de Janeiro—Paris.*

²⁰The response to this recommendation, FRAN-2012-049, was classified as "partially adequate," and the recommendation was closed as of February 2, 2019.

²¹See (a) Mumaw, Randall J. 2017. "Analysis of Alerting System Failures in Commercial Aviation Accidents." Proceedings of the Human Factors and Ergonomics Society 2017 Annual Meeting; and (b) Burian, Barbara K., Immanuel Barshi, and Key Dismukes. 2005. *The Challenge of Aviation Emergency and Abnormal Situations* NASA/TM—2005-213462. NASA Scientific and Technical Information Program Office, Washington, DC.

²²After the Lion Air accident, on November 7, 2018, the FAA issued emergency Airworthiness Directive 2018-23-51, revising the Boeing 737 MAX Airplane Flight Manual (AFM) to expand

and the flight deck interface be designed to help direct pilots to the highest priority action(s).

Research demonstrates that emergency situations increase workload and require additional effort to manage effectively because of the stress involved and the lack of opportunity for pilots to practice these skills compared to those used in normal operations.²³ In addition, research into pilot responses to multiple/simultaneous anomalous situations, along with data from accidents, indicates that multiple competing alerts may exceed available mental resources and narrow attentional focus leading to delayed or inadequately prioritized responses.²⁴ According to FAA research, “in some airplanes, the complexity and variety of ancillary warnings and alerts associated with major system failures can make it difficult for the flightcrew to discern the primary failure.”²⁵ The researchers noted that better system failure diagnostic tools are needed to resolve this issue.

Thus, the NTSB concludes that aircraft systems that can more clearly and concisely inform pilots of the highest priority actions when multiple flight deck alerts and indications are present would minimize confusion and help pilots respond more effectively. Therefore, the NTSB recommends that the FAA develop design standards, with the input of industry and human factors experts, for aircraft system diagnostic tools that improve the prioritization and clarity of failure indications (direct and indirect) presented to pilots to improve the timeliness and effectiveness of their response. The NTSB further recommends that once the design standards have been developed as recommended in Recommendation A-19-15, the FAA require implementation of system diagnostic tools on transport-category aircraft to improve the timeliness and effectiveness of pilots’ response when multiple flight deck alerts and indications are present.

RECOMMENDATIONS

To the Federal Aviation Administration

Require that Boeing (1) ensure that system safety assessments for the 737 MAX in which it assumed immediate and appropriate pilot corrective actions in response to uncommanded flight control inputs, from systems such as the Maneuvering Characteristics Augmentation System, consider the effect of all possible flight deck alerts and indications on pilot recognition and response; and (2) incorporate design enhancements (including flight deck alerts and indications), pilot procedures, and/or training requirements, where needed, to minimize the potential for and safety impact of pilot actions that are inconsistent with manufacturer assumptions. (A-19-10)

Require that for all other U.S. type-certificated transport-category airplanes, manufacturers (1) ensure that system safety assessments for which they assumed immediate and appropriate pilot corrective actions in response to uncommanded flight control inputs consider the effect of all possible flight deck alerts and indications on pilot recognition and response; and (2) incorporate design enhancements (including flight deck alerts and indications), pilot procedures, and/or training requirements, where needed, to minimize the potential for and safety impact of pilot actions that are inconsistent with manufacturer assumptions. (A-19-11)

Notify other international regulators that certify transport-category airplane type designs (for example, the European Union Aviation Safety Agency, Transport Canada, the National Civil Aviation Agency-Brazil, the Civil Aviation Administration of China, and the Russian Federal Air Transport Agency) of Rec-

the existing runaway stabilizer procedure when erroneous AOA input is detected. This revision provided new details about the effects and indications a pilot might experience due to an erroneous AOA input, such as increasing nose-down control forces resulting from repeated AND stabilizer trim inputs. It also instructed pilots to perform the existing AFM runaway stabilizer procedure, emphasizing that the pilot set the STAB TRIM CUTOUT switches to CUTOUT and that the switches stay in the CUTOUT position for the remainder of the flight.

²³ Burian, Barbara K., Immanuel Barshi, and Key Dismukes. 2005. *The Challenge of Aviation Emergency and Abnormal Situations*. NASA/TM-2005-213462. NASA Scientific and Technical Information Program Office. Washington, DC.

²⁴ Burian, Barbara K., Immanuel Barshi, and Key Dismukes. 2005. *The Challenge of Aviation Emergency and Abnormal Situations*. NASA/TM-2005-213462. NASA Scientific and Technical Information Program Office. Washington, DC.

²⁵ Federal Aviation Administration. 1996. *Federal Aviation Administration Human Factors Team Report on: The Interfaces Between Flightcrews and Modern Flight Deck Systems*, June 18, 1996.

ommendation A-19-11 and encourage them to evaluate its relevance to their processes and address any changes, if applicable. (A-19-12)

Develop robust tools and methods, with the input of industry and human factors experts, for use in validating assumptions about pilot recognition and response to safety-significant failure conditions as part of the design certification process. (A-19-13)

Once the tools and methods have been developed as recommended in Recommendation A-19-13, revise existing Federal Aviation Administration (FAA) regulations and guidance to incorporate their use and documentation as part of the design certification process, including re-examining the validity of pilot recognition and response assumptions permitted in existing FAA guidance. (A-19-14)

Develop design standards, with the input of industry and human factors experts, for aircraft system diagnostic tools that improve the prioritization and clarity of failure indications (direct and indirect) presented to pilots to improve the timeliness and effectiveness of their response. (A-19-15)

Once the design standards have been developed as recommended in Recommendation A-19-15, require implementation of system diagnostic tools on transport-category aircraft to improve the timeliness and effectiveness of pilots' response when multiple flight deck alerts and indications are present. (A-19-16)

BY THE NATIONAL TRANSPORTATION SAFETY BOARD

ROBERT L. SUMWALT, III
Chairman

JENNIFER HOMENDY
Member

BRUCE LANDSBERG
Vice Chairman

Report Date: September 19, 2019

The CHAIRMAN. Thank you, Mr. Sumwalt. Mr. Hart, you are recognized.

**STATEMENT OF HON. CHRISTOPHER A. HART, CHAIRMAN,
JOINT AUTHORITIES TECHNICAL REVIEW (JATR)**

Mr. HART. Thank you, Chairman Wicker, Ranking Member Cantwell, and members of the Committee. Thank you for inviting me to this hearing today. First, I would like to extend my condolences, joining others who have already done so, to the families and friends of the passengers and crew on Lion Air flight 610 and Ethiopian Airlines flight 302.

The FAA created the Joint Authorities Technical Review because these crashes revealed a need to review the robustness of the aircraft certification process. The JATR, which included representatives from the FAA, NASA, and nine other civil aviation authorities was created to review the MAX certification process to determine whether the appropriate regulations were applied, to assess whether compliance with those regulations was shown, and to recommend improvements in the process.

I commend the FAA for seeking this certification process peer review and for making it public. The MAX grounding was unprecedented. Two previous groundings were the McDonnell Douglas DC-10 in 1979 when an engine separated from the wing, and the Boeing 787 in 2013 due to battery fires. In those two groundings, the airplanes were rendered unairworthy. Because the airplanes were unairworthy, pilot competence was not an issue. Because those groundings resulted solely from airplane problems, the country where the airplanes were manufactured made the grounding and ungrounding decisions.

The grounding of the MAX, on the other hand, involves automation that usually worked but sometimes failed, and when it failed, some pilots knew how to respond but some, including those who crashed, did not. Because the scenario was not just an airplane problem, but a problem of airplane system/pilot interaction, every country that licenses pilots must also be involved in the grounding and ungrounded decisions.

As automation complexity increases, I anticipate that future problems are more likely to be of the airplane/pilot type rather than airplane only. After three JATR meetings in Seattle in which Boeing and the FAA were very open and helpful, and extensive work between the meetings, the JATR gave the FAA on October 11 a compilation of team members' recommendations in 12 areas. Some of the recommendations derived from the need for the certification process to address how a single system failure may create issues in other systems.

Other recommendations raised the issue of whether a process that has been based largely upon compliance should also address safety. As systems become more complex, the likelihood increases that compliance with applicable regulations will not necessarily ensure safety. Moreover, as systems become more complex, the certification process should ensure that fail-safe design principles prioritize the mitigation of hazards through design, minimizing reliance on pilot action as primary means of risk mitigation. Delegation will probably become more prevalent as regulators encounter increasing difficulty hiring and retaining technology leaders.

Thus, although the recommendations do not address the desirability of delegation. They do recommend examining how to make the ODA process less cumbersome to avoid stifling communications. Query, for example, whether inadequate communications resulted in the failure to address the effects of evolving the Maneuvering Characteristics Augmentation System, MCAS, from a benign system to a more aggressive system. And query whether inadequate communications resulted in the failure to address the effects of modifying MCAS from one scenario to another scenario.

Other recommendations relate to the FAA standards regarding the time for pilots to identify and respond to problems. JATR members recommend reviewing whether existing standards are appropriate for today's complex systems. For example, when a system failure results in cascading failures and multiple alarms, query how adequately the certification process considers the impact of multiple alarms, along with possible startle effect, on the ability of pilots to respond appropriately. These two crashes are the latest of several recent crashes in which pilots encountered scenarios that they had never seen before, even in training, and responded inappropriately. Increasing complexity and reliability exacerbate the challenge of training pilots to respond to problems that they have never seen before.

Increasing complexity exacerbates the challenge because it reduces the likelihood that pilots understand the system. Increasing reliability exacerbates the challenge because it increases the difficulty of determining what types of problems might occur and then including those types of problems in training. In conclusion, the JATR members hope that their recommendations will continue im-

proving aviation safety by helping to improve the certification process.

Thank you again for inviting me and I look forward to your questions.

[The prepared statement of Mr. Hart follows:]

PREPARED STATEMENT OF HON. CHRISTOPHER A. HART, CHAIRMAN,
JOINT AUTHORITIES TECHNICAL REVIEW (JATR)

Introduction. Chairman Wicker, Ranking Member Cantwell, and Members of the Committee, thank you for the opportunity to be here today in my capacity as Chairman of the Joint Authorities Technical Review (JATR) to discuss the JATR's efforts to improve aviation safety.

Before I begin, I would like to extend my sincerest condolences to the families and friends of the passengers and crew on Lion Air Flight JT610 that crashed a year ago today, on October 29, 2019, and on Ethiopian Airlines Flight ET302 that crashed less than five months later, on March 10, 2019.

The following describes the JATR and why it was created, discusses some of the recommendations that it submitted to the Federal Aviation Administration (FAA), and then briefly describes a training challenge that has come to light as a result of the JATR's efforts.

The JATR. The Boeing 737 MAX (MAX) Flight Control System Joint Authorities Technical Review, created by the FAA, had its kickoff meeting in late April/early May 2019, and its charter was signed and became official on June 1, 2019. It consisted of technical representatives from the FAA, the National Aeronautics and Space Administration (NASA), and civil aviation authorities from Australia, Brazil, Canada, China, Europe, Indonesia, Japan, Singapore, and the United Arab Emirates. The FAA intentionally did not include on the JATR team any of its staff who were involved in the MAX certification process.

I was asked to lead the JATR, in part because of my experience in aviation safety and accident investigation. I was at the National Transportation Safety Board for a total of 12 years, including as Chairman. I also have a regulatory perspective from 14 years at the FAA. To ensure a fully objective review, I was not compensated by the FAA for this role. I would also note that I am not a certification process expert, so I don't have the perspective of "this is how we have always done certification and we should keep it that way." I was honored to be asked to lead this important international aviation safety improvement effort.

Why the JATR. The FAA's aircraft certification process has played a major role in producing airliners with an exemplary safety record. Nonetheless, as with any system that is designed and operated by humans, the certification process can never be perfect, and the two tragic MAX crashes noted above revealed a critical need to review the process to determine whether improvement and modernization are warranted. The JATR was created to conduct that review and make improvement recommendations as warranted. The JATR completed its review on October 11, 2019, when it gave its compilation of team members' recommendations (not necessarily with consensus, as noted below) to the FAA.

The JATR was not chartered to become involved in returning the MAX to service, nor was it chartered to become involved in the two accident investigations. Moreover, the JATR was not created to determine fault or blame in the certification process, but to consider whether the appropriate regulations and policy were applied to the MAX; to assess whether compliance was shown with the applicable requirements related to the flight control system; and to recommend improvements to the certification process.

The JATR was unprecedented in that it was the first time an aviation safety regulator has voluntarily called for what is essentially an international peer review of its certification process, and then made that peer review public. The FAA's willingness to use such a process to improve safety, and doing so with such transparency, are indicative of the safety culture that permeates the commercial aviation industry that has produced such an exemplary airline safety record.

Unprecedented Groundings. The grounding of the MAX was also unprecedented and placed the worldwide aviation industry in uncharted territory. The other two airliner groundings by the FAA in the last 40 years were the McDonnell Douglas DC-10 in 1979, after an engine separated from the wing shortly after takeoff; and the Boeing 787 in 2013, due to lithium-ion battery thermal runaways and fires. In those two groundings, the airplanes were rendered unairworthy by mechanical malfunctions.

Because the airplanes were unairworthy, the problem was solely an airplane problem and pilot competence was not an issue. Because those groundings resulted entirely from airplane problems, the primary country that decided when to ground the airplanes and when to return them to service was the country where the airplanes were manufactured—in those two instances, the U.S.

The MAX grounding, on the other hand, involved automation that usually worked but sometimes failed; and when it failed, some pilots knew how to handle the failure (including the pilots on the Lion Air MAX the day before it crashed) but some did not, even after the additional attention to the issue that resulted from the Lion Air crash; and among those who did not know how to handle the failure were those who crashed. Hence, the scenario was not just an airplane problem, but a problem of the interaction between the airplane systems and its pilots. Thus, not only the country where the airplane is manufactured, but also every country that licenses and trains pilots must be involved in the decisions to ground and to return to service.

My expectation is that the international aviation community will be challenged to figure out how to handle this new scenario because future airliner problems are more likely to be of the airplane-pilot interaction type and less likely to be of the airplane-only type. The JATR was a first step in figuring out how the certification process can best address what may be a new normal.

Hence, I commend the FAA's inclusion in the JATR of representatives from nine other civil aviation authorities because this is not just an FAA certification process issue but a worldwide certification process issue. Because most of the aviation authorities in the JATR also certify aviation products, this was an opportunity for the certifying countries to begin working together to determine how best to navigate this uncharted territory. Moreover, all of the aviation authorities in the JATR are involved in the licensing and training of pilots.

The JATR process. The JATR met three times in Seattle, starting with the kickoff meeting in the Spring in Seattle (noted above) for initial briefings from Boeing and the FAA. At that first meeting the JATR was divided into seven subgroups, with the following focus areas:

- A: Applied Regulations and Policy
- B: Compliance with applicable portions of 14 CFR part 25, subparts B (Flight) and G (Operating Limitations and Information)
- C: Compliance with applicable portions of 14 CFR part 25, subparts D (Design and Construction) and F (Equipment)
- D: Boeing Systems Engineering Practices
- E: Organization Designation Authorization (ODA)
- F: Operational Suitability, Maintenance, and Training
- G: Preliminary Accident Information

In mid-Summer the JATR had an intensive follow-up meeting in Seattle with Boeing and FAA personnel, including an extensive review of various certification documents.

Writing the observations, findings, and recommendations commenced after the second meeting, and later in the summer the JATR met again in Seattle to consider the document as a whole as it was shaping up. Boeing and the FAA were very open and helpful to the JATR team in these meetings and in general throughout our review. We also received notable support from a number of FAA aircraft certification, evaluation, and oversight personnel throughout the process. As the document was being finalized, the JATR gave Boeing and the FAA an opportunity to review objective information assembled by the team for the purpose of ensuring the factual accuracy of the information on which the JATR team members based their observations, findings, and recommendations. After several iterations, the JATR submitted its final observations, findings, and compilation of team members' recommendations to the FAA on October 11, 2019.

The Recommendations. The JATR submitted recommendations in eleven areas involving the certification process, and one post-certification area. In order to encourage diversity of views from the team, the JATR's charter encouraged its members to provide recommendations irrespective of whether they reflected consensus. Consequently, the JATR did not check or measure consensus.

The initial scope of the JATR process was limited to the certification process itself, but the charter enabled the co-chairs, in their discretion, to expand the scope if warranted. Hence, one recommendation area pertains to post-certification activities because of its potential to help improve the safety of future certification processes.

In no particular order of priority, the eleven recommendation areas regarding the certification process are:

1. Changed Product Rule
2. Development and use of up-to-date requirements and practices
3. Consistent interpretation and application of requirements
4. Changes during the certification process
5. Delegation of certification authority
6. Holistic, integrated aircraft-level approach
7. Human factors
8. Development assurance
9. Impact of product design changes on certification
10. Impact of product design changes on flightcrew training
11. Impact of product design changes on maintenance training

The post-certification recommendation area is:

12. Post-certification corrective actions and data sharing

Some of the recommendations are very broad in their application and others are more specific.

Broad Recommendations. Some of the broader recommendations derive from the increasing complexity of aircraft systems, particularly automated systems and the interaction and interrelationship between systems. As aircraft systems become more complex, ensuring that the certification process adequately addresses potential operational and safety ramifications for the entire aircraft that may be caused by the failure or inappropriate operation of any system on the aircraft becomes not only more important, but also more difficult.

Other broader recommendations raise the foundational issue of whether a process that has historically served the industry well for decades based largely upon compliance needs to be revisited to address not only compliance but also safety. As systems become more complex and may interact in unforeseeable ways, the likelihood increases that regulations and standards will not address every conceivable scenario. To the extent they do not address every scenario, compliance with every applicable regulation and standard does not necessarily ensure safety.

Moreover, as systems become more complex, the certification process should ensure that aircraft incorporate fail-safe design principles that prioritize the elimination or mitigation of hazards through design, minimizing reliance on pilot action as primary means of risk mitigation.

Specific Recommendations. Some form of delegation will probably become increasingly necessary as the FAA and aviation regulators worldwide encounter increasing difficulty hiring and retaining leading technologists in rapidly advancing technologies. Thus, although the recommendations do not address the desirability of delegation in general or of the ODA concept in particular, they do recommend examining how to make the ODA process less cumbersome and bureaucratic to avoid stifling adequate communications in future certification processes about important characteristics of what is being certificated.

Query, for example, whether inadequate communications were partly responsible for the failure to address potential unintended consequences from the evolution of the Maneuvering Characteristics Augmentation System (MCAS) from a relatively benign system to a much more aggressive system; and query whether inadequate communications played a role in the failure to address potential unintended consequences that can result from designing software for one scenario—in this case, high-speed windup turns—and then modifying the software for a different scenario—in this case reducing the pitch-up tendency at higher angles of attack at low speeds.

Other specific recommendations relate to revisiting the FAA's standards regarding the time needed by pilots to identify and respond to problems. Although existing standards have served the industry well for decades, the JATR members recommended an examination of whether those standards remain appropriate for the complex integrated systems in today's airplanes. For example, when the failure or inappropriate operation of a system results in cascading failures and multiple alarms, query how adequately the certification process considers the impact of multiple alarms, along with possible startle effect, on the ability of pilots to respond appropriately. Inherent in this issue is the adequacy of training to help pilots be able to respond effectively to failures that they may never have encountered before, not even in training.

The Future Training Challenge. The closer automation comes to completely removing the human, the more daunting are the challenges of becoming more automated. One of those challenges was highlighted by these two MAX crashes. These crashes were the latest of several crashes in the previous decade in which pilots encountered scenarios that they had never seen before, even in training, and responded inappropriately.

The increasing complexity and reliability of automation will exacerbate the international aviation community's challenge of training pilots to respond to problems that they have never seen before. Increasing complexity will exacerbate the training challenge because it will reduce the likelihood that pilots will fully understand the system's capabilities and what it does and does not do. Increasing reliability is obviously good, but an unintended consequence is that it will exacerbate the training challenge because it increases the difficulty of forecasting what types of failures might occur, which in turn decreases the likelihood of including the most important potential failure modes in training.

This issue is not within the scope of the JATR's charter because it is not a certification issue, but it has been brought to light by the JATR's activities. Hopefully the international aviation community will follow the collaboration example reflected by the JATR and work together to address this training challenge.

Conclusion. The JATR members hope that their recommendations will continue improving aviation safety by helping to improve the certification process.

The CHAIRMAN. Thank you, gentlemen. Is the work complete regarding the MAX for either of your organizations? Mr. Sumwalt?

Mr. SUMWALT. Mr. Chairman, thank you for that question. We are continuing to go through scores and scores of design certification documents. If we need to make additional recommendations, we certainly will. So, to answer your question, our work is not completed.

The CHAIRMAN. And Mr. Hart?

Mr. HART. Our work is completed because we were chartered to review the situation and give recommendations to the FAA. We did that on October 11. That completed our work and thank you for asking.

The CHAIRMAN. So this particular JATR, Joint Authorities Technical Review, is over and disbanded?

Mr. HART. That is correct.

The CHAIRMAN. Alright. Let's talk about the time between the first crash and the second crash. It was evident after the Lion crash, that the MCAS system was not working correctly. Is that true, Mr. Sumwalt?

Mr. SUMWALT. Yes, sir. That is correct.

The CHAIRMAN. And Mr. Hart, there were many factors involved, but the dysfunction of the MCAS was central?

Mr. HART. That is correct.

The CHAIRMAN. OK. And at that point, what notice was sent out to other airlines and to the pilots to make it clear that the MCAS was the main problem?

Mr. SUMWALT. Mr. Chairman, as you are aware today is the 1-year anniversary of Lion Air. So, on October 29 was the crash. I believe it was October, or correction November the 7th when the FAA put out an airworthiness directive to require certain procedural modifications.

The CHAIRMAN. Was that a typical airworthiness directive or was it highlighted as an emergency airworthiness directive?

Mr. SUMWALT. I am not sure. Chris, do you know?

Mr. HART. Airworthiness directives pretty much by definition are considered an emergency. So I think this one was definitely one that is supposed to command the attention of the entire industry.

The CHAIRMAN. OK, Mr. Sumwalt is consulting with staff and it is fine if he supplements his answer, but this was a red flag sent out about the MAX and the MCAS part of it. Is that correct? Would either of you gentlemen quarrel that this was a red flag warning?

Mr. HART. It was an industry-wide warning that everybody who flies this airplane needs to know about, and so to that extent, yes.

The CHAIRMAN. OK. Well, is there a way that we could have made it more explicit? Was there something about this advisory that didn't get the job done, Mr. Hart?

Mr. HART. I am sorry, but I cannot speak for the FAA and their decision process on how to handle this. The decision process to have the airworthiness directives within days of the second crash was intentional to get the word out as quickly as possible. But I was not privy to the decisionmaking process.

The CHAIRMAN. No, but I am referring to the way it would typically have been received internationally and in the aviation industry. This would have been taken seriously and been given a heightened bit of attention, is that correct?

Mr. HART. That certainly is the purpose of an airworthiness directive, yes. How people responded to it, I do not have a good answer to that.

The CHAIRMAN. OK. Now did I hear you say, Mr. Hart, that some pilots reacted in one way which was sufficient, and some pilots did not for whatever reasons? If you could elaborate on what you were telling the Committee.

Mr. HART. Yes, thank you for that question. I was referring specifically to the fact that before the Lion Air crash, the day before that crash, that same problem was encountered, and the pilots responded to it appropriately.

The CHAIRMAN. Well, do you think that there was a failure at Lion Air to notify the other crews that a problem had occurred, it was resolved in this fashion, and we need to be mindful of that? Do you know if that was communicated between the flight that did land safely and the one the next day?

Mr. HART. Thank you for the question. Unfortunately, I do not know the details of who told what to whom, whether it was the mechanics, or the other pilots. I do not know the details of how that information about what happened the day before was transmitted to the to the subsequent pilots and subsequent mechanics.

The CHAIRMAN. Mr. Sumwalt, do you want to clarify anything that you have said based on some advice that you have been getting?

Mr. SUMWALT. Well, in fact, it was an emergency airworthiness directive that was issued by the FAA as Mr. Hart has indicated.

The CHAIRMAN. That is a term of art, an "emergency airworthiness directive?"

Mr. SUMWALT. That is correct. And that means that it does not allow for public comment. Oftentimes for normal airworthiness directive the FAA has to put it out for public comment unless it is an emergency airworthiness directive.

The CHAIRMAN. Is it fair for me to characterize that as a red flag?

Mr. SUMWALT. Well as Chris Hart indicated, it does indicate that there was something that needed immediate awareness within the aviation community.

The CHAIRMAN. Senator Cantwell.

Senator CANTWELL. Thank you, Mr. Chairman, and I thank the second panel for being here. Wish there was many people listening to this panel as the first because this is the hard work that we have to do in getting this right and moving forward. And I so much appreciate, Mr. Sumwalt, NTSB's recommendations and Mr. Hart, your committee's recommendations.

My colleagues and I, Senator Duckworth, Senator Blumenthal have already introduced legislation on the NTSB and other recommendations last week, and hopefully we will be able to move forward on those. You heard the discussion. I believe we are here for this issue about what happened in the cockpit and the level of distraction, which I think is the point, Mr. Sumwalt. At least two of the recommendations that we put in our legislation, that is your recommendation, that the FAA direct Boeing to have clearer corrective actions from uncommanded systems and that there be some sort of resolution that they have had in other planes to the cockpit situation so that we are not bombarding pilots. Also that they develop the same kind of assessment.

Now when I read the circulars, and I have read many, it is pretty clear to me that, you know, this already should have been done. I mean, it is pretty clear that you have talked about the effectiveness—when you submit a plan for a plane you have to submit this alert plan. So we will see, we will find out at some point what alert plan was submitted and what was reviewed.

But it is very clear that you have to have, you know, this effectiveness intended for human and machine integration, you know, people understanding the alerts, compatibility with other displays and warnings, ensuring that the system is telling the pilots what to do. So listen, I appreciate your recommendations and we are going to get them into law, trust me. The question becomes, what are we doing on top of something that isn't already clear here.

What is it that actually we are doing and helping people understand. What is it we are doing here to make this system safer? And the reason I ask this is because as I said in my opening statement, I actually believe this is the issue *de jure*. I think it is for automobile safety moving forward on more AVs and on airplanes. There is going to be more integration into the cockpit. So anytime you are taking over command of that plane with a response, we need to know, and we need to understand that functionality.

So what are these alert system requirements that were asking the FAA to do both for the MAX and for all planes? What is that really giving us that we do not currently have now in the statute?

Mr. SUMWALT. Thank you for the question, Senator Cantwell, and thank you for your leadership and your advocacy on this area. We issued these seven recommendations a month ago because we did identify holes in the design certification process. I would be glad to get into some of those holes in what those recommendations are, but I do not want to dominate your time. I defer to you.

Senator CANTWELL. Well, my question was, why do you think this is important because you actually do not think that the details are there?

Mr. SUMWALT. That is correct—the long and the short of it, woven throughout each of the seven recommendations is that we found that when pilots are faced with multiple alerts, they are not performing or reacting in the way that Boeing thought that they would react when they developed their design assumptions.

Senator CANTWELL. And what about safety management systems for aerospace manufacturers? What about that recommendation?

Mr. SUMWALT. The NTSB has found the benefits of safety management systems in many modes of transportation including aviation. We do not have specifically a recommendation for an SMS for the manufacturers. However, we do believe that when you are properly analyzing and assessing your risk, that is improving safety. So, personally, I think that would be a good idea for manufacturers to have a safety management system in place.

Senator CANTWELL. And what does that mean to most people who are trying to listen to this conversation post the one we just had? What does that actually mean that happens?

Mr. SUMWALT. You know, I have always looked at safety management systems and I like the term safety management instead of safety management systems because it is an active thing. We want to manage safety the way that we would manage other vital business functions. So, there are generally thought to be four tenets of SMS, one of which is safety risk assessment where you are actively assessing your risk and managing those risk to an acceptable level. And so that is a key component of a safety management system.

Senator CANTWELL. Well this issue of risk management is critical and that is what I believe is that you have to say, what are the highest risks so you can focus on it. It is clear no one thought this change of a new system that took outside information, controlled the plane, gave it different commands with different alerts, that do different things, it wasn't tested.

So we have to implement this. The FAA was given this, I do not know if it was a directive or nudge before, but then they pulled back on a rulemaking in 2014 on this system management. But you believe ICAO, others are recommending this is what we should go forward with because it creates this robust discussion constantly. Is that the right way to describe it?

Mr. SUMWALT. As a safety practitioner, I agree with that and I do want to say again, the NTSB has not gone on the record to have a recommendation for that, but from a safety practitioners perspective, again when you are managing your risk, you are managing safety.

Senator CANTWELL. Thank you. Thank you. My time has passed.
Senator Blumenthal.

Senator BLUMENTHAL. Thank you. Thank you, Senator Cantwell, and I want to express my appreciation to Senator Cantwell and Senator Duckworth for the legislation that we are working on together and additional legislation that we hope will be based on your reports and others. You know, I had a lot of questions for our previous witness, which unfortunately I didn't have time to ask.

One of them would have been, why did he call the President of the United States, in effect circumventing the FAA if they were really going to respect safety? Are either of you aware of the call or calls that were made by Mr. Muilenburg to the President of the United States seeking to prevent grounding of these airplanes in the immediate aftermath of the second crash?

Mr. SUMWALT. Senator Blumenthal, I am not aware of that. I sat in this hearing room in March when you asked Mr. Elwell the same questions. I am not aware of that. We were not involved in the decision to ground the aircraft in any form or fashion.

Senator BLUMENTHAL. Mr. Hart?

Mr. HART. It was not within the purview of the JATR either. We were looking into the certification process to decide how to make it better.

Senator BLUMENTHAL. The fact of the matter is that the United States of America was among the last nations to ground those airplanes, correct?

Mr. SUMWALT. That is certainly my understanding. Us and Canada.

Senator BLUMENTHAL. And normally the United States of America would be at the forefront of safety, correct? Mr. Hart?

Mr. HART. Good question, Senator. Just for your awareness, I am on record through an op-ed in *USA Today* to congratulate the FAA for waiting until they had enough data to see was this a one-off event because if it was a one-off event, they would be grounding airplanes after every crash or was it more than a one-off in other words—

Senator BLUMENTHAL. In retrospect was it a good decision to ground that airplane?

Mr. HART.—after they had enough data to see the similarity of the two, yes.

Senator BLUMENTHAL. But the United States was the last to have enough data for whatever the reason?

Mr. HART. Yes.

Senator BLUMENTHAL. Just saying, right?

Mr. HART. Well, everybody had the same data about the same time. I just think the U.S., the FAA has a reputation for waiting until it has the data to react.

Senator BLUMENTHAL. Let me ask you, your report found that, “key aspects of the MCAS function such as intended function description, its interfaces, and architecture were not directly visible to the FAA in a straightforward manner through the certification deliverable documents.” I am trying to put that in simple English that you would use in the *USA Today* article. They didn’t do full disclosure to the FAA, correct?

Mr. HART. In simple language, the process certainly—the process was complicated enough and challenging enough and bureaucratic enough that the communication was stifled. And so the communication didn’t get where it needed to be when it needed to be there.

Senator BLUMENTHAL. OK. I think that answers my question. And that was something we should correct, correct?

Mr. HART. That is something that the JATR has recommended correcting, and yes, it does need correcting.

Senator BLUMENTHAL. The *Wall Street Journal* recently reported that internal Boeing surveys revealed that about 30 percent of its employees felt potential undue pressure from managers regarding safety related approval. In fact, one of the Boeing engineers, Curtis Ewbank filed a complaint that asserted, "Boeing management was more concerned with cost and schedule than safety or quality." Did your investigative work indicate that kind of undue pressure from Boeing on its employees to move the safety process at the expense of—I am sorry move the certification process at the expense of safety?

Mr. HART. Thank you for your question. Our investigation, our review found enough concern about undue influence that we recommended that it be reviewed carefully for the next time, the next certification process.

Senator BLUMENTHAL. You indicate, I think, in your testimony that you thought delegation would continue, which seems contrary to what we have found here so far that a lot of the thrust of the questioning has been to reverse delegation. So, I hope that maybe we can have your further thoughts on that issue. Let me just ask one more question.

Mr. Sumwalt, on Sunday, just this past Sunday, the *New York Times* reported on Boeing's efforts to undercut regulatory oversight early and often. The story of Boeing sabotaging rigorous safety scrutiny is chilling to all of us and more reason to keep the 737 MAX grounded until certification is really and truly independent and the system is reformed.

What are your views on the amount of delegation authority from the FAA to Boeing? Shouldn't we reverse the delegation that exist right now?

Mr. SUMWALT. Senator Blumenthal, thank you for that question. The NTSB's role in all of this is to serve as an accredited representative to each of the respective accident investigations. As such, we looked at the design certification processes of the 737 MAX and we issued the seven recommendations. We have not looked at the ODA process. That is not something that we have done.

Senator BLUMENTHAL. Why?

Mr. SUMWALT. Well because there are approximately 79 organizations that have ODA approval. We have got about two people that have the expertise to dwell into the design certification issues. We have devoted those energies to come up with these seven recommendations that we issued 1 month ago. That is an enormous task. I am under the impression that the U.S. DOT IG is doing a study of this issue.

The CHAIRMAN. As are numerous other entities. Thank you.

Senator Duckworth.

Senator DUCKWORTH. Thank you, Mr. Chairman. Chairman Sumwalt, welcome. At the March 2019 hearing held by this committee's Aviation subcommittee, Chairman Wicker asked you a simple question concerning Lion Air flight 610, and I quote "what should the pilots have done," and you responded as follows, and I quote "well, I flew the 737 for 10 years and I do believe that there is a procedure at least for the Flintstone version of the 737. I flew a very old 737, but I do believe that the very first thing you would

do is oppose that motion by pulling the yoke back and that would engage the stab break or the stabilizer cutout function.” And to me this answer makes sense. The most reliable initial human response to an uncommanded nose down dive is to pull back on the yoke. Would you concur with this view?

Mr. SUMWALT. Yes, I do. I have actually looked at the procedure and it says to grasp and to hold it firmly but as you know as an experienced pilot, your natural reaction would in fact if it is going in a direction you do not intend it to, you would tend to oppose it, which you should. In the older models of the Boeing aircraft that I flew, the 727 and 737, that would engage the stabilizer brake and stop the stab from running. But as you pointed out in the earlier round, it will not do that when MCAS is active on the 737 MAX.

Senator DUCKWORTH. Right. So that is what I would like to add to your response is the critical importance of the column cutout function, whether aft or forward, is that it is not just limited to the very old 737, but, in fact, according to a former Boeing engineer who was responsible for the control law development, in the 757, 767, and the 747-400. In every Boeing airplane until the 737 MAX, uncommanded stabilizer runaway is stopped by column motion only. You don’t have to do another step. Once you pull back and you have overridden it, that’s it.

There is nothing that resets and then pushes the nose back down 5 seconds later. There is nothing else you have to do. That is it in every other model of Boeing aircraft of 737s. But for the MAX with the MCAS malfunction, the pilot has to also apply the manual electric trim within the same 3 second window, otherwise the MCAS, which the pilots did not know was installed in the aircraft, could reset and put the nose back down. So now you are telling pilots, OK, natural reaction, you have pulled back, you have overridden it, you think that is it.

But now you have to troubleshoot for a system that you do not know exist that is now overriding your pilot’s command input and pulling back the yoke. Mr. Sumwalt, are you aware of Boeing notifying commercial 737 pilots before the Lion Air crash that when MCAS activates during manual flight it disables the aft column cutout safety function? That is, it overrides that safety function?

Mr. SUMWALT. Senator Duckworth, I am under the impression that just as you said that prior to these two tragic crashes that information was not widely known within the piloting community.

Senator DUCKWORTH. Thank you. Mr. Sumwalt, the MCAS malfunction should have been elevated to a hazardous rating, in my opinion, because the aft column cutout was removed and worsened by tripling the stab trim rate, which made severe mistrim likely, especially with a persistent malfunction. Had Boeing done this, instead of rating it as a “Major” hazard, we would not be where we are today. Would you agree with that? It changes how they report to the FAA. Am I correct?

Mr. SUMWALT. Yes, and that hazard category of major, as I understand it, only required there to be one angle of attack sensor. If it was at a higher hazard category, it would have required the input from two.

Senator DUCKWORTH. Thank you. Mr. Chairman, I would like to enter Peter Lemme's "Flawed Assumptions Pave a Path to Disaster" into the hearing record.

The CHAIRMAN. Without objection.

[The information referred to follows:]

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Flawed Assumptions Pave a Path to Disaster

Peter Lemme

28 October 2019

Revised 31 October 2019 – Ineligible Discount discussion, added DP Davies quote

When MCAS (Maneuvering Characteristics Augmentation System) was implicated after Lion Air JT610 plunged into the sea, tragically taking 189 lives, the spotlights converged on the malfunction of a single Angle of Attack (AoA) vane. My first thoughts were that Boeing had somehow overlooked this scenario or viewed it as inconsequential, based on blind faith that no matter what, the pilot would remain vigilant taking correct and timely action as the safety backstop. I could not wrap my head on how repeated applications of MCAS did not create unlimited authority in malfunction which would create a HAZARDOUS hazard.

Boeing had declared MCAS malfunction a MAJOR hazard.

Original results of preliminary hazard assessment

Hazard	Hazard classification
Uncommanded MCAS operation up to its maximum authority	Major
Uncommanded MCAS function operation equivalent to 3 second mistrim	Major

JT610 Final Report

Why wasn't an MCAS malfunction treated as HAZARDOUS, which would have mandated a dual-channel, fail-safe design?

The answer lies in a number of buckets, which overflow beyond just MCAS:

- a desire to justify design rather than direct safety
- over-use of a convenient test condition restriction
- blind reliance on unproven pilot response
- misunderstanding the ramifications from removing an under-appreciated safety interlock
- ignoring escalation from the combination of persistent hazards
- incorrectly applying a convenient probabilistic factor to dodge the obvious conclusion
- overlooking the ramifications from extending Speed Trim to provide Stall Identification

Boeing considered all the hazards that were encountered on Lion Air JT610. There is nothing improper listed specifically to the MCAS system safety assessment, no hiding of information nor lack of close coordination.

Issues were dispositioned using faulty, but openly-declared, stove-pipe reasoning.

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Ultimately a number of named individuals, in this case Engineering Unit-Members (EU-M), have to sign off attesting to the safety of the system. Their analysis is clearly documented with method and assumption, there is no hiding. An EU-M signs off knowing this is their sworn duty to be complete, accurate, honest and forthcoming.

Every design has weaknesses. The majority of the safety analysis is focused on the corner conditions. Judgement comes into play, which is why we have to rely on experts to be the EU-M. Nowhere is it more plainly evident for expertise is with assumption and method, someone has to attest these are reasonable and acceptable. The preferred strategy is to rely on data to conclude pass/fail, rather than judgement. Simulations are used to test judgements. But simulations can be stacked in their procedures towards justifying the assumptions.

I have seen countless design changes go down in flames once we handed it over to the pilots. Sometimes they would break it before we even got airborne. These were changes we had tested and were confident they would work. It is easy to rely on a couple of pilots to take the onus for airplane-wide thinking in a haphazard manner.

If you go into a test saying that if we follow these steps it will pass, you will follow those steps and it will pass. Then you can use that data to justify your assumptions. This is where group-think is evident, and where EU-M must act as individuals, to insist on evidence where there is doubt. There should have been a lot more doubt.

The process should have recognized that removing the aft column cutout switch created the HAZARDOUS mandate.

Repetitive MCAS malfunction should have been declared HAZARDOUS.

The combination of air data, stall warning and MCAS persistent malfunction should have been declared CATASTROPHIC.

HAZARDOUS would have gotten the project to exercise the dual processor (command and monitor) FCC (Flight Control Computer) already built-in.

Boeing was fully aware of the potential for an AoA sensor to malfunction. Boeing was fully aware that a malfunction of a single AoA sensor could cause MCAS to fire repeatedly. These were accounted for, but discounted ultimately, by flawed assumptions and precedent.

The first fatal assumption relates to the level of mistrim encountered if MCAS malfunctions. Boeing assumed a maximum travel of 0.6 units in all cases. Boeing assumed that this level of mistrim was manageable by column response alone.

Subsequent to responding to the MCAS runaway malfunction, Boeing assumed a pilot re-trims the airplane to neutralize column forces. Thus, a subsequent MCAS malfunction is no greater hazard than the first.

From the JATR Report:

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Observation 06.9-H: Boeing concluded that multiple erroneous MCAS activations were not worse than a single erroneous activation, based on the assumption that the crew would return the aircraft to a trimmed state (consistent with AC 25-7C guidance) following each activation.

The level of mistrim is based on how fast the stabilizer is moving and how long before stopping the stabilizer from continued motion. Boeing assumed that the runaway would normally always be stopped leaving plenty of elevator authority. This assumption has prevailed with great success, starting with the 707; 60 years of service across 707, 727, 737, 747, 757, 767.

The removal of the aft column cutout switch undermined Boeing's assumptions that limit the mistrim to 0.6 units, and that sufficient elevator authority would always be preserved.

Stark evidence reveals that the pilot will not rapidly stop the stab runaway from MCAS malfunction, even in the normal flight envelope, because of the override of the aft column cutout.

From the JATR Report:

Finding F6.12-B: Basic assumptions about trained and qualified flight crew response to malfunctions used in the design and certification of the B737-8 MAX did not appear to hold in the two accident cases, based on preliminary information.

Boeing assumed that the 737 MAX pilot would not only pull the column back but also, within three seconds, that the pilot would use manual electric trim to oppose MCAS malfunction. The manual electric trim command will cause MCAS to stop its command. However, MCAS will "wake up" again five seconds later and start the process over again.

For every Boeing airplane until the 737 MAX, uncommanded stabilizer runaway is stopped by column motion only. But for the MAX, with MCAS malfunction, the pilot has to also apply manual electric trim within the same three second window.

The MCAS malfunction hazard should have been elevated to HAZARDOUS because the aft column cutout was removed, and worsened by tripling the stab trim rate, which made severe mistrim likely, especially with persistent malfunction.

The second fatal assumption belies a process breakdown in how failure rate is accounted, specifically, proportional to how often the airplane operates outside of the normal flight envelope.

Boeing applies a factor based on the likelihood that the airplane will leave the normal flight envelope and enter the operational flight envelope as 1 in 1,000 (1E-3). Boeing uses this probability to discount the required MCAS failure rates that are unique to the operational flight envelope.

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If MCAS malfunction were HAZARDOUS, it would have to rely on two sensors and two hardware paths.

Boeing dodged the dual mandate (fail-safe or fail-passive) by discounting the required malfunction rate applied to the HAZARDOUS hazard of $1E-7$ by $1E-3$ (the probability of being in the operational flight envelope). With this logic, they calculated the maximum MCAS malfunction rate in the operational flight envelope to be $1E-4$ (1 in 10,000) malfunctions per hour. Where else has Boeing applied this discount?

Boeing concluded that it is acceptable for it to be **ten times more likely** to have MCAS malfunction in the operational flight envelope which creates a HAZARDOUS hazard, then it was to have MCAS malfunction in the normal flight envelope which creates a MAJOR hazard. Boeing should have not discounted the failure rate assigned to the operational flight envelope, which would have levied a HAZARDOUS hazard mandate against MCAS.

From the JATR Report:

Observation O3.2-A: The JATR team observed that the SSA takes credit for the probability that the aircraft will be flying in certain portions of the flight envelope, as documented in AC 25-7C.

A probability of $1E-3$ for the aircraft in the operational flight envelope (OFE) was used in combination with the probability of the system failure to achieve the $1E-7$ minimum probability required for the "hazardous" MCAS failure condition.

Use of AC 25-7C is not a standard industry approach for 25.1309 compliance.

The JATR team's view of the intent of the probability of $1E-3$ for the OFE in the HQRM is to select flight test cases for handling qualities evaluation, not to support the quantitative aspects of 25.1309 or 25.672(c) compliance.

Speed Trim, with the aft column cutout intact, is still a MAJOR hazard.

The combination of a MAJOR hazard from airspeed and altitude disagree combined with a MAJOR hazard from false stall warning (stick shaker, minspeed/PLI anomaly, feel force increase) is probably a HAZARDOUS hazard all by itself (without MCAS malfunction on top). Adding MCAS malfunction to the mix, in the form it was delivered, has proven to be CATASTROPHIC.

From the JATR Report:

Finding F6.9-A: Evaluating worst-case scenario for the AOA failures was not adequate to identify the hazardous effects (including complete flight deck effects) of the single AOA failures.

A single AoA vane malfunction (actual rate is around $1E-7$, declared rate is $1E-5$ malfunctions per hour) should not create HAZARDOUS or CATASTROPHIC hazards. The answer is probably a third AoA source, possibly synthetic, to be used in conjunction with enhanced

built-in test, to isolate a vane malfunction. This issue is generic across many Boeing airplanes, and should be treated appropriate to the risk it presents, and particularly focused on new or revised designs. There have been 30 occurrences of AoA malfunction (erroneous high angle reading) over an 18 year period, across many Boeing models, without any significant incident, until the MAX MCAS malfunction was added.

Finally, starting with the 737NG, Speed Trim System was modified to become a stall identification function. There are safety features associated with stall identification that do not appear to have been satisfied, notably the need to not trigger based on a single sensor (in this case, it is airspeed). Implementations of Speed Trim System on 757 and 747-400 are both fail-safe. It seems Speed Trim System should have been Fail-Safe from the 737-700.

Following are three detailed discussions:

- Tail Wagging the Dog
- Level of Mistrim
- Ineligible Discount

Tail Wagging the Dog

The safety process is supposed to work from setting requirements top-down and verifying design bottom-up. There seemingly were no enhancements to safety from malfunction, only functional necessities and flawed assumptions.

From the JATR Report:

Finding F6.6-A: There is a perception that the FHA reports are not used to drive the design; rather, they are used to document the design as already defined.

The STS and flight control computer (FCC) FHAs were updated reports from the B737 NG, and in the JATR team's assessment, they did not appear to be used as tools to identify new hazards related to MCAS and drive design mitigations.

As an example, in the hierarchy of safety solutions, mitigation by design should be prioritized over warnings and training/procedures.

By documenting the as-is configuration, Boeing concluded that pilot training and procedures were sufficient to ensure safety.

Opportunity for Fail-Safe design was squandered because of a failure to use equipment already available, to its full capability. The Fail-Safe mandate should have been obvious from the beginning, once the aft column cutout override was added. If nothing less, to follow the other Boeing model implementations (which are all Fail-Safe).

From the [JATR Report](#):

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Recommendation R6.1: The FAA should ensure applicants improve adherence to fail-safe design concept principles when designing or modifying systems.

The FAA should encourage applicants not to design only for compliance, but also to follow basic principles to design for safety when developing or changing system functions.

This should include elimination of hazards and use of design features, warnings, and procedures.

- *Observation O6.1-A: Proper flight crew action was considered an adequate mitigation to risks such as erroneous activation of MCAS.*
- *Finding F6.1-A: The JATR team identified that the design process was not sufficient to identify all the potential MCAS hazards. As part of the single-channel speed trim system, the MCAS function did not include fault tolerant features, such as sensors voting or limits of authority, to limit failure effects consistent with the hazard classification.*
- *Finding F6.1-B: The use of pilot action as a primary mitigation means for MCAS hazards, before considering eliminating such hazards or providing design features or warnings to mitigate them, is not in accordance with Boeing's process instructions for safe design in the conception of MCAS for the B737 MAX.*
- *Finding F6.1-C: The JATR team found that there was a missed opportunity to further improve the system design through the use of available fail-safe design principles and techniques presented in AC 25.1309-1A and in EASA AMC 25.1309 in the MCAS design.*

The safety analysis was thorough and complete, but fragmented. In general, the analysis was limited to areas that changed, reusing prior certification basis to complete the process. It was bad assumptions, driven by justifying a design, rather than establishing a safety benchmark that challenges the design.

From the JATR Report:

Finding F6.5-A: An integrated SSA to investigate the MCAS as a complete function was not performed.

The safety analyses were fragmented among several documents, and parts of the SSA from the B737 NG were reused in the B737 MAX without sufficient evaluation.

The FCC is capable of high integrity fail-safe design features. Each FCC is a dual processor (command and monitor processor) that can be used together to overcome any single point failure, including AoA sensor disagreement.

The 737 Speed Trim System had been in service without significant issue for over thirty years.

It appears that the motivation was to shoe-horn MCAS into Speed Trim System. That may have been sensible except for the removal of the aft column cutout feature, and the single-

sensor malfunction leading to persistent and overwhelming MCAS malfunction combined with other MAJOR hazards.

The new risks were "written off" by clever analysis that

- failed to properly account for expected pilot action
- ignored workload increase from simultaneous failures in multiple systems
- gave short-shrift to repetitive malfunction without workload increase
- discounted an obvious mandate for fail-safe design
- did not reveal the hazards from excessive mistrim
- without any basis, assumed pilot would use manual electric trim as quickly as before when pilots were only expected to pull on the column in response to runaway

Boeing is ignoring the fact that speed trim is a fail-safe, dual-inputs, dual-processor design on 757 and 747-400 (both with the aft column cutout switch active).

The 737 Speed Trim System single threaded design is a singularity in augmentation systems that have full control of the stabilizer. It survives without greater hazard because of the ability for the aft and forward column cutout switches to constrain its malfunction. The removal of the aft column cutout broke that protection which should have itself driven a fail-safe design mandate in compensation and to bring the design into conformance with other models and in general for augmentation systems.

Level of Mistrim

Mistrim reflects the displacement of the column under static condition. In general, trim is applied to neutralize column forces. Mistrim has greater import when stall warning is active, as the Elevator Feel Shift feature is activated, making column pull forces much higher than normal. An MCAS malfunction trims the stabilizer to drop the nose, the pilot has to pull against EFS elevated feel forces to counter it.

Another aspect of mistrim relates to binding the manual stab trim wheel, in this case making it very difficult to trim Airplane Nose Up, as appears to have been manifested in ET302.

The level of mistrim scales the degree of hazard. A small mistrim affords easy response, a large mistrim can create difficulty in control.

Boeing accounted for the level of mistrim in all scenarios using the same amount, a value of 0.6 units. This seems to have been the standard value for mistrim based on a presumption of the time to respond to a "runaway".

The System Safety Analysis starts very early in the design process, notably with the Preliminary System Safety Assessment and the Functional Hazard Assessment.

From the JT610 Final Report:

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As part of the MCAS development phase, in late 2012, Boeing performed a preliminary functional hazard assessment of MCAS using piloted simulations in their full motion Engineering Flight Simulator (E-Cab).

Several hazards were assessed at that time, however, this section of the report will focus only on the following two hazards: uncommanded MCAS operation up to its maximum authority (0.6 degrees of aircraft nose down stabilizer) and uncommanded MCAS operation equivalent to a 3 second stabilizer trim runaway.

Boeing used two scenarios to assess this hazard: a runaway at MCAS activation during a wind-up turn maneuver (operational envelope) and a wings-level recovery from a stabilizer runaway during level flight (normal flight envelope).

To perform these simulator tests, Boeing induced a stabilizer trim input that would simulate the stabilizer moving at a rate and duration consistent with the MCAS function.

Using this method to induce the hazard resulted in the following: motion of the stabilizer trim wheel, increased column forces, and indication that the aircraft was moving nose down.

Boeing indicated that this evaluation was focused on the flight crew response to uncommanded MCAS operation, regardless of underlying cause.

Original results of preliminary hazard assessment	
Hazard	Hazard classification
Uncommanded MCAS operation up to its maximum authority	Major
Uncommanded MCAS function operation equivalent to 3 second mistrim	Major

MCAS command authority started out applicable to high altitude (high Mach) high-AoA conditions. Boeing originally proposed that MCAS would have 0.6 units of command. A malfunction of MCAS would result in 0.6 units of stabilizer mistrim.

Later Boeing expanded the MCAS command to 2.5 units at low altitude (low Mach) high-AoA conditions. A malfunction of MCAS would result in 2.5 units of stabilizer mistrim.

In this context, a malfunction is a false trigger of MCAS.

In another context, MCAS output is falsely set by malfunction of hardware or software, against intended function. This has different characteristics, in that the failure may be persistent, commanding continuous stab trim changes without regard.

From the JT610 Final Report:

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The FHA evaluations were conducted by Boeing in their Engineering Cab using FAA guidance regarding flight crew response to flight control failures requiring trim input that is contained in FAA Advisory Circular AC25.7C. In particular, Boeing uses the following assumptions in its flight controls FHAs:

- *Uncommanded system inputs are readily recognizable and can be counteracted by overriding the failure by movement of the flight controls in the normal sense by the flight crew and do not require specific procedures.*
- *Action to counter the failure shall not require exceptional piloting skill or strength.*
- *The flight crew will take immediate action to reduce or eliminate increased control forces by re-trimming or changing configuration or flight conditions.*
- *Trained flight crew memory procedures shall be followed to address and eliminate or mitigate the failure.*

Boeing advised that these assumptions are used across all Boeing models when performing functional hazard assessments of flight control systems and that these assumptions are consistent with the requirements contained in 14 CFR 25.671 & 25.672 and within the guidance contained in FAA Advisory Circular (AC) 25-7C for compliance evaluation of 14 CFR 25.143.

The requirements document also indicated that the preliminary functional hazard assessments of MCAS were re-evaluated by flight crew assessments in the motion simulator and by engineering analysis and determined to have not changed in hazard classification as a result of the increase in MCAS authority to 2.5 degrees.

The FCC provides the software functions that calculate the MCAS command. A command processor provides those logical software outputs to the FCC hardware discrete outputs that direct stab trim to move, and that can also override the aft column cutout and select high trim speed.

A false trigger of MCAS would be manifested by the stab moving until either

- using manual electric trim,
- the appropriate trim cutout is applied, or
- grabbing the trim wheel;

upon which the stab would stop moving.

Boeing assumed that elevator would always be available to counteract anytime the stab would move for one MCAS step.

Stabilizer trim is susceptible to runaway without MCAS as a factor. Boeing has provided measures to limit the stabilizer mistrim in a runaway to ensure that the elevator remains effective.

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The aft column cutout and the forward column cutout are switches that automatically stop the stabilizer from trimming in opposition to the column.

If the stabilizer is running away by trimming the airplane nose down, the pilot flying will respond with aft column travel to command sufficient airplane nose up elevator to exactly offset the stabilizer mistrim.

At the point the aft column cutout is reached, the stabilizer trimming is stopped, to which the level of mistrim is now prescribed by the rigging of the aft column cutout switch. If the switch is rigged at 50% travel, then the pilot still has the remaining 50% of travel available. It does not matter what type of runaway, when the pilot responds with column travel, the trim will stop with the same level of mistrim.

Boeing assumed that a pilot will take one second to recognize the runaway malfunction (by noting the nose starting to drop), and then three seconds to respond to the malfunction, which in this case is by pulling back on the column sufficiently to trip the aft column cutout.

Where does this three-second mistrim criteria originate?

From 25.255 (a) (1):

25.255 Out-of-trim characteristics.

(a) From an initial condition with the airplane trimmed at cruise speeds up to VMO/MMO, the airplane must have satisfactory maneuvering stability and controllability with the degree of out-of-trim in both the airplane nose-up and nose-down directions, which results from the greater of –

(1) A three-second movement of the longitudinal trim system at its normal rate for the particular flight condition with no aerodynamic load (or an equivalent degree of trim for airplanes that do not have a power-operated trim system), except as limited by stops in the trim system, including those required by § 25.655(b) for adjustable stabilizers; or

(f) In the out-of-trim condition specified in paragraph (a) of this section, it must be possible from an overspeed condition at VDF/MDF to produce at least 1.5 g for recovery by applying not more than 125 pounds of longitudinal control force using either the primary longitudinal control alone or the primary longitudinal control and the longitudinal trim system.

25.255 (f) enforces the requirement that at the level of mistrim (from three seconds), there shall be sufficient load factor to pull out of a dive at 1.5 g.

By this interpretation of 25.255, the most mistrim you must demonstrate is three seconds. How can pilot response to stopping the runaway stabilizer be assured within three seconds? The answer lies in the aft and forward column cutout switches.

The aft column cutout switch performs two functions.

1. Stop the stabilizer from running away
2. Limiting the level of mistrim to preserve elevator effectiveness.

Boeing has used the aft and forward column cutout switches starting with the 707 and then including 727, 737, 747, 757, and 767. In all those airplanes, over all those years, the column cutout switches performed exactly as designed.

Boeing consistently assumed that the most mistrim to account for was 0.6 units. This was the level of mistrim resulting in three seconds of runaway. This value is debatable, if accounting for one second of recognition and if accounting for relevant stab trim rates.

The level of mistrim seemingly was independent of other factors, such as MCAS command authority in the range of 0.65 units to 2.5 units.

From the JT610 Final Report:

In March 2016, Boeing determined that MCAS should be revised to improve wings-level, flaps up, low Mach stall characteristics and identification. The MCAS was revised such that depending on AOA, it would be capable of commanding incremental stabilizer to a maximum of 2.5 degrees at low Mach decreasing to a maximum of 0.65 degrees at high Mach.

If MCAS were to achieve its command, the mistrim range should be 0.65 units to 2.5 units.

JATR also questioned how 0.6 units was selected. The normal trim rate for autopilot, flaps up, is 0.09 deg/sec. Assuming four seconds (one to recognize, three to respond), the stab should move about 0.4 units. Perhaps a fifty percent addition to make it worse case, that gets to 0.6 units. Under MCAS control, the rate is 0.27 deg/sec. A four second runaway would be about 1.1 units.

From the JT610 Final Report:

Observation O3.8-A: Out-of-trim characteristics, per the requirements of 25.255, were found acceptable for a 0.6 unit nose-down out-of-trim condition.

This out-of-trim value was determined by 3 seconds of trim input at the flaps-up main electric stabilizer trim rate of 0.2 degrees per second, which is greater than the autopilot trim rate.

Observation O3.8-B: The higher MCAS trim rate of 0.27 degrees per second was not selected for the demonstration of compliance with § 25.255, even though failures could result in un-commanded stabilizer trim movement at this rate.

From the JATR Report:

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Observation O2.8-C: Although the above guidance is aimed at test pilots conducting test flights, applicants seem to use this guidance as a design assumption that the pilot will be able to respond correctly within 4 seconds of the occurrence of a malfunction.

For example, in the case of the B737 MAX, it was assumed that, since MCAS activation rate is 0.27 degrees of horizontal stabilizer movement per second, during the 4 seconds that it would take a pilot to respond to an erroneous activation, the stabilizer will only move a little over 1 degree, which should not create a problem for the pilot to overcome.

Any reference to 0.6 units is more likely a long held historical value to relate to the pilot response with opposing column and tripping the column cutout switch.

From the JATR Report:

Finding F2.8-D: The 3-second reaction time assumption dates back decades, to where the performance of the autopilot was constantly monitored by the crew in flight (e.g., guidance given in AC 25.1329-1A, Automatic Pilot Systems Approval, dated July 8, 1968).

However, with increasing reliability and advances in flight deck alerting and displays, it may no longer be appropriate to assume that the pilot flying will be monitoring the automation as closely as in the past.

For the 737 MAX, with MCAS, the pilot response to stop the mistrim from growing is to the point of opposing manual electric trim.

Boeing recognized that removing the aft column cutout switch would change the pilot response to mandate or strongly encourage rapid manual electric trim to stop MCAS and to quickly neutralize column forces.

While not knowing the detail for JT610, the crew from JT043 could have instantly confirmed that the pilot response was clearly inconsistent from expectation.

There was neither special emphasis nor imperative for quickly using manual electric trim to oppose MCAS in the multi-operator message sent by Boeing on 10 Nov. 2018, shortly after the JT610 disaster, nor in any other communication revealed so far.

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FROM: THE BOEING COMPANY
 TO: Boeing Correspondence (MOM)
 [MESSAGE NUMBER: MOM-MOM-18-0664-01B] Multi Operator Message
 MESSAGE DATE: 10 Nov 2018 1810 US PACIFIC TIME / 11 Nov 2018 0210 GMT

This message is sent to all 737NG/MAX Customers, Regional Directors, Regional Managers and Boeing Field Service Bases.

CATEGORY: Maintenance, Engineering, Flight Operations, Management, Safety

SERVICE REQUEST ID: 4-4298138108
 ACCOUNT: Boeing Correspondence (MOM)
 DUE DATE: No Action Required
 PRODUCT TYPE: Airplane
 PRODUCT LINE: 737
 PRODUCT: SEVERAL
 ATA: 0000-57

SUBJECT: Information - Multi-Model Stall Warning and Pitch Augmentation Operation

A description of MCAS was provided, revealing the level of stab trim authority (2.5 deg) and the high trim rate (0.27 deg/sec). The Boeing message states that you can use the column trim switches or aisle stand cutout switches to oppose MCAS.

A pitch augmentation system function called "Maneuvering Characteristics Augmentation System" (MCAS) is implemented on the 737-8, -9 (MAX) to enhance pitch characteristics with flaps UP and at elevated angles of attack. The MCAS function commands nose down stabilizer to enhance pitch characteristics during steep turns with elevated load factors and during flaps up flight at airspeeds approaching stall. MCAS is activated without pilot input and only operates in manual, flaps up flight. The system is designed to allow the flight crew to use column trim switch or stabilizer aisle stand cutout switches to override MCAS input. The function is commanded by the Flight Control computer using input data from sensors and other airplane systems.

The MCAS function becomes active when the airplane Angle of Attack exceeds a threshold based on airspeed and altitude. Stabilizer incremental commands are limited to 2.5 degrees and are provided at a rate of 0.27 degrees per second. The magnitude of the stabilizer input is lower at high Mach number and greater at low Mach numbers. The function is reset once angle of attack falls below the Angle of Attack threshold or if manual stabilizer commands are provided by the flight crew. If the original elevated AOA condition persists, the MCAS function commands another incremental stabilizer nose down command according to current aircraft Mach number at actuation.

The MCAS function is not incorporated on 737NG airplanes.

The Boeing message does not make mention specifically that the aft column cutout switch function is disabled. It is apparent by its omission in the list of countermeasures.

The Boeing message does not emphasize the critical criteria they base proper pilot response on:

- *The flight crew will take immediate action to reduce or eliminate increased control forces by re-trimming or changing configuration or flight conditions.*

The ops bulletin Boeing released on 6 Nov 2018 background discussion does state that manual electric trim can be used to stop MCAS. It further states that the cutout switches can deactivate MCAS. It also states that MCAS has unlimited authority. This is really a remarkable admission.

Background Information

The Indonesian National Transportation Safety Committee has indicated that Lion Air flight 610 experienced erroneous AOA data. Boeing would like to call attention to an AOA failure condition that can occur **during manual flight only**. This bulletin directs flight crews to existing procedures to address this condition.

In the event of erroneous AOA data, the pitch trim system can trim the stabilizer nose down in increments lasting up to 10 seconds. The nose down stabilizer trim movement can be stopped and reversed with the use of the electric stabilizer trim switches but may restart 5 seconds after the electric stabilizer trim switches are released. Repetitive cycles of uncommanded nose down stabilizer continue to occur unless the stabilizer trim system is deactivated through use of both STAB TRIM CUTOUT switches in accordance with the existing procedures in the Runaway Stabilizer NNC. It is possible for the stabilizer to reach the nose down limit unless the system inputs are counteracted completely by pilot trim inputs and both STAB TRIM CUTOUT switches are moved to CUTOUT.

It was apparent, once the flight data was available, that the assumptions Boeing had relied on were not holding up. The level of mistrim was excessive. Pilots did not reliably respond within three seconds. Pilots did not always trim back to neutralize column forces. Pilots did not rely on manual electric trim to counter nose down trim malfunction.

Boeing had an option, once realizing that with the assumptions flawed, to immediately disable MCAS, and to fix the system based on HAZARDOUS malfunction (as they are doing).

The only action that was going to prevent ET302 was for Boeing to either turn off MCAS or fix MCAS. Clearly fixing MCAS wasn't a quick undertaking. Boeing tip-toed with their fix, starting with detecting disagreement (no single sensor), then by assuring it could never be re-triggered, then limiting command authority to preserve elevator authority, and finally to bring in a monitor processor with tandem hardware control to meet fail-safe in the presence of a single fault.

The issues were plainly obvious. I came to question the HAZARDOUS (fail-safe) assumption myself when I published [737 MCAS - Failure is an Option on 15 Nov 2018](#) and [737 FCC Pitch Axis Augmentation - Command Integrity Mandate for Dual Channel, Fail-Safe on 20 Nov 2018](#), both before any flight data was even available, having concluded MCAS was single-thread.

Boeing failed to properly re-assess the situation, doubling down on their assumptions instead of immediately disabling MCAS to remove any chance of further disaster. This stay-the-course, admit-no-fault mentality was plainly evident with the 787 battery fiasco, where the answer was to install a chimney.

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The JATR report expressed a need to emphasize the use of main electric trim as a countermeasure to MCAS malfunction and that the level of mistrim needs to be conservative, and that significant mistrim can lead to greater hazards.

From the JATR Report:

Recommendation R3.8: The FAA should review the prescriptive use of 3 seconds under 14 CFR 25.255 (Out-of-Trim Characteristics) for the evaluation of mis-trim conditions, especially for automatic trim systems where pilot recognition is relied upon to detect and arrest runaway failures.

The rate of trim used by these automatic systems should also be considered in showing compliance to § 25.255.

Finding F3.8-A: Section 25.255 applies to jet upset events and uses a prescriptive 3 seconds as the amount of out-of-trim that could occur before pilot reaction.

For automatic trim systems, the 3-second reaction time may not be appropriate, depending on the cockpit alerting philosophy and trim system architecture and controls.

Recommendation R3.9: The FAA should review the AFM procedure for stabilizer runaway and ensure that adequate emphasis is placed on the importance of using main electric stabilizer trim to return to a trimmed state.

Crew error should be considered in the event that aisle stand stabilizer cutout switches are used before returning to trim conditions.

Finding F3.9-A: Certain stabilizer runaway failures may generate significant out-of-trim conditions.

Main electric stabilizer trim is considered the primary means to stop runaway stabilizer in Boeing's assumptions and validation tests.

The degree of stabilizer mis-trim and resulting transient from steady-state flight may result in hazardous or even catastrophic failure conditions.

Recommendation R3.10: The FAA should review the Boeing assumption of a 4-second pilot reaction time to stabilizer runaway failures to ensure that a conservative value is used, since pilot action is required to counter these failures.

Finding F3.10-A: Manual stabilizer trim wheel forces increase with increased speed and degree of out-of-trim condition.

The degree of out-of-trim condition is dependent on pilot recognition and reaction technique and time.

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Manual stabilizer trim wheel forces could become significant when assumed pilot reaction times are reasonably exceeded, especially for high-speed conditions.

During stabilizer runaway conditions where main electric stabilizer trim is not available, either due to system failures or the erroneous selection of stabilizer cutout switches prior to returning to trim, the crew must use the manual stabilizer trim wheel to return to a trimmed condition.

The FAA issue an AD on 7 Nov 2018 stating the importance of following the stabilizer runaway non-normal checklist if encountering an AoA vane malfunction.

From the JT610 Final Report:

FAA Emergency Airworthiness Directive (AD) Number 2018-23-51



FAA
Aviation Safety

**EMERGENCY
AIRWORTHINESS
DIRECTIVE**

www.faa.gov/aircraft/safety/alerts/

DATE: November 7, 2018
AD #: 2018-23-51

Emergency Airworthiness Directive (AD) 2018-23-51 is sent to owners and operators of The Boeing Company Model 737-8 and -9 airplanes.

Background

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.

Required by AD 2018-23-51
<u>Runaway Stabilizer</u> In the event of an uncommanded horizontal stabilizer trim movement, combined with any of the following potential effects or indications resulting from an erroneous Angle of Attack (AOA) input, the flight crew must comply with the Runaway Stabilizer procedure in the Operating Procedures chapter of this manual: • Continuous or intermittent stick shaker on the affected side only. • Minimum speed bar (red and black) on the affected side only. • Increasing nose down control forces. • IAS DISAGREE alert. • ALT DISAGREE alert. • AOA DISAGREE alert (if the option is installed). • FEEL DIFF PRESS light. • Autopilot may disengage. • Inability to engage autopilot.

The AD provided the following entry. It states that the pilot should control with column and main electric trim as required. It then expresses the need to set the cutout switches. The comment, if relaxing the column causes the trim to move, is referring to the column cutout switch, which would not be active with MCAS.

From the JT610 Final Report:

Runaway Stabilizer

Disengage autopilot and control airplane pitch attitude with control column and main electric trim as required. If relaxing the column causes the trim to move, set stabilizer trim switches to CUTOUT. If runaway continues, hold the stabilizer trim wheel against rotation and trim the airplane manually.

Note: The 737-8/-9 uses a Flight Control Computer command of pitch trim to improve longitudinal handling characteristics. In the event of erroneous Angle of Attack (AOA) input, the pitch trim system can trim the stabilizer nose down in increments lasting up to 10 seconds.

In the event an uncommanded nose down stabilizer trim is experienced on the 737-8/-9, in conjunction with one or more of the indications or effects listed below, do the existing AFM Runaway Stabilizer procedure above, ensuring that the STAB TRIM CUTOUT switches are set to CUTOUT and stay in the CUTOUT position for the remainder of the flight.

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The statement "Electric stabilizer trim can be used to neutralize column pitch forces before moving the STAB TRIM CUTOUT switches to CUTOUT does not match with the imperative stated as their foundation assumptions on pilot behavior. The statement should have been written with emphasis and insistence "Electric stabilizer trim should be or shall be used to neutralize..."

From the JT610 Final Report:

Initially, higher control forces may be needed to overcome any stabilizer nose down trim already applied. Electric stabilizer trim can be used to neutralize control column pitch forces before moving the STAB TRIM CUTOUT switches to CUTOUT. Manual stabilizer trim can be used before and after the STAB TRIM CUTOUT switches are moved to CUTOUT.

Boeing assumed that opposing MCAS malfunction with electric trim would be achieved within the three seconds normally allotted to the pilot pulling back on the column. Instead of automatically stopping mistrim by simple aft column cutout, the pilot uses manual electric trim to stop it and to retrim.

From the JT610 Final Report:

The assessment was also based on an assumption that the flight crew was highly reliable to respond correctly and in time. Boeing followed FAA guidance that the flight crew would respond within 3 seconds to any changes in flight condition. The assessment was that each MCAS input could be controlled with control column alone and subsequently re-trimmed to zero column force while maintaining flight path.

The expected pilot response in a runaway (nose down) is to pull the column. With the aft column cutout switch in place, pulling the column alone will stop the stab from trimming further. For MCAS, the pilot has to both pull the column to counter the mistrim while simultaneously using the manual electric trim to oppose the runaway. Boeing placed complete confidence in their assumptions that pilots would promptly use manual electric trim in this case.

From the JT610 Final Report:

In the event of repetitive MCAS activation with repeated electric trim inputs by flight crew, but without sufficient flight crew response to return the aircraft to a trimmed state, the control column force to maintain level flight could eventually increase to a level where control forces alone may not be adequate to control the aircraft.

During the accident flight, the DFDR recorded a control force of 103 lbs., after repetitive MCAS activation was responded with the FO had responded with inadequate trim to counter MCAS. At this point, the flight crew was unable to maintain altitude.

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It has been Boeing's proposition that an MCAS malfunction to its full authority can be easily countered by elevator. The situation highlighted is high altitude, where the MCAS authority has been shown to be a MAJOR hazard, except outside the normal flight envelope it is HAZARDOUS.

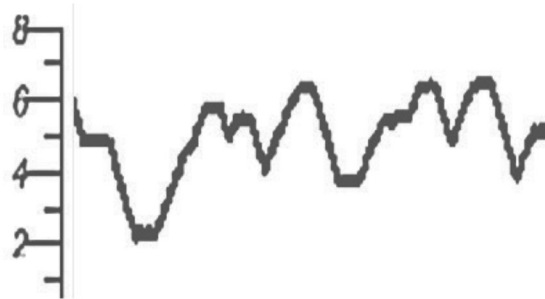
Boeing determined that a mistrim of 0.6 units at low altitude was only a MINOR hazard. Boeing did not conduct any flight tests that confirmed, but they claim with good confidence, that a 2.5 unit step of stabilizer at low altitude is controllable by column as well.

The data from JT610 and JT043 shows that the pilot can counter MCAS with manual electric trim and column, but that the excursions can exceed 0.6 units and even 2 units. It also shows that pilots failing to neutralize column forces after each MCAS malfunction can lead to loss of control.



Stub trim - JT610

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Stab trim - JT043

A simulator test was conducted ****after**** the JT610 accident to judge the hazard from successive MCAS commands without trimming in between. The conclusion was that two successive commands could not be countered by column alone.

From the JT610 report:

The fourth case of the third scenario was for the flight crew to feel the control column forces during single and repetitive MCAS activations while trying to keep the aircraft level. The AOA bias was introduced and the MCAS function activated. The observations were as follows:

1. *Significant aft control column force was necessary to hold the control column after one activation of MCAS.*
2. *After two full applications of MCAS and no restoring electric manual trim up, one participant characterized the control column force as "too heavy."*

Prior to the 737 MAX Certification, Boeing revised the hazard assessment due to the change in MCAS authority at low altitude. There was no change in classification.

From the JT610 Final Report:

Flawed Assumptions Pave a Path to Disaster - COPYRIGHT – ALL RIGHTS RESERVED

**Results of preliminary hazard assessment
for revised MCAS authority**

Hazard	Hazard classification
Uncommanded MCAS function operation up to its maximum authority	Major*
Uncommanded MCAS function operation equivalent to 3 second mistrim **	Major

* Major only for high altitude conditions

** Piloted Simulation not Required

When assessing unintended MCAS activation in the simulator for the FHAs, the function was allowed to perform to its authority and beyond before flight crew action was taken to recover. Failures were able to be countered by using elevator alone. Stabilizer trim was available to offload column forces, and stabilizer cutouts were available but not required to counter failures. This was true both for the preliminary FHAs performed in 2012 and for the reassessment of the FHAs in 2016.

The uncommanded MCAS command to the maximum nose down authority at low Mach numbers was evaluated in the Boeing 737-8 (MAX) cab and rated as Minor. According to Boeing, Engineering analysis determined no low Mach piloted simulation to be required as this failure is less critical than MCAS function operation to maximum authority. Stabilizer motion for three seconds would not reach maximum authority in low Mach conditions.

The high Mach uncommanded MCAS command and subsequent recovery is the critical flight phase in establishing the hazard rating for erroneous MCAS commands. The existing high Mach evaluations remain valid as the aerodynamic configuration has not changed significantly since the preflight evaluations, and the 3 second stabilizer motion is the same magnitude.

According to Boeing, engineering analysis determined that the existing high Mach evaluations remain valid as the aerodynamic configuration had not changed significantly since the pre-flight evaluations, and the MCAS authority limit at high Mach did not change significantly in the flight test update.

As the ratings for these high Mach evaluations were more severe than for low Mach, the overall flight envelope hazard ratings remain the same as the pre-flight evaluations. During the process of developing and validating the Functional Hazard Analysis (FHA), Boeing considered four failure scenarios including uncommanded MCAS function to the maximum authority limit of 2.5° of stabilizer movement.

However, the uncommanded MCAS function to maximum authority was only flight simulated to high speed maximum limit of 0.6°, but not to low speed maximum limit of 2.5° of stabilizer movement.

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To perform the simulator tests, Boeing induced a stabilizer trim input that would simulate the stabilizer moving at a rate and duration consistent with the MCAS function.

Boeing also indicated that engineering and test pilots discussed the scenario of repeated uncommanded MCAS activation during development of the Boeing 737-8 (MAX) and deemed it no worse than single uncommanded MCAS activation because it was assumed that the pilots would trim out uncommanded trim inputs to maintain control of the aircraft.

Repetitive MCAS activations without adequate trim reaction by the flight crew would escalate the workload and hence failure effects should have been reconsidered.

During FHA, the simulator test had never considered a scenario in which the MCAS activation allowed the stabilizer movement to reach the maximum MCAS command limit of 2.5° of stabilizer movement. Therefore, their combined flight deck effects were not evaluated.

Boeing indicated the following key conclusions supporting the MAJOR hazard classification.

From the JT610 Final Report:

In a 2019 presentation to the investigation team, Boeing indicated that the MCAS hazard classification of "major" for uncommanded MCAS function (including up to the new authority limits) in the Normal flight envelope were based on the following conclusions:

- *Unintended stabilizer trim inputs are readily recognized by movement of the stabilizer trim wheel, flight path change or increased column forces.*
- *Aircraft can be returned to steady level flight using available column (elevator) alone or stabilizer trim.*
- *Continuous unintended nose down stabilizer trim inputs would be recognized as a Stab Trim or Stab Runaway failure and procedure for Stab Runaway would be followed.*

The conclusions Boeing professed are not evident in the data from both Lion Air flights.

From the JT610 Final Report:

Without prior knowledge of MCAS functions, the flight crew would depend on the visual and motion cues, prior training for runaway stabilizer, and general training on pitch control to be able to analyze the situation and recognize the non-normal condition.

Review of the DFDR data showed that during both the accident and the previous LNI043 flights, the flight crew responded within 2-3 seconds using control column to control the flight path and subsequently trimmed out column forces using electric trim.

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In the previous LNI043 flight, the flight crew required 3 minutes and 40 seconds rather than seconds to recognize and understand the problem, during which repetitive uncommanded MCAS activations occurred.

During the accident flight, recognition of the uncommanded stabilizer movement as a runaway stabilizer condition did not occur thereby, the execution of the non-normal procedure did not occur.

Using manual electric trim as a countermeasure to persistent MCAS malfunctions proves generally unsuccessful and greatly distracting.

From the JT610 Final Report:

A combination of repetitive MCAS-commanded coupled with flight crew electric trim input led to a flight condition that considerably increased the flight crew workload of maintaining control.

The previous LNI043 flight showed that repetitive MCAS-commanded stabilizer movement was able to be countered by the flight crew by repeatedly trimming out erroneous aircraft nose down trim and was only able to be stopped by Stabilizer Trim Cutout switches, enabling the flight crew to safely continue flight and land in Jakarta.

Boeing admits in their ops bulletin from 6 Nov that the cutout switch is available to stop persistent MCAS malfunction. The safety analysis assumes indefinite manual electric trim is just a MAJOR hazard. The issue is MCAS malfunction a runaway stabilizer? There has been no end of testimony that a pilot would recognize MCAS malfunction as runaway and perform the checklist and use the cutout switches.

The FAA insists on using the runaway stabilizer checklist and using the cutout switches in their AD from 7 Nov 2018. It makes it clear that non-compliance could result in catastrophe.

From AD 2018-23-51:

(e) Unsafe Condition

This 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. We are issuing this AD to address this potential resulting nose-down trim, which 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.

Required by AD 2018-23-51**Runaway Stabilizer**

In the event of an uncommanded horizontal stabilizer trim movement, combined with any of the following potential effects or indications resulting from an erroneous Angle of Attack (AOA) input, the flight crew must comply with the Runaway Stabilizer procedure in the Operating Procedures chapter of this manual:

Required by AD 2018-23-51**Runaway Stabilizer**

Disengage autopilot and control airplane pitch attitude with control column and main electric trim as required. If relaxing the column causes the trim to move, set stabilizer trim switches to CUTOUT. If runaway continues, hold the stabilizer trim wheel against rotation and trim the airplane manually.

Note: The 737-8/-9 uses a Flight Control Computer command of pitch trim to improve longitudinal handling characteristics. In the event of erroneous Angle of Attack (AOA) input, the pitch trim system can trim the stabilizer nose down in increments lasting up to 10 seconds.

In the event an uncommanded nose down stabilizer trim is experienced on the 737-8/-9, in conjunction with one or more of the indications or effects listed below, do the existing AFM Runaway Stabilizer procedure above, ensuring that the STAB TRIM CUTOUT switches are set to CUTOUT and stay in the CUTOUT position for the remainder of the flight.

It took JT610 tragedy to demand re-evaluation of the assumptions around MCAS malfunction and expected pilot behavior. Overnight, it was recognized that pilots must be vigilant, that the hazard could lead to loss of control.

From the JT610 Final Report:

Boeing reasoning that the stabilizer cutout is available but not required is incorrect. During the FHA, Boeing did not adequately assess the effect of repetitive MCAS activation.

The repetitive MCAS-commands coupled with insufficient flight crew electric trim inputs, may have led to increasing flight crew workload.

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Per Boeing, stabilizer trim cutouts switches were available but not required to counter MCAS activations.

The only procedure that directs selecting the stabilizer cutout switches is the Runaway Stabilizer non-normal checklist (NNC). This NNC is used to stop un-commanded stabilizer trim wheel movement, which would stop MCAS-commanded stabilizer trim movement.

However, erroneous MCAS activation does not look like a typical stabilizer runaway, which is continuous un-commanded (runaway) movement of the stabilizer.

During the accident flight, the stabilizer movement was not continuous; the MCAS commands were bounded by the MCAS authority (up to 2.5°); the pilots were able to counter the nose-down movement using opposing manual electric trim inputs; and after the pilots released the manual electric input and MCAS was reset, there was not another MCAS command for 5 seconds.

Repetitive, false MCAS commands result in higher workload than a single false MCAS command. The existence of repetitive commands is yet another mandate for declaring this malfunction HAZARDOUS.

As is evident, Boeing made no provision to modify the MCAS command authority for application when the airplane is not flying at high AoA.

As was evident in ET302, MCAS command applied at low AoA (high airspeed) is overly aggressive.

The removal of the aft column cutout took away any limit to MCAS over-authority.

It should be noted that in addition to preserving elevator authority, MCAS should stop if the airplane experiences negative normal acceleration.

Knowing the potential for large mistrim would have also revealed the issues regarding recovery using the manual wheel trim only.

Ineligible Discount

The safety analysis is inherently based on assumptions and combinational methods. The assumptions around combinational methods are the most insidious. Boeing applied a factor, a reduction in system integrity requirement of one thousand, that allowed a HAZARDOUS hazard to be ignored. Without the discount, MCAS would have been developed as a dual-channel, fail-safe solution. Even with the discount, it is not apparent if the resultant software design assurance was discounted as well, which does not seem reasonable at all.

Hot Potato

Three systems are factored into the Safety Analysis, each done as a project:

1. ADIRS (source of AoA vane data to MCAS)
 2. EDFCS (MCAS function)
 3. Stab Trim Control System (MCAS actuator)
- ADIRS assumes that its AoA output may malfunction at a 1E-5 rate.
 - EDFCS only responds to AoA inputs that are not valid, and makes no further mandate on integrity. It leaves integrity to ADIRS.
 - Stab Trim is left holding the bag, for it is the system that actually presents a hazard.

ADIRS was largely unchanged.

EDFCS (Enhanced Digital Flight Control System) includes the Flight Control Computer (FCC) which hosts Speed Trim System and MCAS. The FCC is changed by the addition of the MCAS software function and use of output discretes. It is implied that these output discretes were available in the same FCC that was used on 737 NG, the software being the only difference.

From the JT610 Final Report:

CP13471 indicated that certification of the MCAS implementation and function will be addressed in certification plan (CP13474), "737-8 Amended Type Certificate – Flight Controls – Autoflight (EDFCS/FCC)."

The development of EDFCS certification plan (CP13474) began with Boeing's initial submission of CP13484, revision NEW to the FAA for review in March, 2014.

A review of CP13474 found that changes to the EDFCS for the 737-8, as compared to the baseline 737-800, were limited to the Flight Control Computer (FCC) software only. CP13474 indicated that the FCC Operational Program Software (OPS) will be revised to add the MCAS function.

The Stabilizer Trim Control system is changed by the addition of relays that can bypass the aft column cutout function and that can allow override of the trim speed control.

From the JT610 Final Report:

The development of the Elevator and Stabilizer Trim Control system certification plan (CP13471), began with Boeing's initial submission of CP13471, labeled "NEW", to the FAA for review in March 2014.

According to CP13471, one of the changes to the Stabilizer Trim Control system from the baseline 737-800 (NG) was the incorporation of the MCAS. Implementation of this new function required two new analog discrete signals, generated by the FCCs, to be sent to components within the stabilizer system.

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One discrete will override the control column cut-out switches located in the First Officer's Column Switching Module in the "pull" direction when MCAS is operating to prevent the stabilizer command from cutting out during the pilot maneuver.

The second discrete overrides the flap position input to enable the higher stabilizer trim motor (STM) operating speed with flaps retracted when MCAS is operating.

Functional Hazard Assessment (FHA)

The Stab trim FHA and the EDFCS FHA offered specific MCAS considerations.

From the JT610 Final Report:

The Functional Hazard Assessment section of Appendix "G" summarized the FHA that was performed as part of the 737 MAX Stabilizer Trim Control System Safety Analysis, and addressed each system function and the result of loss of availability or loss of integrity of that function.

The analysis considered all phases of flight for both the Normal and Operating flight envelopes, interfacing systems, and established the effect category for each failure condition. Hazard assessments were determined in consideration of the impact to crew workload for the maximum flight time and longest diversion time (where a diversion is required).

An NTSB review of the FHA found that it identified and classified, pursuant to the guidance in AC 25.1309-1A, the following six hazards related to MCAS:

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Table 7 Functional Hazard Assessment for MCAS

Effect Category	Hazard Event	Flight Phase
Hazardous	Uncommanded MCAS function	All (Operating Flight Envelope)
Major ⁶³	Loss of MCAS Function	All (Operating Flight Envelope)
Major	Uncommanded MCAS function operation to maximum authority (0.6 deg)	All (Normal Flight Envelope)
Major	Uncommanded MCAS function operation equivalent to 3 second mistrim	All (Normal Flight Envelope)
Minor	Loss of MCAS Function	All (Normal Flight Envelope)
Minor	Stabilizer trim runaway with MCAS operation	Cruise (ETOPS)

CP13474 According to this FHA, the EDFCS Functional Hazard Assessment for the 737-8 will be based on the FHA for the 737NG as documented in the document titled, "Enhanced Digital Flight Control System, Autothrottle, and Yaw Damper Safety Analysis, Model 737-600/700/800/900."

The FHA was to be updated to address any functional hazards associated with the addition of the Maneuvering Characteristics Augmentation System (MCAS), and other system changes.

A review of the functional hazard assessment found that it addressed each system function and the result of loss of function or erroneous operation.

Because MCAS only operates with the autopilot off, one hazard contained within the assessment was relevant. This hazard is: "Autopilot Malfunction at Low Altitude Which Results in Unsafe Flight Path in an A/P OFF, Single Channel, or Fail-Passive Configuration (FHA 1)."

System Safety Assessment (SSA)

Three System Safety Assessments are applicable: Air Data Inertial Reference System (ADIRS), the Stabilizer and the EDFCS.

From the JT610 Final Report:

The ADIRS SSA is relevant because AoA is processed by ADIRS for use by the FCC. The Angle of Attack Failure section of the SSA includes only AoA resolver circuit failures (open circuit, high impedance, etc.) that can be detected by the associated computer

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(ADIRU or SMYD). The SSA does not discuss the category of AoA sensor failures not related to the electrical circuitry that could provide misleading (erroneous) data to the ADIRU (e.g. frozen or seized vane with limited or no motion, or a bent or broken vane resulting in angular offset). AoA values are transmitted as "valid" to user systems, because the ADIRU does not detect these faults.

It was determined that the ADIRU, air data module (ADM), pitot probe head and AoA vane (and heat) have potential undetected failure modes that may result in undetected, and misleading data. An NTSB review of the functional failure rates table found the following information for AoA sensors.

Table 5 ADIRS Functional Failure Rates

ADIRS Functional Group	Loss of function	Misleading Data
Angle of Attack	Left	<1E-3
	Right	<1E-3
	All	<1E-7

The review also found that Boeing considered the effects of a single AoA sensor providing "erroneous data" within the lower branches of a fault tree with the "Top Event" titled "Misleading Air Data from the Left and Right ADIRU - Airspeed/Altitude". The fault tree showed there were two failure conditions that contributed to this top event:

- Misleading Air Data from the Left ADIRU, and
- Misleading Air Data from the Right ADIRU

There are four failure conditions that contribute to the "Misleading Air Data from the Left ADIRU" hazard. One of these conditions was titled "Erroneous AoA-L data from the Captain's side". The fault tree showed the following two ways (or failure conditions) that could lead to "Erroneous AoA-L data from the Captain's side".

- Failure of the AoA-L vane/Annunciation
- incorrect AoA output from the ADIRU-L output

For the "failure of AoA-L vane / annunciation", the fault tree showed that this event could occur by the combined (ANDed) result of the following two failure conditions:

- Loss of AoA-L Heat Annunciation
- Erroneous AoA-L Sensor

In 2019, Boeing advised NTSB of an error in this fault tree in that the two conditions should not have been combined with an AND gate. In a June 28, 2019, revision to the SSA, "Erroneous AoA-L data from the Captain's side" is revised to show three separate conditions combined with an OR gate, meaning any one by itself could result in erroneous AoA data:

- Erroneous AoA-L Sensor

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- *Incorrect AoA output from ADIRU-L output*
- *Loss of Power to AoA-L Heater*

Because the ADIRS top level event was a combination of Misleading data from both ADIRUs, there was no further elaboration. A combination of two AOA misleading events equates to no greater than 1E-9, or sufficient to meet a catastrophic hazard. Effectively, the safety assessment of the ADIRS protected its own functions and leaves it to downstream users to deal with a likelihood of 1E-5 failure rate to receive AoA erroneous data.

It should be noted that the ADIRS SSA does not account for stall warning; that is the SMYD and it was not discussed (presumably unchanged from the 737 NG). ADIRS does declare a MAJOR hazard if one source of airspeed and/or altitude is misleading.

The EDFCS SSA is focused on the software and hardware contribution to failures of the EDFCS equipment.

From the JT610 Final Report:

With regards to MCAS, the SSA indicated that the inclusion of the new MCAS function creates new failure modes affecting the probability of runaway stabilizer trim which cannot be arrested by the column cutout switches.

As previously described, the MCAS function normally activates only during manual flight, and operates by trimming the horizontal stabilizer in the nose-down direction while the aircraft is executing a high-AOA maneuver.

Any erroneous activation of the MCAS ENGAGE output will energize the bypass relay and prevent aft column inputs from interrupting nose-down automatic trim commands. To prevent a failure condition of an erroneous MCAS activation preventing the column cutout mechanism from interrupting an uncommanded nose-down automatic stabilizer trim command, Boeing modified the fault tree for the failure conditions titled "Erroneous Runaway/oscillatory stab output un-arrested by column cutout".

The failure was one of eight conditions that contributed to a higher-level failure condition titled "Autopilot Malfunction in the Pitch Axis at Low Altitude." This failure condition is one of four conditions that contributes to the Top-Level event titled "Autoflight malfunction at low altitude which results in unsafe flight path in autopilot OFF, single channel, or fail passive configuration." This Top-Level event was identified as a catastrophic hazard as part of Boeing's EDFCS functional hazard assessment.

An NTSB review of the modifications incorporated into the fault tree titled "Erroneous Runaway/Oscillatory stab output un-arrested by column cutout" revealed that the following two failure conditions "AND'ed" together resulted in the hazard.

- *Column Trim Cutout Fails to Interrupt Stab Motion*
- *Undetected Stabilizer trim runaway*

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For the "Column Trim Cutout Fails to Interrupt Stab Motion" hazard, the fault tree identified two potential failure conditions (OR'ed together) that could result in the hazard. One of the failure conditions "FCC-730 produces undetected erroneous MCAS or FLAPS Up/Dn discrete" is where the fault tree begins to address the erroneous activation of the MCAS Engage outputs.

Tracing the failure conditions that could lead to the hazard identified by the SCD led to the event titled "input failures cause FCC to produce an undetectable erroneous MCAS engage discrete". The probability for this event was <1E-9.

In this context, the FCC protects against its own hardware or software introducing misleading data. In this context, a valid AoA reception is judged to be accurate, not misleading. The conclusion from the FCC SSA is that the catastrophic hazard relating to MCAS malfunction from erroneous input was solely from the corruption within the FCC itself to the hazard.

While input failures within the FCC may be protected to 1E-9, from what is known, the Stab Trim and MCAS outputs from one FCC is probably 1E-5 if operating on a single processor, but could be 1E-9 if operating on both processors with tandem output control.

The Stabilizer Trim Control SSA includes an Appendix with an FHA that identified the severity of hazards due to the implementation of stabilizer trim changes.

From the JT610 Final Report:

An NTSB review of Appendix "G" found that the introductory section of the SSA had not been updated to reflect the March 2016 MCAS maximum authority changes...There was no mention that MCAS had been revised to improve flaps up, low Mach stall characteristics and identification...the Appendix still reflected a pre-March 2016 MCAS maximum authority limit of 0.6 degrees.

However, an NTSB review of Boeing internal documents confirmed that the FHAs had in fact been reassessed each time that MCAS requirements were changed, include the change in authority limit from 0.6 to 2.5 degrees. In all cases, the reassessment found that the FHA categories had not changed.

In a July 2016 briefing, Boeing provided the FAA with a presentation on stall characteristics and configuration changes. At this briefing, Boeing discussed some of the physical aerodynamic devices (relocation of stall strip, vortex generators (VG) configurations, etc.) they used to improve the stall characteristics with only limited success. During the briefing Boeing discussed their intent to expand the MCAS function to activate at lower Mach speeds. FAA well understood that greater MCAS authority would likely be necessary...In the Fall of 2016...the maximum MCAS authority of 2.5 deg in the low speed region was specifically covered.

Boeing indicated that fault tree analysis were only performed on the FHA events that were determined to be either Catastrophic or Hazardous, which is constant with the

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guidance in SAE ARP 4761. As described above, unintended MCAS activation was shown to be Major in the normal flight envelope and Hazardous in the operational flight envelope.

Flight Envelope

Flight envelope is a term to describe the range of conditions an airplane is exposed to from departure to arrival. [FAA Advisory Circular AC 25-7D](#) provides a definition of the normal flight envelope, the operational flight envelope, and the limit flight envelope. Each flight envelope is more and more extreme, edging to precipice of controlled flight itself.

Considering only speed and angle of attack (α), flaps-up.

Normal Flight Envelope (NFE) extends between the minimum and maximum operating speeds. The maximum speed would be V_{mo} or M_{mo} . The minimum speed is the lowest you can select, affording at least 40 deg. bank angle (or 1.3g maneuver margin).

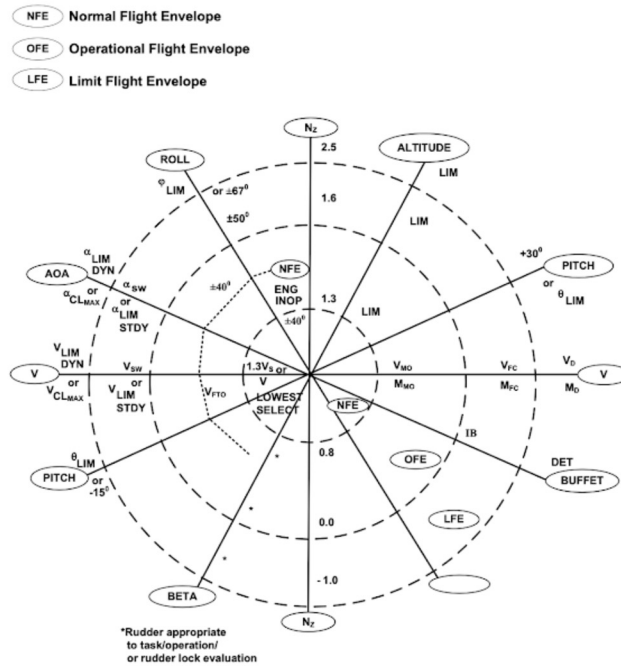
The NFE border with the Operational Flight Envelope (OFE) begins at speeds below the 1.3g minspeed.

The OFE border with the Limit Flight Envelope (LFE) begins at the stall warning speed, or α_{sw} . This is the point that the stick shaker is activated.

The LFE extends then to the point of maximum coefficient of lift (Cl_{max}), beyond which the airplane is stalled.

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Figure E-4. Flaps UP Flight Envelopes



AC 25-7D

For the purpose of AC 25-7D Handling Qualities Rating Method (HQR), a method of determining probable Versus improbable flight conditions, the probability of encountering the OFE was determined to be 1 in 1000 (1E-3) and for entering the LFE to be 1 in 100,000 (1E-5).

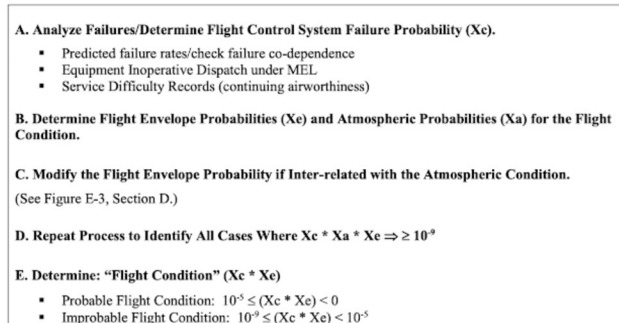
Figure E-3. Probability of Occurrence Guidelines

A. Flight Envelope (Xe)		
		Probability of occurrence (at flight envelope boundary)
Normal Flight Envelope	Generally associated with routine operational and/or prescribed conditions, either all engines operating or one engine inoperative.	10^0
Operational Flight Envelope	Generally associated with warning onset; outside the normal flight envelope.	10^{-3}
Limit Flight Envelope	Generally associated with airplane design limits or EFCS protection limits.	10^{-5}
Refer to this figure and figures E-4 and E-5 for more detail on determining which flight envelope is applicable. It may be necessary to consider several of the pertinent flight parameters together to determine which flight envelope a given flight condition is in. For the more influential flight parameters, such as angle-of-attack (AOA), speed, and load factor normal to the flight path (N_z), the choice of which flight envelope a condition is in may be determined by as few as one of the parameter values. Since the flight envelopes cover ranges of parameters (e.g., for Flaps UP, N_z in the LFE can be from 1.6 to 2.5), the above target probabilities for OFE and LFE might vary slightly depending on the expected airplane behavior and the assigned task.		

AC 25-7D

Further to the calculation, AC 25-7D teaches that you combine the predicted failure rate (or the likelihood of malfunction) with the probability of encountering the failure.

Figure E-6. Combining Values

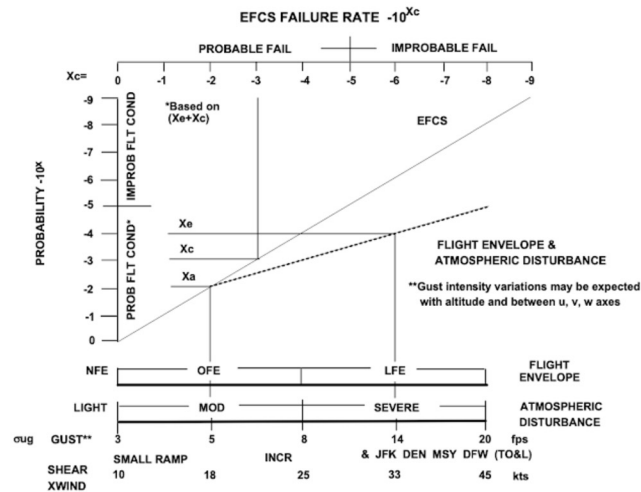


AC 25-7D

- E.2.7 Figure E-6 presents the method for combining the various flight condition parameter probabilities to determine the minimum acceptable handling qualities rating for each combination of these parameters. This method is shown graphically in Figure E-7.

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Figure E-7. Probability Guidelines to Determine HQ Requirements



AC 25-7D

The stated purpose of the determination of probable Vs improbable fail was solely for determining the required handling qualities depending. In the following table E-2, the further delineation of atmospheric disturbance, demonstrates the increasing demand on controllability as the airplane gets pushed around.

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Table E-2. Minimum HQ Requirements

Flight Condition (Xe*Xe)	Atmospheric Disturbance (Xa)								
	Light			Moderate			Severe		
	Flight Envelope (Xe)								
	NFE	OFE	LFE	NFE	OFE	LFE	NFE	OFE	LFE
Probable Condition	S	S	A	A	C	C	C	C	C
Improbable Condition	A	A	C	C	C		C		

NFE = Normal Flight Envelope

OFE = Operational Flight Envelope

LFE = Limit Flight Envelope

S = Satisfactory

A = Adequate

C = Controllable

AC 25-7D

From the JT610 Final Report:

FAA advisory Circular 25-7C Appendix 5 lists the probability of being outside the normal flight envelope as 1E-3. Therefore, a condition that meets the integrity requirements for Major within the normal flight envelope also meets the Hazardous integrity requirements for operational flight envelope.

Therefore, unintended MCAS operation FHA events were not evaluated in the fault tree analysis as there were assess MAJOR in the normal flight envelope; Boeing indicated that is consistent with FAA regulations and the Boeing process.

Claiming the Discount

The safety analysis is ultimately managing functional development assurance level.

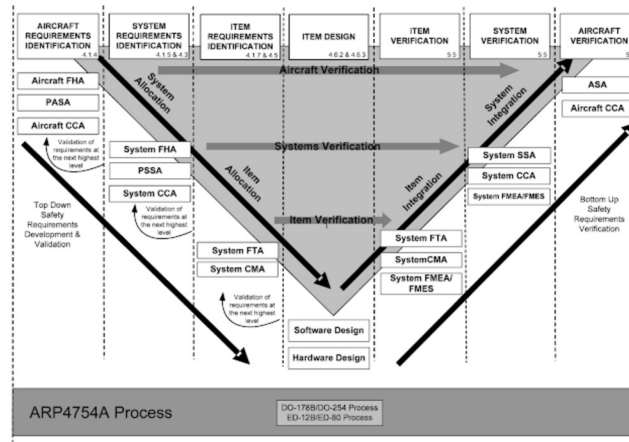
Functional development assurance level applies at the airplane level, and down to both hardware and software.

A system meeting a HAZARDOUS criteria is functional development assurance level B.

The functional development assurance level prescribes the software and hardware levels.

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From ARP4754A:



From DO-178C:

Software Level Definition

This document recognizes five software levels, Level A to Level E. For the example failure condition categories listed in section 2.3.2, the relationships between these software levels and failure conditions are:

- Level A:** Software whose anomalous behavior, as shown by the system safety assessment process, would cause or contribute to a failure of system function resulting in a catastrophic failure condition for the aircraft.
- Level B:** Software whose anomalous behavior, as shown by the system safety assessment process, would cause or contribute to a failure of system function resulting in a hazardous failure condition for the aircraft.
- Level C:** Software whose anomalous behavior, as shown by the system safety assessment process, would cause or contribute to a failure of system function resulting in a major failure condition for the aircraft.

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RTCA ARP 4754A describes the influence of system architecture on Functional Development Assurance Level with multiple members. Effectively, a level B hazard requires a single member FDAL level B or two members FDAL C. A system whose software that is developed to meet a level C hazard does not necessarily satisfy a level B hazard.

From ARP4754A:

TABLE 3 - DEVELOPMENT ASSURANCE LEVEL ASSIGNMENT TO MEMBERS OF A FUNCTIONAL FAILURE SET

TOP-LEVEL FAILURE CONDITION CLASSIFICATION	DEVELOPMENT ASSURANCE LEVEL (NOTES 2 & 4)		
	FUNCTIONAL FAILURE SETS WITH A SINGLE MEMBER	FUNCTIONAL FAILURE SETS WITH MULTIPLE MEMBERS	
		OPTION 1 (NOTE 3)	OPTION 2
Column 1	Column 2	Column 3	Column 4
Catastrophic	FDAL A (NOTE 1)	FDAL A for one Member, additional Member(s) contributing to the top-level Failure Condition at the level associated with the most severe individual effects of an error in their development process for all applicable top-level Failure Conditions (but no lower than level C for the additional Members).	FDAL B for two of the Members leading to top-level Failure Condition. The other Member(s) at the level associated with the most severe individual effects of an error in their development process for all applicable top-level Failure Conditions (but no lower than level C for the additional Member(s)).
Hazardous/ Severe Major	FDAL B	FDAL B for one Member, additional Member(s) contributing to the top-level Failure Condition at the level associated with the most severe individual effects of an error in their development process for all applicable top-level Failure Conditions (but no lower than level D for the additional Members).	FDAL C for two of the Members leading to top-level Failure Condition. The other Members at the level associated with the most severe individual effects of an error in their development process for all applicable top-level Failure Conditions (but no lower than level D for the additional Members).
Major	FDAL C	FDAL C for one Member, additional Member(s) contributing to the top-level Failure Condition at the level associated with the most severe individual effects of an error in their development process for all applicable top-level Failure Conditions.	FDAL D for two of the Members leading to top-level Failure Condition. The other Members at the level associated with the most severe individual effects of an error in their development process for all applicable top-level Failure Conditions.
Minor	FDAL D	FDAL D for one Member, additional Member(s) contributing to the top-level Failure Condition at the level associated with the most severe individual effects of an error in their development process for all applicable top-level Failure Conditions.	
No Safety Effect	FDAL E	FDAL E	
NOTE 1: When a FFS has a single Member and the mitigation strategy for systematic errors is to be FDAL A alone, then the applicant may be required to substantiate that the development process for that Member has sufficient independent validation/verification activities, techniques and completion criteria to ensure that potential development error(s) having a catastrophic effect have been removed or mitigated.			
NOTE 2: It is necessary to stay in the same row no matter the number of functional decompositions performed (e.g. for a Catastrophic Failure Condition any degree of decomposition from a top FDAL A FFS should include at least one FDAL A or two FDAL B Members).			
NOTE 3: If there is a large disparity on the numerical availability of the Members in the Functional Failure Set, the higher level FDAL should generally be assigned to the higher availability Member.			
NOTE 4: Some classes of 14CFR Part 23 /CS-23 aircraft have FDALs lower than shown in Table 3. See the current FAA AC23.1309 and equivalent EASA policy for specific guidance.			

On the hardware front, the goal in general is to limit the failure rate to an acceptable level.

The malfunction of MCAS is HAZARDOUS in the operational flight envelope. That is to be construed, if you are in the operational flight envelope, if MCAS then fails, it is HAZARDOUS. The concern is serial, not independent. There is no relief for the malfunction case.

The loss of MCAS and being in the operational flight envelope is a different question. For this case, the failure of MCAS is independent of being inside the operational flight envelope.

The failure rate for MCAS malfunction AND being in the operational flight envelope is no greater than $1E-7$. If the probability of being in the operational flight envelope is $1E-3$, then MCAS must limit its failure rate to no more than once time in 10,000 hours.

Malfunction rate is distinguishable (in this context) from failure rate, where malfunction is a valid but misleading hazard and failure is a simple loss of function (passive hazard).

An MCAS malfunction was treated as MAJOR in the normal flight envelope, a 1 in 100,000 ($1E-5$) malfunctions per hour rate.

An MCAS malfunction was treated as HAZARDOUS in the operational flight envelope, or 1 in 10,000,000 ($1E-7$) malfunctions per hour rate.

A MAJOR malfunction rate can be met by a single threaded system.

A HAZARDOUS malfunction rate cannot be met by a single threaded avionics system reliant on a single sensor.

If two channels are required to achieve a fail-safe architecture, then the function is only available if both channels are available. The loss of function is more likely with a fail-safe system than it would be for a single thread.

From the JT610 Final Report:

The FHA for uncommanded MCAS activation was classified as Major therefore, the FMEA and FTA were not required.

FMEA would have been able to identify single-point and latent failures which have significant effects as in the case of MCAS design.

It also provides significant insight into means for detecting identified failures, flight crew impact on resolution of failure effect, maintenance impact on isolation of failure and corresponding restitution of system.

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FTA would have also been able to show if the system architecture meets the numerical criteria set by the FHA. Again, in general, only failures categorized as Hazardous or Catastrophic are evaluated, even though in some situations, complex single-string Major failures are evaluated. Another benefit of FTA that had been missed was to demonstrate compliance with probabilities for combinations of failures. If a system does not meet minimum allowable probability, FTA can indicate where system is deficient and where mitigating action can be applied.

No Discount

The discount proposition is sensible based on combining independent factors to set loss of function failure rate. This is the very basis of high integrity design.

Exposure window is applied to failure rate to arrive at probability. Exposure window does not relieve the malfunction-based design assurance level. It does provide for required inspection intervals or other factors required for continuing certification.

The probability of being in the operational flight envelope applies to exposure window.

On one hand, the chance of MCAS malfunction happening at the same time the airplane is outside of the normal flight envelope are combined to achieve a composite failure rate. This leads to approving a system with one-tenth the integrity to achieve a MAJOR hazard as acceptable for a HAZARDOUS hazard. It does make numerical sense when considering loss of function.

On the other hand, if the airplane is outside of the normal flight envelope and the malfunction of MCAS is still HAZARDOUS, then there is no discount in malfunction rate.

The malfunction rate, once you are outside the normal flight envelope, should still be 1E-7 malfunctions per hour.

D.P. Davies wrote about this very issue regarding stick pushers in "Handling the Big Jets", first published in 1967, third edition in 1971. Stick pushers were used as a stall identification device specifically to prevent "super stall" on high-tail jets.

All this philosophy is conditional upon the qualification imposed that the device must be sufficiently reliable. Now 'sufficiently reliable' in this case is defined as:

On failing to operate when required to operate

The stall probability rate of 1 in 100,000 x the per flight failure rate of 1 in 100 flights = 1 in 10 million; which is the same rate as that as assumed for failure in a blind landing.

Expressed more simply this means that, 99 times out of a 100 occasions on which the airplane is stalled (with is one in every 100,000 flights), the pusher will push and

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recover the airplane.; on the hundredth occasion the pusher is assumed to have failed and the airplane possibly suffers a catastrophe. But this will occur only once in 10 million flights.

However much you might object to this possibility, it is an acceptable level (because it is extremely remote) and one on which are based a lot of other risks with are run in civil airline operation.

On operating when not required to operate (the runaway case)

For a modest upset, 1 in 100,000 flights; for a severe upset 1 in 10,000,000 flights.

Modest upset is defined as not worse than zero g.

A severe upset is defined as significantly negative g but not beyond proof negative.

These values are closely related to autopilot certification which even the stoutest opponent of stick pushers never seems to question.

Davies confirms that the method summarized for MCAS below, regarding HAZARDOUS in the operational flight envelope:

- loss of function
 - take the 1E-3 discount off of HAZARDOUS failure rate
 - 1E-4 per hour failure rate in MCAS case
- malfunction (runaway) case
 - Full HAZARDOUS malfunction rate 1E-7 per hour

From the JATR Report:

Recommendation R3.2: The FAA should issue a policy statement on the need for caution and early negotiation with the certification authority when an applicant proposes using additional guidance not originally intended for showing compliance to system safety requirements.

Observation O3.2-A: The JATR team observed that the SSA takes credit for the probability that the aircraft will be flying in certain portions of the flight envelope, as documented in AC 25-7C. A probability of 1E-3 for the aircraft in the operational flight envelope (OFE) was used in combination with the probability of the system failure to achieve the 1E-7 minimum probability required for the "hazardous" MCAS failure condition. Use of AC 25-7C is not a standard industry approach for 25.1309 compliance. The JATR team's view of the intent of the probability of 1E-3 for the OFE in the HQRM is to select flight test cases for handling qualities evaluation, not to support the quantitative aspects of 25.1309 or 25.672(c) compliance.

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Finding F3.11-A: HQRM guidance from AC 25-7C was applied for the evaluation of control systems malfunctions. The application of the probabilistic aspects of this guidance was appropriate to the determination of the required handling qualities, but may not be suitable for evaluation of the failure condition per AC 25.1309-1A, System Design and Analysis, and AC 25-7C.

Finding F3.11-B: For § 25.1309 compliance, the criticality of the failure condition should account for intensifying conditions, such as crew workload or multiple cockpit indications, and effects and interrelationship of failures with the flight envelopes.

Finding F3.11-C: Boeing's application of HQRM allowed for a reduced envelope in the evaluation of SPEED TRIM FAIL, which may not meet the intent of guidance within AC 25-7C and AC 25-1309-1A.

The FAA will need to offer some commentary, but the fact that JATR rejected the discount claim is very, very troubling. Boeing discounted MCAS to achieve this one condition. But Boeing has stated that this discount is business-as-usual. How many other system malfunctions are discounted in this manner?

The combination of effects from one misleading AoA vane are a MAJOR effect from ADIRS, of no consequence to EDFCS, and was concluded a MAJOR hazard from Stabilizer Trim.

The combination of effects from one AoA malfunction to MAJOR effects in Air Data, in Stall Warning, and in MCAS was not evaluated. Three MAJOR effects, each demanding non-normal checklists, in the takeoff and climb out flight phase, has been shown to be overwhelming workload, apparently CATASTROPHIC.

Is MCAS Stall Identification?

Boeing has consistently characterized MCAS as modifying the handling characteristics of the airplane, and in particular, was not a part of stall warning or stall identification. Boeing has absolutely described Speed Trim as part of Stall Identification.

Stall warning is just that, a warning. It normally does not take any action on the flight controls. Stick shaker is a clear stall warning. Elevator Feel Shift is an opposing force, not a driving force.

Stall identification (augmentation) is an action - it is doing something to the airplane to push the nose down. Stick pushers and stick nudgers are commonly used for stall identification. A stick nudger would have performed nicely in place of MCAS, but that would have required redesign of the feel system. Speed Trim is performing a stall identification function.

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Stall Identification should not suffer from single point malfunction, it should be inhibited if commanding negative g, and it should have an OFF switch.

Speed trim is single thread, has no normal acceleration inhibit, and has no OFF switch. It is not at all clear how the situation has been reached, as it extends into the 737NG at least. MCAS would benefit from each of these features.

Speed Trim was added to the 737-300. The original version of Speed Trim was inhibited in high alpha scenarios.

The 737-700 certification was held up by the European Joint Aviation Authorities (JAA) after the FAA had certificated it, in part over making a change to the Speed Trim System such that it would operate at any speed. The issue is plainly discussed as Stall Identification.

25 FEBRUARY, 1998

SOURCE: FLIGHT INTERNATIONAL

737-700 receives JAA approval after stall warning changes

Guy Norris/LOS ANGELES

Boeing's 737-700 obtained European Joint Aviation Authorities certification on 18 February after changes were made to increase stall warning. The modifications meet the JAA's insistence that the pilot be able to identify clearly the occurrence of a stall, even after the activation of the stick shaker. The resulting changes to the speed trim system, and related wiring, ...

Boeing Next Generation 737 chief project engineer Pete Rumsey says, "The JAA asked us to fly beyond the stick shaker. We came close to the specific requirements, but did not meet the letter of the law, which was written for older aircraft." The advanced design of the new wing means that, in a stall, "lift degrades very gradually. The aircraft continues to be controllable", says Rumsey.

The JAA insisted on the addition of a system to raise pilot awareness. "We are adding a speed trim system that will demonstrate the stall characteristics more. It will push the nose down as the aircraft goes into a stall," he says. Normally, the speed trim system is switched off automatically as the stick shaker is activated. The JAA ruling means that original safety systems have been redesigned to allow the trim system to activate in the event of a stall.

From AC25-7D:

The airplane is considered to be fully stalled when any one or a combination of the characteristics listed below occurs to give the pilot a clear and distinctive indication to cease any further increase in angle-of-attack, at which time recovery should be initiated using normal techniques.

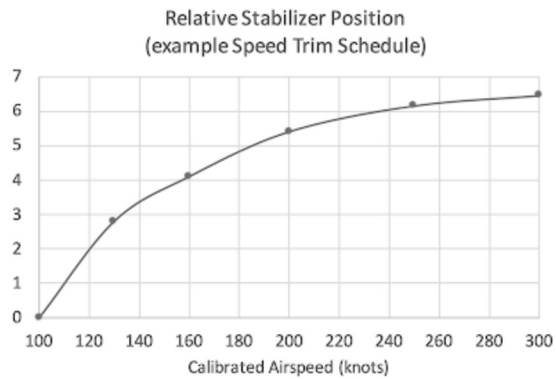
1. *The pitch control reaches the aft stop and is held full aft for two seconds, or until the pitch attitude stops increasing, whichever occurs later.*

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2. *An uncommanded, distinctive, and easily recognizable nose down pitch that cannot be readily arrested.*
3. *The airplane demonstrates an unmistakable, inherent aerodynamic warning of a magnitude and severity that is a strong and effective deterrent to further speed reduction. This deterrent level of aerodynamic warning (i.e., buffet) should be of a much greater magnitude than the initial buffet ordinarily associated with stall warning.*
4. *The activation point of a stall identification device that provides one of the characteristics listed above.*

Speed Trim command Airplane Nose Down as the airplane slows down. This meets criteria 4 adding to criteria 2 (above).

An example of a Speed Trim schedule is shown below:



The 737 NG FCOM does describe Speed Trim as part of Stall Identification.

737 Flight Crew Operations Manual

Stall Identification

Stall identification and control is enhanced by the yaw damper, the Elevator Feel Shift (EFS) module and the speed trim system. These three systems work together to help the pilot identify and prevent further movement into a stall condition.

During high AOA operations, the SMYD reduces yaw damper commanded rudder movement.

The EFS module increases hydraulic system A pressure to the elevator feel and centering unit during a stall. This increases forward control column force to approximately four times normal feel pressure. The EFS module is armed whenever an inhibit condition is not present. Inhibit conditions are: on the ground, radio altitude less than 100 feet and autopilot engaged. However, if EFS is active when descending through 100 feet RA, it remains active until AOA is reduced below approximately stickshaker threshold. There are no flight deck indications that the system is properly armed or activated.

As airspeed decreases towards stall speed, the speed trim system trims the stabilizer nose down and enables trim above stickshaker AOA. With this trim schedule the pilot must pull more aft column to stall the airplane. With the column aft, the amount of column force increase with the onset of EFS module is more pronounced.

From AC25-7D:

Probability of artificial stall warning and stall identification systems operating inadvertently:

The probability of inadvertent operation of artificial stall warning systems, during critical phases of flight, should not be greater than 10-5 per flight hour.

To ensure that inadvertent operation of the stall identification system does not jeopardize safe flight, and to maintain crew confidence in the system, it should be shown that:

- *No single failure will result in inadvertent operation of the stall identification system; and*
- *The probability of inadvertent operation from all causes is improbable (not greater than 10-5 per flight hour).*

A single failure of an AoA vane causes both MCAS to trigger and Stall Warning to trigger "inadvertently", but it does not cause Speed Trim to trigger (it is based on airspeed). Speed Trim is still single-thread on airspeed malfunction, and from hardware output.

Boeing has previously denied MCAS to be a part of stall identification.

The JATR report was justifiably concerned on the need to protect from a single-point malfunction.

From the JATR Report:

Recommendation R3.7: The FAA should review how compliance was shown for the stall identification system on the B737 MAX with respect to inadvertent operation due to single failures.

Finding F3.7-A: The JATR team considers that system features on the B737 MAX might constitute a stall identification system. This system is vulnerable to inadvertent actuation due to a single failure, which would not meet the accepted guidance contained within AC 25-7C, Chapter 8, Section 228.

MCAS is used only with flaps up, so it is not expected to be in operation close to the ground.

Speed Trim is described to operate when flaps are down or gear is up or airspeed below a threshold. I am assuming it is flaps down and gear up or flaps up and airspeed below a threshold. This allows the gear down discrete to block Speed Trim activation near the ground.

Ultimately, Speed Trim (and MCAS) are unbounded. They are allowed to drive the stabilizer to its full travel. A stick nudger or pusher, or any dedicated actuator used for augmentation is designed with limited authority by mechanical capability.

From the JT610 Final Report:

Inadvertent operation of the stall identification system should not cause catastrophic ground contact. This should be achieved by limiting the effect of the stall identification system to that necessary for stall identification purposes, without undue flight path deviation (e.g., by limiting the stroke of a stick pusher).

Alternatively, if inadvertent operation could result in catastrophic ground contact according to 25.1309(b)(1), the probability of inadvertent operation must be extremely improbable.

Inhibition of the system close to the ground (e.g., for a fixed time after liftoff or below a radar altitude) would not normally be an acceptable means of compliance with this requirement.

I am personally quite surprised that a normal acceleration factor was not included in MCAS. While I understood that Boeing had removed the "above 1g" criteria when MCAS was extended to low altitude, wing-level conditions, I would have expected an inhibit term, something like normal acceleration less than 0.7g.

From AC25-7D:

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Normal operation of the stall identification system should not result in the total normal acceleration of the airplane becoming negative.

AC25-7D Paragraph 42 offers further guidance for stall identification, from which it seems that there should be a procedure to deactivate the augmentation, an OFF switch.

From AC25-7D:

A means to quickly deactivate the stall identification system should be provided and be available to both pilots.

It should be effective at all times and should be capable of preventing the system from making any input to the longitudinal control system.

It should also be capable of canceling any input that has already been applied, from either normal operation or from a failure condition.

One of the flights (from the last 18 years) that dealt with stuck stall warning took action to suppress stall warning. This seems a very reasonable feature.

From the JT610 Final Report:

On the fourth flight, the stick shaker occurred after takeoff.

The flight crew elected to continue as returning would result in overweight landing and the weather along the route was clear.

About 40 minutes after takeoff, the flight crew pulled the circuit breaker of the affected control column with intention to eliminate noise and to make the stick shaker warning on the other side functioning normally.

JATR pointed out that the role of Speed Trim System (STS) and MCAS relate specifically to the suitability of the aircraft without any augmentation.

From the JATR Report:

Finding F3.4-A: The acceptability of the natural stalling characteristics of the aircraft should form the basis for the design and certification of augmentation functions such as EFS and STS (including MCAS) that are used in support of meeting 14 CFR part 25, subpart B requirements.

Recommendation R3.5: The FAA should review 14 CFR 25.201 (Stall Demonstration) compliance for the B737 MAX and determine if the flight control augmentation functions provided by STS/MCAS/EFS constitute a stall identification system.

Finding F3.5-C: The JATR team considers that the STS/MCAS and EFS functions could be considered as stall identification systems or stall protection systems, depending on the natural (unaugmented) stall characteristics of the aircraft. From its data review, the

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JATR team was unable to completely rule out the possibility that these augmentation systems function as a stall protection system.

What about Speed Trim?

Speed Trim System was introduced in 1984 on the 737-300. Speed Trim has performed well over the course of all these years. Speed Trim System includes a second monitor processor with a SPEED TRIM FAIL alert. The monitor processor cannot prevent the command processor from erroneous output. The discussions above would be relevant to Speed Trim and are likely based largely on how Speed Trim System was originally approved. Speed Trim System (not just the MCAS sub-function) is subject to the same hazards that MCAS prescribes. As long as the MCAS specific output discretes are protected sufficiently, the aft column cutout function is therefore intact, and any malfunction of Speed Trim (not MCAS) is likely at most a MAJOR hazard, as with any runaway.

The subsequent installations of Speed Trim on 757 and on 747-400 were designed with a command and monitor processor, each with an independent source of air data, whereby both processors can stop a malfunction (fail-safe). There was no open mandate to upgrade the 737 Speed Trim System to fail-safe, especially with the addition of MCAS, as part of a company-wide assessment of safety. Each model has unique factors, and those other models have two fully functioning stab trims systems, whereas the 737 has one stab trim system and a wheel.

Misleading AoA Vane is HAZARDOUS

I would conclude it also as a MAJOR effect for false stall warning from one SMYD.

The fragmented safety analysis process does not reflect the natural combination that will occur from this one single sensor failure - instead it is treated like a bunch of small bits, failing to appreciate the combined workload that can overwhelm pilots.

From The Boeing Ops Bulletin (6 Nov 2018)

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Additionally, pilots are reminded that an erroneous AOA can cause some or all of the following indications and effects:

- Continuous or intermittent stick shaker on the affected side only.
- Minimum speed bar (red and black) on the affected side only.
- Increasing nose down control forces.
- Inability to engage autopilot.
- Automatic disengagement of autopilot.
- IAS DISAGREE alert.
- ALT DISAGREE alert.
- AOA DISAGREE alert (if the AOA indicator option is installed)
- FEEL DIFF PRESS light.

There is no denying that Boeing and the FAA were presented with a cacophony of flight deck effects, and adding MCAS malfunction on top of this. Both the FAA and Boeing continued to view the situation as business-as-usual, no alarm bells were going off that a single AoA malfunction generated HAZARDOUS workload.

If a single AoA vane still causes a MAJOR event (Airspeed and Altitude disagree) and also another MAJOR event of false stall warning (stick shaker, minspeed/PLI anomaly, feel force increase), then the combination of two MAJOR events simultaneously is HAZARDOUS.

The addition of MCAS malfunction takes the combination to CATASTROPHIC. Two tragedies stand in testimony, there can be no denial.

With a need for continued functionality in the presence of one failed sensor, a third AoA source or enhanced means is needed to detect malfunction in either existing AoA vane. A synthetic AoA may be achieved by reference to airspeed and a basis for gross weight sufficiently accurate to resolve AoA differences. This is a generic problem facing many Boeing airplane models, and while not urgent, demands corrective action, if even on a go-forward, best-practices basis.

The entire series on 737 MCAS

[Connecting the Dots: From Command to Action](#)
[Movable Stabilizer](#)

[737 Pitch Trim Incidents](#)
[The Beat Goes On](#)
[What Happens on ET302?](#)
[AoA Vane must have Failed, the Boeing Fix is In, Senate Grills FAA](#)
[How Did MCAS Get Here and What Hurdles Remain?](#)
[Taking the Next Steps while Awaiting on the Preliminary Report from ET302](#)
[Ethiopian ET302 similarities to Lion Air JT610](#)
[What have we learned this week?](#)

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[Comparing Ethiopian ET302 to Lion Air JT043, JT610](#)

[Angle of Attack Vane Failure Modes](#)

[First Look at JT610 Flight Data](#)

[737 FCC Pitch Axis Augmentation - Command Integrity Mandate for Dual Channel, Fail-Safe](#)

[737 MCAS - Failure is an Option](#)

[Stabilizer Trim](#)

Stay tuned!

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Peter Lemme has been a leader in avionics engineering for 38 years. He offers independent consulting services largely focused on avionics and L, Ku, and Ka band satellite communications to aircraft. Peter chaired the SAE-ITC AEEC Ku/Ka-band satcom subcommittee for more than ten years, developing ARINC 791 and 792 characteristics, and continues as a member. He contributes to the Network Infrastructure and Interfaces (NIS) subcommittee developing Project Paper 848, standard for Media Independent Secure Offboard Network.

Peter was Boeing avionics supervisor for 767 and 747-400 data link recording, data link reporting, and satellite communications. He was an FAA designated engineering representative (DER) for ACARS, satellite communications, DFDAU, DFDR, ACMS and printers. Peter was lead engineer for Thrust Management System (757, 767, 747-400), also supervisor for satellite communications for 777, and was manager of terminal-area projects (GLS, MLS, enhanced vision).

An instrument-rated private pilot, single engine land and sea, Peter has enjoyed perspectives from both operating and designing airplanes. Hundreds of hours of flight test analysis and thousands of hours in simulators have given him an appreciation for the many aspects that drive aviation; whether tandem complexity, policy, human, or technical; and the difficulties and challenges to achieving success.

Senator DUCKWORTH. Thank you. Mr. Sumwalt, can you talk about the accident chain, the concept of these decisions that pile up and leads up to those Lion Air pilots, for example, fighting to save that aircraft and how these decisions add up?

Mr. SUMWALT. Yes. As you know Senator Duckworth, the NTSB was an accredited representative to the Lion Air investigation as well as the Ethiopian accident investigation. We participated closely with both of them. But since the Lion Air is wrapped up, we have worked closely with the Indonesian authorities. We commented on their report. We feel that their report, the Indonesian report, the KNKT report is comprehensive and we are satisfied with that report. So, I think that report outlines the chain of events was not just one factor, there were several issues that led to that crash.

Senator DUCKWORTH. Thank you. I yield back.

The CHAIRMAN. Thank you, Senator, Duckworth.

Senator Cruz.

Senator CRUZ. Thank you, Mr. Chairman. Chairman Sumwalt, the NTSB report that you mentioned in your testimony stated that the NTSB is, "concerned that the accident pilot responses to the unintended MCAS operation were not consistent with the underlying assumptions about pilot recognition and response that Boeing used based on FAA guidance for flight control system functional hazard assessments, including for MCAS as part of the 737 MAX design." Why do you think it was that Boeing made the wrong assumptions?

Mr. SUMWALT. Senator Cruz, thank you for that question. And what we do know is that to simulate the MCAS or to assess the level of hazard, the less level of risk associated with that, they put Boeing pilots, test pilots, in the engineering simulator. And while they were flying, all of a sudden, the trim started moving. They wanted to see how a pilot would have reacted.

And if they reacted the way that Boeing expected them to do, then they said OK, well the pilot will immediately recognize this problem. They will notice because the nose is starting to pitch down, they will notice because it has increased pressure on the control wheel, and one other thing—and the stab trim wheel was moving. That is all correct. But what Boeing failed to account for in their assumptions was to consider that the MCAS could have failed because of another reason.

The MCAS could have activated because of a failure of the angle of attack which would have led to numerous other alerts and warnings in the cockpit. So, with a failed angle of attack sensor, they would have had a low air speed indication on their primary flight display. They would have gotten a stick shaker or stall warning which is rattling the stick and making a lot of noise. They would have gotten an oral warning that says "air speed low, air speed low." They would have had various lights in the cockpit.

So, the long and the short of it is that Boeing only evaluated pilots performance with the stab trim itself moving. They did not simulate or replicate how multiple failures could affect a pilot's performance.

Senator CRUZ. And why did the FAA processes not catch these failed assumptions?

Mr. SUMWALT. Well, that is a great question, Senator. And I am not sure that I know the answer to that. But that is why we have issued these seven recommendations, is so that these design assumptions can be more realistic. We found in three incidences in the two accident flights plus the Lion Air flight prior to the accident flight, we have seen three cases where the pilots did not perform in accordance with the assumptions that Boeing used.

Senator CRUZ. And is a bird strike a scenario that engineers designing a plane should anticipate and the regulators focusing on a plane should anticipate?

Mr. SUMWALT. I believe so and I believe they do in certain areas. I am not sure how it might apply to this. As you know, there is conjecture that perhaps a bird might have taken out the AOA sensor on the Ethiopian aircraft. I do not know if that is a part of the total risk assessment for the 737 MAX as it relates to MCAS.

Senator CRUZ. Is there any indication either Boeing or the FAA considered the possibility that a bird strike would share off the angle of attack sensor?

Mr. SUMWALT. I do not know but I can certainly look into that and get back with you if you like.

Senator CRUZ. I would appreciate that very much. Mr. Hart, one of the key findings of the Joint Technical Review Committee report is that the FAA's visibility into important system safety information was, "incomplete and fragmented." JATR then went on to say, if the FAA had been more involved in the certification of the MCAS, this, "would likely have resulted in design changes that would have improved safety." Based on the JATR's findings, why would the FAA accept incomplete and fragmented safety information from Boeing and what can be done to fix that?

Mr. HART. Thank you for the question. That is the purpose of the recommendation that the communication process that the ODA be less bureaucratic and less complicated, so the communication process isn't undermined by the complexity of that situation. So the FAA was not adequately aware of the evolution of the MCAS from a relatively weak system to a much more robust system.

The FAA wasn't aware of the details of how adequately the transformation of the MCAS from a high-speed wind up turn correction to a low speed angle of attack correction and were the assumptions properly considered in that process. The communications to the FAA were not adequate for it to be fully aware of the impact of those issues.

Senator CRUZ. Thank you.

The CHAIRMAN. Thank you, Senator Cruz.

Senator Blumenthal.

Senator BLUMENTHAL. I have just one question and you may consider it outside of your expertise, but the CEO of Boeing told us today that they made mistakes and regretted them and wanted to take action in response to do the right thing for the families who were affected, the loved ones of the victims.

Boeing has said that it will take responsibility specifically for the Lion Air crash resulting in the deaths of 189 people in Indonesia last year and the Ethiopian Airlines crash that killed 157 people. But it has filed court documents for the Lion's aircraft indicating that it will move to change the venue of the case to Indonesia

where the plane was maintained if settlement talks fail. The case was filed in the Northern district of Illinois where Boeing is headquartered, as you know.

Resolving these claims in Indonesia seems a lot less likely to provide justice to those families. There is no Seventh Amendment right to a jury trial there. There is no requirement of discovery. There is no rule allowing for depositions. Would you agree with me that equity, fairness, justice would argue in favor of keeping these cases in the United States?

Mr. SUMWALT. My friend, Chris Hart, is a Harvard-educated lawyer.

Senator BLUMENTHAL. He is a Harvard Law School graduate and practicing lawyer in addition to being a pilot so if you want to defer to him, that is fine.

Mr. SUMWALT. Absolutely.

Mr. HART. Thank you for the question. I am a Harvard-trained attorney but I do not know anything about the litigation strategy to be able to comment on what they want to do regarding litigation. That is way outside of my lane. JATR did not consider it and I am not really—I do not consider myself competent enough to speak to that issue.

Senator BLUMENTHAL. Well in general, wouldn't you consider this court to the United States to be a better place to do justice for American families than the courts of Indonesia?

Mr. HART. I thank you for the question, but I am not enough of a litigator to be able to give you a competent answer.

Senator BLUMENTHAL. Thank you, Mr. Chairman.

The CHAIRMAN. Thank you, Senator Blumenthal. We are going to close this hearing now.

Senator CANTWELL. Can I just ask one more thing?

The CHAIRMAN. Sure. Senator Cantwell.

Senator CANTWELL. Thank you, Mr. Chairman for a second round. I just wanted to clarify, Mr. Hart, I think I heard earlier from the testimony from the company that they actually do think that the FAA knew about the level of trim. I think this is going to be a big issue. I think we are going to hear a lot more about this, but you would hope that a plan at the very beginning of certification would include that data then they would make the decisions, but I am concerned that the level of automation and technology and human response.

I want to see the best engineers. I think when the automobile industry and Toyota went through this and we didn't know what happened, we basically called NASA and said would you look at this code and figure out what happened? OK. I do not want to call NASA to look at software code. I want the FAA to be the best technology engineers in understanding problems with software, problems with automation, and challenges with human response. That is why part of our legislation is that center of excellence for the FAA.

Just by the way, I have done two other center of excellences, one on composite manufacturing because the FAA didn't know enough about composite to know how to certify the plane, and one on biofuels for jets because they also do not know how to certify fuel sources for planes if they do not understand jet fuel themselves. So

I am a believer that we give the FAA the extra resources and tools so they can stay ahead or at least, you know, know the right parameters of debate.

But isn't the right parameter of debate have to focus on this human technology interface today? Isn't that where we are? Because we saw those 10 years of making us safer, and yet this level of integration has also told us that 5 of the last accidents were all around this. And I think, you know, for me and many Americans are waking up wondering what is a pitot tube and, you know, an AOA sensor on the outside of the plane giving commands and responses to inside the cockpit without the pilots understanding.

So I just feel that the FAA, and we have had this discussion with Captain Sullenberger, needs to understand human response to these automation systems. What do you say about that recommendation of a center of excellence, Mr. Hart or Mr. Sumwalt?

Mr. HART. Thank you for the question. It also gives you an opportunity to respond to Senator Blumenthal raising the same issue. And that is, I think that as first of all the type of problem we are going to see with airplane safety in the future in my view is not going to be things falling off the airplane like the DC-10 engines. It is going to be the pilot/airplane interaction issue.

So the human factors piece is crucial and that is why I am totally on board with the human factors recommendations that the NTSB made. There are two problems. One is the reference to multiple things going wrong at the same time. I would add to that, it is not just multiple things going wrong, it is also never having seen it before even in training. That is really the challenge. It is when they are seeing this for the first time in real time, as in a series of accidents where this has happened, and it has been unsuccessful.

The one exception to that was Sully when he had a kind of situation that he had never seen before, even in training, and he handled it masterfully.

Senator CANTWELL. And that—listen I think I have consulted him a lot about this but that is why he came to us after the Colgan Air and said do not change the regulations on the copilot for regional aircraft because you do not have enough time. You do not have enough time to talk. So I think if you are going to develop a system for certification and give it to the FAA, I think the FAA has to know the parameters of human response and what pilots are capable of, we just need a lot more data.

If this is the route we are going to keep going on innovation, then we just need to know a lot more about what is that factor. I think even, I do not want to speak for him, but I think his perception is that that is where you have to start because you do not have any way to judge a system if you do not really understand what the human limitation is.

Mr. HART. And that goes to my point that the leading technologists in these rapidly advancing and innovative technologies, the leading technologists are not going to be with the regulator. That is why this is not an FAA problem, this is an international certification problem, because the regulators are not able to hire and retain the leading technologists in these rapidly advancing technologies. They are going to be with the companies.

Senator CANTWELL. But I want the FAA to have enough data, information, and understanding to ask the right questions. Because if they are not asking the right questions because they do not understand the technological impact, we are going to have a problem. OK, so we have to make sure they understand the R&D and at least the parameters, whether that is composites, biofuels, or cockpit automation.

Mr. HART. That is precisely why adequate information is so crucial. Straight to your point.

Senator CANTWELL. Yes.

Mr. HART. Thank you for making that point.

Senator CANTWELL. Thank you, Mr. Chairman.

The CHAIRMAN. Senator Blumenthal.

Senator BLUMENTHAL. Just one quick question. If the FAA were able to pay enough to offer career opportunities would that affect your judgment that they cannot hire the leading technologist as you put it?

Mr. HART. I cannot speak to the totality of the circumstances why the regulators do not have those people but that is probably part of it, yes.

Senator BLUMENTHAL. Well, I am just really discouraged and frankly somewhat skeptical about your view that the FAA should be sort of doomed to failure and has to outsource safety.

Mr. HART. I do not mean to suggest they are doomed to failure. I am suggesting that is why I think the collaborative process of the delegation will continue because there is no way that in my view, in the way that things are currently situated, the FAA is going to have the expertise within house to do it without the collaboration.

Senator BLUMENTHAL. Well, putting aside the word collaboration, I hope we can prove you wrong by in fact incentivizing both financially and otherwise people with those skills to go to work for the FAA because that is where the disinterested and independent safety function belongs. If you outsource safety, that is doomed to failure.

Mr. HART. I certainly agree with you. That would be ideal. Yes, Senator Blumenthal.

Senator BLUMENTHAL. Thank you.

The CHAIRMAN. Well, thank you very much. And thanks to the members of the Committee who have participated throughout. I have to say, this has been one of the most difficult hearings I have ever participated in, and I know it has been difficult for the family members who are still with us in the room. Some of them had to leave. Let me reiterate what I said at the outset, that this Committee, under my leadership and Senator Cantwell's leadership, is working to obtain as full of an answer as possible. We owe it to the public and we owe it to the families and to the victims. You have my assurance that we are not finished with the work.

That said, the hearing record will remain open for two weeks. During this time, Senators are asked to submit any questions for the record. Upon receipt, all witnesses are requested to submit their written answers to the Committee as soon as possible. I thank the witnesses for appearing today, and the hearing is now adjourned.

[Whereupon, at 1:16 p.m., the hearing was adjourned.]

A P P E N D I X

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. ROGER WICKER TO DENNIS MUILENBURG

Question 1. Mr. Muilenburg, the Maneuvering Characteristics Augmentation System (MCAS) has been described as an anti-stall system that Boeing installed on the Boeing 737 MAX to address pitch stability concerns caused by the use of larger engines on the aircraft than earlier versions of the 737. However, it has also been said that MCAS was added to the 737 MAX so that it handled similarly to the 737 NG from a pilot's perspective.

What was the original purpose of MCAS? What would have been the risks associated with the 737 MAX had MCAS not been added as a flight control law?

Answer. In 2009, Boeing began to explore a possible re-engining of the 737 NG series airplane to improve noise pollution and fuel efficiency. In approximately 2010, early in the development process, testing and analysis showed that the contemplated design changes affected the airplane's handling characteristics in certain high-speed, high angle of attack conditions involving a rarely encountered maneuver known as a wind-up turn. Although most commercial pilots go their entire career without making such a turn in commercial flight, certification requirements exist for handling characteristics in these scenarios.

If MCAS had not been added as a flight control law to the 737 MAX, a different solution would have been necessary to achieve the required handling characteristics. Boeing personnel, including engineers and pilots from multiple disciplines, considered a number of alternatives for improving the airplane's handling qualities in these unusual scenarios, including physical changes to the airplane. Ultimately, Boeing determined that the addition of MCAS, coupled with the implementation of a modified outboard wing vortex generator pattern, represented an appropriate solution for addressing the handling qualities issue. This approach in designing MCAS allowed for a straightforward expansion of the pre-existing Speed Trim function, as an integrated part of an existing flight control system. The incorporation of MCAS allowed Boeing to safely satisfy certification requirements for handling characteristics while staying within the framework of the existing airplane architecture, consistent with a fundamental airplane design principle of minimizing unnecessary complexity. Boeing implemented the initial MCAS requirements in early 2012, although evaluation of the function continued afterwards, and the technical team recognized that further refinement of the design would likely be necessary going forward. The incorporation of MCAS was validated through rigorous testing and analysis, including piloted simulator sessions, wind tunnel tests, and a variety of engineering analytical techniques.

Question 2. During the hearing you were asked about two sets of documents involving former Boeing employee Mark Forkner: (1) a November 16, 2016 instant message between Mr. Forkner and a Boeing colleague, and (2) e-mails between Mr. Forkner and someone at the FAA in which Mr. Forkner used the phrase "jedi mind tricking." Please clarify when Mr. Muilenburg learned of each.

Answer. As to the instant message exchange involving former Boeing employee Mark Forkner: while Mr. Muilenburg does not recall seeing the document itself until it became public a few weeks before the hearing, he was made aware of the document in a briefing earlier this year, including the fact that the message contained a reference by Mr. Forkner to having unknowingly lied to regulators. Since the document became public, Mr. Muilenburg has had the opportunity to review the entire exchange and become familiar with all of its details. With respect to the other e-mails from Mr. Forkner that were referenced by Chairman Wicker in his question, Mr. Muilenburg was not aware of those e-mails until he read about them in the media in the weeks prior to the hearing.

Question 3. Please describe the steps Boeing took after it learned that the AOA DISAGREE alert on the MAX was not operable on all airplanes.

Answer. In August 2017, several months after the software delivery and the commencement of MAX deliveries, Boeing engineers identified that the display system software delivered to Boeing by a supplier incorrectly linked the AOA DISAGREE alert to an optional AOA indicator, after internal testing revealed that the alert was not working as expected.

Immediately upon identifying the discrepancy between the requirements and the software, Boeing initiated its standard process for determining the appropriate resolution of such discrepancies. Boeing quickly initiated a “problem report”—the name for the standard process—and assigned it to the supplier to verify Boeing’s assessment. The supplier conducted testing and confirmed the issue Boeing had identified.

Under Boeing’s procedures, any inconsistency between the airplane requirements and the product delivered by a supplier must be immediately resolved if it renders the airplane unsafe. Deferring the solution to a later date is appropriate only if Boeing’s experts can determine that the airplane remains safe, it remains certifiable, and there is no adverse operational impact. Here, to decide the appropriate disposition of the AOA DISAGREE alert issue, Boeing conducted a rigorous review that involved multiple company subject matter experts, including systems engineers, pilots, and crew operations specialists. This review determined that the absence of the AOA DISAGREE alert did not adversely impact airplane safety, certification, or operations, and therefore correction of the issue appropriately could be deferred until the next routine software update. The responsible authorized representative, who exercises authority delegated by the FAA, concurred with this recommendation for deferral.

Boeing’s review identified three main factors supporting the conclusion that deferral was permissible. First, no airplane or system safety assessment takes credit for the activation of the AOA DISAGREE alert as part of the analysis—accordingly, the absence of the alert did not alter the analysis in these assessments demonstrating that the airplane is safe. Second, based on consultations with pilots, the team determined that the same conditions that would activate the AOA DISAGREE alert would also likely cause unreliable airspeed information, and thereby trigger the indicated airspeed (IAS) DISAGREE alert. Thus, even without the AOA DISAGREE alert, the IAS DISAGREE alert would remain available to prompt pilot action in response to the expected effects of erroneous AOA data. Third, the team noted that other maintenance indicators on the airplane would detect a damaged AOA vane that remains faulty for two consecutive flights. Thus, a damaged vane would likely persist for only a limited amount of time before prompting maintenance action, even in the absence of the AOA DISAGREE alert.

Based on these considerations, the review concluded that the existing functionality was acceptable until the next planned display system software update, when the alert and the indicator could be delinked, and the AOA DISAGREE alert made standard per the requirements. That update was scheduled for 2020, when the Dash-10 variant of the MAX was expected to enter into service. Boeing recorded this disposition in its certification summary documentation for the MAX dated September 2017.

Boeing personnel discussed notifying 737 MAX operators about the deferral decision. Boeing pilots and other technical experts considered issuing an Operations Manual Bulletin (“OMB”) on the issue. After internal discussion, it was determined that an OMB was not the appropriate vehicle for notification because the linkage of the AOA DISAGREE alert to the AOA indicator did not present a safety of flight issue, and because there was no specific crew guidance to be provided for dealing with the absence of the alert. Boeing personnel prepared a Fleet Team Digest on the issue, but ultimately it was not issued.

When the MAX returns to service, all MAX airplanes will have an activated and operable AOA DISAGREE alert as a stand-alone, standard feature.

Question 4. How many certification plans for the MAX did the FAA delegate to Boeing and how many did the FAA retain?

Answer. The FAA initially accepted the Master Certification Plan for the 737–8 in November 2013, and it accepted the Detailed Certification Plans in August 2015. When the Master Certification Plan was initially accepted by the FAA, approximately 28 percent of the detailed Certification Plans were delegated. As the FAA reviewed the certification deliverables, those deliverables evolved. The number of delegated tasks increased as a result. However, even for certifications that are delegated, all testing and reviews that Boeing conducts to demonstrate compliance with applicable standards and requirements are subject to FAA oversight.

Question 5. Please describe the changes Boeing has made since the Lion Air accident to the MAX Flight Control Computer software beyond updates to MCAS, and the considerations that led to those changes?

Answer. In late March, as part of a comprehensive supplemental review of the updated MCAS software, Boeing discovered that a monitor to address erroneous processor commands was not as robust as originally assumed. Although this fault had never occurred in 125 million flight hours, Boeing decided to implement an improved monitor to avoid even the theoretical risk of a stabilizer runaway near the ground, where the flight crew would have less time to respond than at a higher altitude.

During a simulator certification demonstration on June 26, an FAA pilot raised an additional concern regarding the possibility that this failure condition could occur at cruising altitude. The pilot determined that, while the flight crew could reverse the stabilizer runaway effect through use of the electric trim switches, this response might—if the crew delayed in recognizing the condition—require a level of piloting skills that could not be assumed. Based on this finding, the FAA asked Boeing to develop additional redundancies in the flight control computer software to prevent this type of failure. Boeing has since been working on new software functionality to address the possibility of such uncommanded stabilizer motion in all phases of flight

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. JOHN THUNE TO
DENNIS MULENBURG

Question 1. Both the National Transportation Safety Board (NTSB) and Joint Authorities Technical Review Board (JATR) reports mentioned a need for greater consideration of crew workload when designing flight control systems.

For example, the JATR report cited a lack of communication between divisions within Boeing as one reason a more holistic evaluation of crew workload may not have been considered in the development of the Maneuvering Characteristics Augmentation System (MCAS).

Could you speak to how some of the organizational changes at Boeing you mentioned in your testimony will help address issues with communication?

Answer. The review undertaken by a committee of the Boeing Board of Directors following the ET302 accident made a series of recommendations, all accepted by the Board, that will enhance safety throughout the design and manufacturing process.

First, all engineering employees now report to the Company's chief engineer. By keeping engineering functions within the engineering department, rather than having engineers report up to program leaders, our engineers will have the enhanced ability to holistically assess key factors as we develop and design flight control and other systems on future airplanes. This organization change will also help ensure that lessons learned in one program will be shared with, and considered with respect to, other programs.

Second, Boeing created a Product and Services Safety organization. Building off of Boeing's already robust avenues for reporting engineering and safety concerns, this organization will further encourage reporting and investigation of any potential safety issues, by anyone within the company.

Third, Boeing created a Design Requirements Program. This program will strengthen information sharing and education among our engineering corps regarding design issues, and also further enhance Boeing's ability to incorporate lessons learned and detailed after action reports. This will help strengthen our existing process to ensure that issues identified and resolved in one program become training tools that improve safety across all Boeing's programs.

These changes will enhance and reinforce Boeing's safety culture, and help to ensure that all safety matters, including lessons learned from these accidents, are appropriately addressed.

Question 2. The NTSB report mentioned that while a safety assessment was performed on MCAS, it may not have considered an MCAS activation in concert with other potential alerts and indications.

Do you believe that the establishment of the Product and Services Safety organization within Boeing will provide more comprehensive safety assessments that adequately assess crew workload?

Answer. While Boeing already employs a rigorous process to perform the safety assessments required to demonstrate compliance to the Federal Aviation Regulations, we expect that the Product and Services Safety organization will heighten Boeing's focus on all safety matters, including the safety assessment process. The other changes outlined in response to the previous question will also further enhance Boeing's safety processes.

RESPONSE TO WRITTEN QUESTION SUBMITTED BY HON. JERRY MORAN TO
DENNIS MUILENBURG

Question. Mr. Muilenburg, regarding the Federal Aviation Administration's (FAA) role in the certification process, what specific recommendations of change at the FAA would you suggest?

Answer. Boeing strongly supports robust FAA oversight of the certification process. As the last major commercial airplane manufacturer in the United States, Boeing believes the certification process, and the FAA's role in that process, are vital to the safety of the traveling public, and have been an important factor driving substantial improvements in aviation safety in recent decades. Boeing supports increasing the FAA's global engagement and leadership in order to strengthen safety standards, safety culture, and safety-related best practices throughout the world.

The certification process requires significant technical expertise and considerable resources. Boeing believes that any changes made should continue to ensure the FAA's resources are focused on areas such as new technologies, systems integration, and development. Moreover, the FAA must be able to attract and retain strong technical capability, commensurate with industry. To achieve those goals, Boeing supports the following changes:

- Increasing integration across organizations within FAA Aviation Safety, especially between Aircraft Certification and Flight Standards. This would facilitate earlier engagement by the operational evaluation teams in the airplane design and certification process, and strengthen the understanding of how certification and operational decisions impact each other.
- The FAA's System Oversight capability could be strengthened by setting clear expectations for applicants' processes and procedures to ensure compliance for lower risk areas, as identified by the FAA. This would allow FAA to dedicate the majority of its resources on areas the FAA has determined to be the highest safety risk.
- The rulemaking process should be strengthened so that the FAA has the capability to incorporate new rules and update existing rules to more quickly accommodate new technology and lessons learned from the existing fleet. For example, FAA should quickly incorporate International Civil Aviation Organization Safety Management System standards for manufacturers into domestic FAA regulations.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. MARIA CANTWELL TO
DENNIS MUILENBURG

Boeing is developing a software fix to correct the deadly flaws in the Maneuvering Characteristics Augmentation System ("MCAS"). The Federal Aviation Administration ("FAA") and international regulators are reviewing Boeing's work.

I believe thorough transparency about the specific testing and evaluation is essential to ensure public confidence in the safety of the 737 MAX aircraft.

Question 1. Will you commit to full public transparency about the technical details and the specific tests and evaluations conducted in order to correct MCAS and return the 737 MAX to service?

Answer. Boeing is committed to keeping the public informed about the status of the enhancements being made to the MCAS system. Boeing has created a public website with information regarding the MAX to facilitate dissemination of information regarding the MAX. That website is located at <http://www.boeing.com/737-max-updates/>. Boeing will continue to provide information regarding the MAX as we work to rebuild the public's confidence in what we do, as well as work with our regulators to ensure that the public, our customers, and other stakeholders can understand the rigor and scope of the return to service process.

Boeing has already disclosed the changes it is making to the MCAS system. When the MAX returns to service, MCAS will compare inputs from both Angle-of-Attack sensors on the MAX, it will only activate one time per high angle-of-attack event, and MCAS will never command more stabilizer input than can be counteracted by the flight crew pulling back on the control column.

Boeing extensively tested these updates. As of November 26, Boeing has dedicated over 190,000 engineering and test hours relating to updates to the MAX, flown more than 1100 test and production flights, and conducted simulator sessions with 41 international regulators as well as 99 of our airline customers. Testing has included evaluation of the system in normal operation, operation when subject to failures (in both the normal and operational flight envelopes), and the potential effect of pilot

crew error and workload. When the MAX returns to service, we are confident it will be one of the safest aircraft ever to fly.

Moreover, the FAA established a Technical Advisory Board (TAB) to review Boeing's updates to MCAS. As Matthew Kiefer, a member of the TAB, testified before the Committee on Transportation and Infrastructure of the House of Representatives, this panel consists of independent experts, with no past involvement in the development or certification of the 737 MAX. In his written testimony, Mr. Kiefer stated that, pending final testing and the results of their review, the TAB "feels the changes made to the flight control software in the B737 MAX should vastly improve the safety of the aircraft, in keeping with the highly successful safety record of the previous models of the Boeing 737."

Question 2. Will you publicly release the specific results of the testing and evaluation of the MCAS "fix?"

Answer. Please see the response to Question 1.

Question 3. The current Organization Designation Authorization ("ODA") process hinders the ability of designated Boeing certification engineers, or "unit members," from communicating directly with their FAA counterparts. Instead, issues are resolved internally within Boeing, which can lead the certification process to potentially be influenced by cost and delivery schedule pressures. Some Boeing engineers are concerned that important dialogue with FAA about problems is being hindered or does not happen as a result of this process.

Further, Boeing recently developed a new program called "Verification Optimization." Under that program, up to 1,000 quality inspector positions will be cut over the next two years. Boeing quality inspectors have ensured mechanic work was performed per engineering requirements. Now, in many critical areas, mechanics will be the only set of eyes to verify they performed their work to Boeing specifications and procedures.

Are you aware Boeing employees have raised concerns about being required to complete an internal review process before being allowed to speak with their FAA counterparts about potential problems?

Answer. The procedures for communications between the ODA unit and the FAA, and the process for coordinating such communications, are defined in Boeing's ODA procedures manual, which is approved by the FAA. The procedures manual governs the conduct of Boeing's ODA unit members. Boeing's ODA procedures manual, as well as Boeing policy, contains procedures to comply with regulatory requirements by ensuring certain communications between Boeing and ODA unit members are coordinated, documented, and retained.

Neither these regulatory requirements nor Boeing's ODA procedures manual prevent members of Boeing's ODA from communicating with their FAA counterparts. Boeing employees have multiple avenues they can use to raise concerns or potential problems, including within the ODA, within the company, and directly to the FAA.

As discussed in more detail in response to Question 4, Boeing's "Verification Optimization" program is unrelated to the ODA unit.

Question 4. Does Boeing still plan to move forward with its plan to cut visual inspections by Boeing quality inspectors?

Answer. Boeing's "Verification Optimization" program is part of Boeing's effort to ensure first-time quality and increase the overall quality of its products. Under this program, in coordination with the FAA, Boeing has introduced a robust verification plan that allows quality inspectors to focus on certain areas: (1) critical items or areas of that pose higher risks; (2) new or unique build processes; and (3) areas where inspection data demonstrates existing processes result in a high rate of defects. For areas outside these categories, quality is still verified by experts in the work being performed. This program includes continuously evaluating regulatory and design requirements for specific inspections, ensuring those inspections are conducted, as well as monitoring results to re-evaluate where additional inspections could be needed. Through this program, Boeing is able to effectively use its quality inspector workforce to focus on the areas of production most in need of additional inspection. Moreover, as part of this program, Boeing has introduced a reporting process and review panel in its factories to identify and report any issues or concerns.

Question 5. Does removal of quality inspectors increase the likelihood of human factor errors?

Answer. The verification optimization program does not eliminate checking our work. Instead, it focuses resources on more critical, difficult, or high risk areas where the likelihood or consequence of a human error is higher.

Question 6. Reports indicate that Boeing's original design of MCAS called for the system to move the horizontal stabilizer only 0.6 degrees. However, the final design

authorized MCAS to move the horizontal stabilizer more than four times as far, by 2.5 degrees for each activation.

Was FAA made aware of the change of design providing for MCAS movements of 2.5 degrees for each activation? If so, when and under what circumstances? Please specify who at FAA was made aware of the change of design.

Answer. The FAA was made aware of the change in the design. Boeing was transparent with the FAA about MCAS's design, including changes in that design over time. The development and certification process for the MAX took over five years. During that time, Boeing worked with numerous FAA employees across multiple departments regarding all aspects of MAX certification, including MCAS. This includes FAA employees at the Boeing Aviation Safety Oversight Office (BASOO) within the FAA's Aircraft Certification Service, as well as FAA test pilots and other FAA personnel who participated in flight tests and evaluated the activation of and data related to MCAS.

On numerous occasions, Boeing shared with the FAA and international regulators that MCAS's final design had changed from its earlier parameters, and that its operating range had expanded to include low-speed conditions. The meetings and information exchanges regarding these topics began in mid-2016 and continued over subsequent months. The information provided to the FAA in these interactions included MCAS's maximum stabilizer authority of 2.5 degrees, as well as other aspects of the function's performance.

In addition to these briefings, FAA personnel also observed the operation of expanded MCAS during certification flight testing. The conditions tested included MCAS's performance during low speed stall, and during these tests MCAS was activated nearly to the limit of its maximum stabilizer authority of 2.5 degrees. FAA personnel—including engineers, pilots, and at times both—were on board many of these flight tests to observe the performance of the flight conditions, including those involving MCAS. In some cases, FAA test pilots were at the controls and flew the relevant conditions. Boeing also provided the FAA with data related to MCAS activation in low speed conditions.

Dan Elwell, then-Acting Administrator of the FAA, has testified before Congress that the certification process “included 297 test flights, some of which encompassed tests of MCAS functions. FAA engineers and flight test pilots were involved in the MCAS operational evaluation flight test.”

Question 7. If FAA was not made aware of the change of design, explain why Boeing failed to bring the change to FAA's attention.

Answer. As noted in the response to Question 6, the FAA was made aware of the change of design.

Question 8. Was MCAS installed on the 737 MAX for the purpose of ensuring the stability of the aircraft? Or was the system installed for the purpose of more closely approximating the handling characteristics of previous models of the 737 aircraft?

Answer. MCAS was initially implemented to improve aircraft handling characteristics in certain rarely encountered high-speed, high-angle-of-attack flight conditions. As development of the 737 MAX continued, flight testing showed that other changes to the airplane's design affected the 737 MAX 8's handling characteristics in certain low speed scenarios involving high angles of attack. Boeing analyzed both control law and physical changes as possibilities to address this issue and ultimately determined that a combination of the two approaches, including an expansion of MCAS's operating range to lower speeds, was the most promising solution for achieving appropriate and certifiable handling characteristics.

Question 9. Can the 737 MAX aircraft be operated safely without MCAS within the normal flight envelope? Can it be operated safely without MCAS within the operational flight envelope?

Answer. As described more fully in the answer to the previous questions, MCAS was initially implemented to improve handling characteristics in certain rarely encountered high angle of attack situations, and was expanded to achieve appropriate and certifiable handling characteristics in certain low-speed situations. As part of the safety process described more fully in the answer to Question 10, Boeing evaluated the loss of the MCAS function within both the normal and operational envelope. Loss of the MCAS function was rated minor within the normal flight envelope, and major within the operational flight envelope.

Question 10. The Lion Air report finds that MCAS was designed to rely on a single Angle of Attack (“AoA”) sensor, making it vulnerable to erroneous input from that sensor. Did Boeing test the consequences of relying on only one sensor? Explain why or why not.

Answer. The 737 MAX was a derivative of the 737 NG, an airplane with one of the best safety records of all large commercial aircraft. MCAS was an extension of

the 737 NG Speed Trim System, which is also based on a single sensor. Boeing uses an established safety analysis process to implement and validate changes to an airplane design. This process entails a comprehensive and iterative assessment of the new design, and identification and resolution of any potential safety issues.

Central to the safety analysis process is evaluating how a design performs in the presence of a series of hypothetical failure scenarios. In identifying and evaluating potential failure conditions, Boeing follows the industry standard approach of preparing functional hazard assessments. Boeing experts identify potential failure conditions using a variety of techniques, including pilot feedback and evaluation, in-service experience, lessons from prior accidents and incidents, and engineering performance analysis. They then assess the level of hazard that these failure conditions present at an airplane level. The design is then validated through a combination of lab, simulator, and flight testing, to ensure that the probability of each identified failure condition is appropriate for the level of hazard assessed. The results of this testing are in turn evaluated by cross-functional teams of subject matter experts across the enterprise, and changes are made to the design as appropriate. The testing is then repeated after the incorporation of any changes. Multiple levels of review, conducted both at the working level and by program and functional management, occur throughout the process, as does regular information sharing and interaction with the FAA. These reviews and regulator interactions frequently result in direction to the team to further refine the design, and to conduct additional testing and analysis, in order to ensure that the design is safe and meets all certification and performance requirements and expectations.

Boeing's evaluation of MCAS was consistent with this process. Boeing experts performed a thorough safety assessment for the initial MCAS design, with Boeing test pilots and engineers conducting a number of piloted simulator sessions in 2012 and 2013 to evaluate possible hazards. In March 2016, concurrently with developing the requirements for the expanded MCAS design, Boeing subject matter experts—including both engineers and experienced pilots—conducted an additional targeted assessment of the potential hazards posed by MCAS's greater stabilizer authority at low speeds. Among other conditions tested during the MAX development process, Boeing considered uncommanded MCAS operation resulting in unintended nose down trim to the maximum stabilizer authority for both the earlier and expanded MCAS designs.

Question 11. The Lion Air report finds that the absence of guidance on MCAS or more detailed use of trim in the flight manuals and in pilot training made it more difficult for flight crews to properly respond to uncommanded MCAS activations.

Did Boeing consult with pilots employed by domestic or foreign air carriers about the removal of information about MCAS in flight manuals and in flight crew training? Explain why or why not.

Answer. In accordance with FAA regulatory guidance, flight training for all Boeing airplanes, including the 737 MAX, is designed to give pilots the knowledge, skills, and abilities necessary to safely operate each model on which they are licensed (or "type-rated"). Boeing and the FAA coordinated closely over the course of several years in developing the necessary training requirements and flight manual content for the MAX. Many items were considered for inclusion, including MCAS, and the content of the manuals and training evolved over time, as is common. Ultimately, relying on the professional judgment of those involved in this process, Boeing proposed, and the FAA agreed, not to include a description of MCAS in the final version of the Flight Crew Operations Manual for the MAX. When the MAX returns to service, Boeing has recommended that pilots receive simulator training on the MAX and the flight manuals will have specific references to the MCAS system.

Question 12. Have any Boeing personnel been terminated, reassigned, or suffered any internal disciplinary action as a result of actions or omissions regarding any activities concerning the certification or approval of the Boeing 737 MAX or any systems therein? If so, please provide details on the actions taken, including the dates.

Answer. Boeing has recently made several high-level leadership changes to ensure that it has the right leadership going forward. Boeing has also made several structural changes to enhance the company's culture of safety and accountability. These include the creation of a permanent Aerospace Safety Committee within our Board of Directors to ensure greater Board oversight and visibility, creation of a Product and Services Safety organization that will, among other things, centralize investigations of safety concerns, and realignment of the engineering function within the company, to ensure technical accountability to the Chief Engineer. In addition, several external reviews are ongoing. As those conclude, we will evaluate the results of those reviews and will not hesitate to hold individuals accountable, where appropriate.

Question 13. Is Boeing committed to returning the 737 MAX to service only as part of a unified review process with other international regulators (such as the European Aviation Safety Agency)?

Answer. Boeing's regulators will determine the process for the MAX's return to service, and Boeing will support whatever process the FAA and other international regulators determine is appropriate. Boeing is working with both the FAA and other global regulators, including through multi-regulator assessments such as the Joint Operations Evaluation Board, to safely return the MAX to service worldwide. Boeing is committed to providing any information needed by those regulatory authorities to support their reviews.

Question 14. The Lion Air report finds that the AoA DISAGREE alert was not correctly enabled during 737 MAX development. Did Boeing test the AoA sensor DISAGREE alert to ensure reliability prior to receiving type certification? Explain why or why not.

Answer. Boeing tests all software it receives prior to type certification. Boeing's testing did not immediately detect this software issue. In August 2017, several months after the software delivery and the commencement of MAX deliveries, Boeing engineers identified the issue after internal testing revealed that the alert was not working as expected.

Question 15. The Lion Air report finds that the crew was unable to effectively manage the multiple alerts, repetitive MCAS activations, and distractions related to numerous air traffic control communications. Did Boeing test the human factors impact of multiple alerts, repetitive MCAS activations, and other distractions that would make it difficult for a flight crew to manage a catastrophic failure? Explain why or why not.

Answer. As described in the answer to Question 10, Boeing uses an established safety-analysis process, and that process was used for the 737 MAX and MCAS specifically. Boeing experts performed a thorough safety assessment for the initial MCAS design, with Boeing test pilots and engineers conducting a number of piloted simulator sessions in 2012 and 2013 to evaluate possible hazards. In March 2016, concurrently with developing the requirements for the expanded MCAS design, Boeing subject matter experts—including both engineers and experienced pilots—conducted an additional targeted assessment of the potential hazards posed by MCAS's greater stabilizer authority at low speeds. In performing this assessment, Boeing's experts applied their engineering judgment and piloting experience to the existing safety analysis and data for the earlier MCAS design, and also considered new performance data generated through piloted simulator testing and computer analysis of MCAS's operation at low speeds.

In the initial analysis, Boeing's subject matter experts had concluded that MCAS's earlier design met all applicable functional hazard assessment thresholds. Based on their updated hazard analysis, Boeing's subject matter experts concluded at the end of March 2016 that the expanded version of MCAS also met all applicable requirements, and did not create any heightened risks beyond the earlier design.

Since the accidents, a number of reports have recommended revisions to the safety-analysis process. Boeing is evaluating those recommendations, as well as the lessons learned during the process of returning the MAX to service, to make improvements to its safety analysis processes. Boeing also supports updating the industry-wide assumptions reflected in existing regulatory guidance.

Question 16. To replace or to supplement flight data generated by external sensors, Boeing has developed such virtual technologies as "synthetic airspeed" and "synthetic AoA." Currently, these state-of-the-art technologies are present only on the 787 aircraft, although they will reportedly be installed on the new 777X aircraft, as well. Exclusive reliance on external sensors such as AoA sensors raises concerns because of their exposure to inadvertent or intentional damage.

Why weren't these state-of-the-art technologies incorporated into the design of the 737 MAX? Why isn't Boeing setting the standard by deploying the best available technologies in new aircraft?

Answer. Boeing routinely introduces best-available and industry-leading technologies on its airplanes. However, not every new technology is appropriate for every aircraft. Synthetic airspeed is a technology that allows for the indirect calculation of a plane's airspeed from various inputs, including external sensor data. Boeing carefully considered the possible inclusion of synthetic airspeed during the development of the 737 MAX, and determined not to implement synthetic airspeed on the 737-8. Boeing subject matter experts evaluated the potential advantages and disadvantages of implementing synthetic airspeed. This evaluation process included the relevant technical experts and decision-makers, and different views were appro-

privately considered. Boeing continues to assess the potential application of synthetic airspeed to its airplanes.

Question 17. Why was MCAS designed with authority to “issue” uncommanded flight control inputs while relying on only one AoA sensor—a single point of failure with no redundancy? Did any Boeing employees raise concerns about the reliance on one AoA sensor during MCAS’ development?

Answer. Please see the answers to questions 8 and 10 regarding MCAS’s original design. As discussed therein, the MCAS flight control law was designed as an extension of the 737 NG’s Speed Trim System. That system is a single sensor design that has hundreds of millions of hours of safe flight.

Regarding potential employee concerns, as is normal during the airplane development process, Boeing technical personnel raised and discussed many technical issues related to the design and development of the MAX, including MCAS. Boeing maintains an Employee Issue Tracking System, a single, common system for entering and tracking employee issues and complaints. Boeing has searched EITS and located no records indicating an employee raised concerns with the design of MCAS prior to the Lion Air accident in October 2018.

Question 18. Are there other systems installed on Boeing aircraft which are given such authority based on data from only one sensor?

Answer. Whether an airplane system is allowed to rely on a single input is determined by FAA regulation. For an aircraft to be certified, it must meet all regulatory requirements.

Note: The following questions refer to the Aircraft Certification “Transformation” Pre-Decisional Involvement Report, Union Recommendations and Dissenting Opinion that was published on February 6, 2017. The report is attached for your reference.

Question 19. Will Boeing upgrade the single string rudder control before the MAX is returned to service? Why or why not? (See Dissenting Opinion, 2017 sec. 12.2.3)

Answer. Boeing’s rudder control design has been certified by the FAA multiple times, most recently on the 737 MAX. As part of the MAX certification process, Boeing discussed its rudder cable design with the FAA in multiple meetings over several years. These meetings focused on how the planned changes from the certified NG design to the MAX could affect hazards related to engine failure as well as design precautions taken by Boeing to minimize such hazards in accordance with FAA regulations. Boeing also shared with the FAA several potential additional design changes. Because changes to an existing, proven design can increase risks in other areas, design changes were evaluated based on their potential utility to mitigate the overall level of risk. As Administrator Dickson testified before the Transportation and Infrastructure Committee of the House of Representatives on December 11, 2013, adding complexity to existing systems often introduces new risks.

Boeing’s analysis of these potential design changes indicated that they would increase the overall level of risk to the airplane, by introducing significant new risks. In addition, the risk of this type of hazard for the MAX was determined to be similar to the 737 NG, an airplane with an excellent safety record. As a result of these discussions, Boeing made additional changes to the MAX floor beam structure to further reduce the likelihood for damage to control surface cables in the event of an uncontained engine rotor failure. Boeing and the FAA also agreed on the methods and analysis that Boeing would use to demonstrate regulatory compliance. Boeing worked with the FAA and responded to all of its concerns to ensure that the 737 MAX complied with applicable requirements.

Question 20. Will Boeing upgrade the single float switch that is vulnerable to single failures and that can cause fuel spillage onto the ramp area and the potential for uncontrolled fire? Why or why not? (See Dissenting Opinion, 2017 sec. 12.2.3)

Answer. The single float switch design is based on the 737 NG, which has hundreds of millions of hours of safe flight. During the certification process, Boeing discussed the design and the means of compliance with the FAA. As a result of those discussions, Boeing provided data and analysis that demonstrated Boeing’s design provided an equivalent level of safety to existing regulatory requirements, and the FAA certified the design.

Question 21. Will Boeing upgrade the engine mount on the auxiliary power unit, which is aluminum and not fireproof, as required by current regulations? (See Dissenting Opinion, 2017 sec. 12.2.3)

Answer. The initial design of the auxiliary power unit structural mount on the 737 MAX is unchanged from the 737 NG, which has hundreds of millions of hours of safe flight. During the certification process, Boeing improved the design to further reduce the risk of certain failure scenarios beyond regulatory requirements. Boeing documented these changes and provided data and analysis to the FAA identifying

how Boeing's design provided an equivalent level of safety to existing regulatory requirements. The FAA certified Boeing's design.

Note: The following questions refer to the Joint Authorities Technical Review ("JATR") Boeing 737 MAX Flight Control System Observations, Findings, and Recommendations report that was published on October 11, 2019. The report is attached for your reference.

Question 22. Please describe—and provide the documents showing—the changes Boeing has made and the testing the company has done regarding human factors and human system integration with relation to the MCAS fix, as suggested by Recommendation R7 of the JATR report.

Answer. Boeing has engaged in extensive testing of its MCAS updates. As of November 26, Boeing has dedicated over 190,000 engineering and test hours relating to the MAX updates, flown nearly 1100 test and production flights, and conducted simulator sessions with 41 international regulators as well as 99 of our airline customers. This testing included simulator sessions, with regulators, to evaluate workload and human factors aspects of the updated procedures, training, and design.

In the process of developing the MCAS update, Boeing incorporated human factors considerations into the design development, analysis, and testing process. Boeing has ensured that human-factors-focused specialists participate in the design reviews of the update, review its relevant safety analyses, and participate in simulator sessions where human-factors issues were evaluated. Boeing is also ensuring that relevant human-factors analyses are documented in its certification compliance submissions. Before engaging in human factors testing, Boeing shared its proposed approach with regulators, and Boeing incorporated the feedback it received into the tests.

Question 23. Has Boeing created an independent system safety function to challenge the assumptions and work of Boeing's design and manufacturing personnel? (JATR report pgs. 30, 32). If so, has this independent system safety function been applied to the MCAS fix? What authority did that function have in relation to the design and other personnel? Please describe.

Answer. Pursuant to a recommendation by a special Board committee, Boeing has created an independent Product and Services Safety organization that, among other responsibilities, will provide an independent review of safety assessments completed by design personnel. Although this specific organization was created after design of the upgrades to the MCAS flight control law were begun, those updates were scrutinized through a similar process.

Question 24. The JATR report (pg. VIII) found that MCAS was not evaluated as a complete and integrated function and that the design was based upon data, architecture, and assumptions that were reused from the past. What has Boeing done to update these evaluations?

Answer. As part of the 737 MAX's return to service, revised individual system safety assessments were consolidated into one Integrated System Safety Assessment (ISSA) for the entire Speed Trim System. The ISSA combines the analysis and results of several different systems and components of the airplane into a single compliance document, providing an integrated perspective into the flight control system's overall level of safety. As Boeing continues to work to return the MAX to service, we will use knowledge we have gained from that process to improve our safety processes for future airplanes. Moreover, as discussed in the response to Question 26, Boeing also supports updating the industry-wide assumptions reflected in existing regulatory guidance.

Question 25. Who made the ultimate decision to remove information relating to MCAS functionality from the Flight Crew Operating Manual?

Answer. Consistent with the established regulatory process, the development of the training requirements and manuals for the MAX was a complex, multi-year effort that involved close coordination between Boeing and the FAA. Ultimately, relying on the professional judgment of those involved in this process, Boeing proposed, and the FAA agreed, not to include MCAS in required pilot training for the MAX. Likewise, the FAA reviewed Boeing's flight manuals, which did not reference the MCAS function by name. Boeing has learned from these accidents, however, and the responses we have received from regulators, our customers, and other stakeholders, and Boeing is also in the process of updating flight crew training and manuals to reflect the updates to MCAS, as appropriate.

Question 26. What assumptions has Boeing changed regarding pilot response time in the flight control functional hazard assessment? What data and testing did Boeing engage in, and what studies, if any, did the company rely upon when changing these pilot response time assumptions? (JTAR report pg. XII)

Answer. Boeing's design, analysis and evaluation approach is based on FAA guidance and published industry standards, including FAA Advisory Circular 25-7C¹ ("Flight Test Guide for Certification of Transport Category Airplanes"). This was the approach used when designing and certifying the 737 MAX. Boeing supports an industry-wide effort to update those standards.

In updating MCAS, Boeing has implemented a number of changes to the MCAS system that will minimize the risk that pilots encounter erroneous, repeated or non-command limited MCAS activation. Those changes include:

- The flight control system will compare inputs from both angle of attack sensors, and MCAS will not activate if the sensors disagree by 5.5 degrees or more.
- MCAS will no longer activate repeatedly. It will provide one input for each elevated angle of attack event.
- Finally, MCAS will never be able to command more stabilizer input than can be counteracted by the flight crew pulling back on the control column.

This design does not require the flight crew to promptly use sustained electric trim to mitigate potential stabilizer failures caused by MCAS. Moreover, this design meets all certification requirements whether or not flight crews follow all of the steps in the Runaway Stabilizer Non-Normal Checklist. As discussed in response to the previous question, Boeing is also in the process of updating flight crew training and manuals to reflect the updates to MCAS, as appropriate.

Question 27. FAA Advisory Circular ("AC") 25.1302-1 requires a showing that MCAS, individually and in combination with other systems and equipment, is designed so that qualified flight crew members trained in their use can safely perform all the tasks associated with the systems and equipment. The JATR report (pg. 12) found that Boeing wrongly failed to identify MCAS as requiring compliance with 25.1302-1. Has Boeing now complied with sec 25.1302-1 with regard to MCAS? If so, how?

Answer. As part of the MAX's return to service, Boeing will demonstrate compliance with 14 C.F.R. § 25.1302. The specific means of compliance are determined by the FAA. Boeing will provide all necessary information to the FAA as part of the return-to-service process.

Question 28. The JATR report (pg. 18) found that a review of the natural (bare airframe) stalling characteristics of the 737 MAX should be performed to determine if unsafe characteristics exist. Has this been conducted? If so, please provide the data and testing documentation underling that review and conclusions.

Answer. As part of the MAX's return to service and in response to a request from a regulator, Boeing conducted both simulator sessions and flight testing designed to verify that the MAX's characteristics and systems were compliant with relevant regulatory requirements regarding stall identification and subsequent airplane behavior. This testing included tests with the Speed Trim System (including MCAS) turned off. The testing verified the original finding of compliance.

Question 29. Has Boeing performed stall demonstration compliance as required by 14 CFR 25.201 before or after the 737 MAX was grounded? (JATR report pg. 18) If so, when was this done? Please describe the testing, analysis and results.

Answer. As part of the initial certification process, the 737 MAX demonstrated compliance with 14 C.F.R. § 25.201. As part of the MAX's return to service, Boeing is working with the FAA to demonstrate compliance with this section, and will provide any necessary data and analysis required by the FAA.

Question 30. Prior to the crashes, 737 MAX simulators did not exhibit the problems that occurred and caused the crashes. What has Boeing done to verify that simulators accurately simulate all aspects and potential problems of flying the 737 MAX? How many such simulators exist?

Answer. Pursuant to Federal regulation, the FAA certifies flight simulators for use as aviation training devices. Boeing does not manufacture aircraft simulators, though Boeing does provide software to the manufacturers of these products. Though it is impossible to simulate every possible aircraft malfunction or combination of malfunctions, the 737 MAX training simulation software contains hundreds of malfunction scenarios. Those scenarios were identified based on industry standards and an assessment of training value. The available malfunction scenarios are continuously reviewed based on changing training techniques, operator feedback,

¹ FAA Advisory Circular 25-7C was canceled in May 2018 and replaced by FAA Advisory Circular 25-7D, which contains the same guidance on these points. This is true for all references to Advisory Circular 25-7C in this document.

and operational data. For instance, in March 2019 Boeing added a malfunction scenario that simulates the effects of erroneously high Angle of Attack data.

Boeing owns one MAX engineering simulator in Seattle, as well as 8 MAX training simulators at locations around the globe. As of December 2019, Boeing is aware of approximately 26 others worldwide.

Question 31. Has Boeing changed its prior practice (JATR report pg. 29) of failing to identify personnel recommending approval with airworthiness standards via FAA Form 8100-9 Statement of Compliance with Airworthiness Standards? Does this change apply to submissions relating to the MCAS fix? If not, please describe how Boeing identifies employees who make airworthiness recommendation decisions and hold them accountable.

Answer. Boeing's existing Organization Designation Authority (ODA) procedures require the submission of signed FAA Form 8100-9 for all compliance data submissions except in limited circumstances, such as flight test reports where the FAA retained the compliance deliverable and conducted the test. In all cases where Boeing submits a Form 8100-9, the individual signing the form is identified.

Boeing's Organization Designation Authority procedures are outlined in its ODA procedures manual, which is the product of an agreement with the FAA. As such, Boeing cannot unilaterally change its ODA procedures. However, Boeing is evaluating changes to these procedures and will make any necessary changes in coordination with the FAA.

Question 32. The JATR report recommended that all "major hazards" determined under AC 25.1309.1A, which include flight crew action in mitigation, should be examined to determine if they are potentially catastrophic. (JTAR report pg. 30) Has Boeing conducted a review of other systems in the 737 MAX since the accidents? Please describe what systems were examined, what testing and analysis was done, and what were the results of the examinations?

Answer. As part of the process to return the MAX to service, Boeing has re-evaluated its analysis of any system that could have a failure effect on the flight control computer (FCC), as well as any system potentially affected by a failure of the FCC. Boeing used a comprehensive failure analysis process, focusing on cascading system effects as well as the flight crew's ability to cope with the failure during different phases of flight. The testing and analysis included identifying the effects of a particular failure, conducting a thorough review of each failure case, and, where necessary, conducting simulator testing to finalize the appropriate hazard classification.

After reviewing the individual system effects for the failure (first, second, third order effects), Boeing prepared an airplane level analysis of the system effects and expected flight crew response. The results of the testing and analysis were provided to the FAA for use during the return-to-service process. As described previously, Boeing will use the knowledge we have gained during the process of returning the MAX to service to make improvements to its processes going forward.

Question 33. The JATR report determined that the single and multiple failure analysis of MCAS was never performed (JTAR report pg. 34). Please describe all possible failures of MCAS and related systems that were examined in the process of returning the MAX to service, and how Boeing intends to mitigate those potential failures.

Answer. The JATR report indicates that an aircraft-level single-and multiple-failure analysis, although not a certification deliverable, was developed and used by Boeing in evaluating the MAX. *JATR Report* at 33.

In the process of returning the MAX to service, Boeing has conducted extensive testing of the updates to the MCAS flight control law, and has documented that testing in submissions to the FAA. This testing has included failure modes such as unexpected loss of MCAS operation and three different types of erroneous MCAS operation: (1) MCAS operating when unnecessary; (2) MCAS operation based on incorrect data input; and (3) MCAS stopping in the middle of expected operation. As described in the answer to the previous question, Boeing has also re-evaluated other potential flight-control-computer failures.

In updating MCAS, Boeing has implemented a number of changes to the MCAS system that will minimize the risk that pilots encounter erroneous, repeated, or non-command-limited MCAS activation. Those changes include:

- The flight control system will compare inputs from both angle of attack sensors, and MCAS will not activate if the sensors disagree by 5.5 degrees or more.
- MCAS will no longer activate repeatedly. It will provide one input for each elevated angle of attack event.
- Finally, MCAS will never be able to command more stabilizer input than can be counteracted by the flight crew pulling back on the control column.

This design does not require the flight crew to promptly use sustained electric trim to mitigate potential stabilizer failures caused by MCAS. Moreover, this design meets all certification requirements whether or not flight crews follow all of the steps in the Runaway Stabilizer Non-Normal Checklist. Boeing is also in the process of updating flight crew training and manuals to reflect the updates to MCAS, as appropriate.

Question 34. The JATR report found that Boeing did not meet the objectives of Society of Automotive Engineers Aerospace Recommended Practice 4754A (“ARP4754A”) for an integrated approach to design when integrating complex systems like MCAS into the legacy 737. (JTAR report pg. 38) Please describe what Boeing has done to meet the objectives of ARP4754A in this regard, as it attempts to return the MAX to service.

Answer. During the certification of 737 MAX systems, Boeing worked with the FAA to develop specific methods of compliance with FAA regulations. These methods are consistent with the intent of ARP4754A. As described in the answer to Question 24, for the updates to the MCAS flight control law, Boeing has consolidated individual system hazard assessments into an Integrated System Safety Assessment for the Speed Trim System. The ISSA combines the analysis and results of several different systems and components of the airplane into a single compliance document, providing an integrated perspective into the flight control system’s overall level of safety.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. AMY KLOBUCHAR TO
DENNIS MUILENBURG

At Tuesday’s hearing, you indicated that you would follow up with information in response to my questions on how often Boeing engineers—rather than Federal Aviation Administration (FAA) employees—conduct safety certifications for Boeing aircraft.

Question 1. What percentage of FAA certifications do Boeing employees—rather than FAA employees—approve for Boeing aircraft?

Answer. The FAA initially accepted the Master Certification Plan for the 737–8 in November 2013, and it accepted the Detailed Certification Plans in August 2015. When the Master Certification Plan was initially accepted by the FAA, approximately 28 percent of the detailed Certification Plans were delegated. As the FAA reviewed the certification deliverables, those deliverables evolved. The number of delegated tasks increased as a result. For example, the FAA often will review a Boeing proposal for compliance, provide comments and require changes to that proposal and then delegate the final implementation work to Boeing’s ODA. However, even for certifications that are delegated, all testing and reviews that Boeing conducts to demonstrate compliance with applicable standards and requirements are subject to FAA oversight.

Question 2. How many Boeing engineers both work on automated systems for the company and then certify those systems for the FAA?

Answer. Boeing employs approximately 16,000 engineers that work on designing commercial airplanes. Of those, approximately 3700 work specifically on airplane systems, and approximately 350 work on flight control systems. Approximately ten flight control engineers have credentials as Engineering Unit Members in the Boeing Organization Delegation Authority (ODA), which would allow them to make a compliance finding on behalf of the FAA regarding flight controls, if the FAA delegates such findings to Boeing’s ODA.

In response to my question regarding whether certain aircraft should be allowed to carry passengers in some countries and not others, you declined to respond and stated that you “respect the jurisdiction of the regulatory authorities around the world.”

Question 3. How would you explain that to a passenger who is rightly concerned about their safety?

Answer. Boeing respects the authority of all individual civil aviation authorities to make decisions regarding the airspace they control and the pilots, maintenance personnel, and airlines they oversee. Individual civil aviation authorities around the world, working in collaboration with other regulators and the broader aviation community, are best positioned to determine how to achieve safety goals in the context of their individual regions and operations. Boeing is committed to ensuring the MAX returns to service worldwide, and to providing any information and support needed by those civil aviation authorities, and our customers, to achieve their goals and ensure the MAX safely returns to service worldwide.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. RICHARD BLUMENTHAL TO
DENNIS MUILENBURG

Boeing's attempt to move all the Lion Air cases overseas to Indonesia. Boeing says that it will take responsibility for the Lion Air crash resulting in the deaths of 189 people in Indonesia last year and the Ethiopian Airlines crashed that killed a 157 people from a pair of defectively designed 737 MAX aircraft. However, your company is threatening not to. Boeing has filed court documents for the Lion Air crash indicating that it will move to change the venue of the case to Indonesia, where the plane was maintained, if settlement talks fail. The case was filed in the Northern District of Illinois, where Boeing is headquartered. Resolving these claims in Indonesia is a travesty of justice because:

- There is no Seventh Amendment Constitutional right to a jury trial;
- There is no requirement of discovery, so there is limited or no ability for the plaintiffs to uncover the documents showing what Boeing knew, when it knew it, what information was withheld from the FAA, and other critical information;
- There is no rule allowing for depositions to be taken of key Boeing decision-makers; and
- There is no right to cross-examine witnesses to see what they know.

Question 1. Is the threat to move the case to Indonesia a litigation tactic or is this attempt to evade responsibility for corporate misconduct?

Answer. In response to both MAX accidents, Boeing has offered to engage in mediations in the United States to resolve the families' claims without the need for any litigation. To facilitate this, Boeing arranged for a prominent Chicago mediator, a former Chief Judge of the Circuit Court of Cook County, to assist, and is paying the full costs of all mediations. Since the middle of July, Boeing has been working with the mediator and the families who lost loved ones in the Lion Air accident to settle these cases. We have resolved approximately one half of the Lion Air claims filed in the United States on terms that compensate the victims' families. We remain committed to this mediation process. If, at some point and despite Boeing's best efforts, an impasse is reached in the mediation process, the litigation may resume. And at that point, well-settled U.S. law will give Boeing the option of requesting that the court determine whether, consistent with well-settled legal principles adopted by the United States Supreme Court, another jurisdiction is the appropriate venue for such cases.

Question 2. It seems that you want the advantages of being treated like an American company except that you don't want to utilize U.S. courts, which recognize the rights of both parties in a dispute. Why are you threatening to move the claims filed against you to Indonesia?

Answer. Please see the response to the previous question.

Question 3. Traditionally, companies complain that they don't want to be sued in the plaintiff's backyard, yet, you are being sued in your home state. Why are you threatening to leave courts conveniently located in your backyard?

Answer. Please see the response to your first question.

Clarification on Boeing's support for changes to the certification process. On October 27, 2019, the *New York Times* reported on Boeing efforts to undercut regulatory oversight—early and often. The story of Boeing sabotaging rigorous safety scrutiny is chilling—and more reason to keep 737 MAX aircraft grounded until certification is truly independent and the system reformed.

Your company has lost the trust of the public, and I am evaluating changes to the Organizational Designation Authorization (ODA) program. At the hearing, you were unclear about Boeing's position on changes to the current certification process.

Question 4. Do you support reducing the amount of delegation authority from the FAA to Boeing to restore public trust?

Answer. Boeing strongly supports robust FAA oversight of the certification process. As the last major commercial airplane manufacturer in the United States, Boeing believes the certification process, and the FAA's role in that process, are vital to the safety of the traveling public, and have been an important factor driving substantial improvements in aviation safety in recent decades.

Delegation has strongly correlated with safety. Delegation is decades old; and as delegation has increased, safety has as well. The data does not support the idea that reducing the amount of delegation will result in an increase in safety. Boeing believes that any changes made should continue to ensure the FAA's resources are focused on areas such as new technologies, systems integration, and development, and providing the FAA with the resources needed to effectively administer that process as well as ensure FAA has the required technical expertise.

Question 5. What is the current timeline for returning the 737 MAX to service and how can the public be assured of its safety?

Answer. The relevant civil aviation authorities will determine when the MAX returns to service. When the MAX returns to service, it will be one of the most scrutinized aircraft in history, and Boeing is committed to ensuring that it will also be one of the safest aircraft ever to fly.

Boeing's decision to label MCAS failure as "major" rather than "catastrophic". As you are aware, Boeing decided to classify failure of the MCAS system during flight as merely "major"—lowering the classification of risk and exempting Boeing from having to fully test and analyze the effects of system failure.

Question 6. How can you explain the failure to label the MCAS as "catastrophic?" Answer, Boeing engaged in a multi-step process for evaluating the potential safety considerations involved in the implementation of MCAS. At each stage of the design, development, and testing of MCAS, Boeing subject matter experts reviewed and evaluated the design and the potential safety implications of design changes.

As authorized by applicable FAA guidance, including FAA Advisory Circular 25-7C ("Flight Test Guide for Certification of Transport Category Airplanes"), in conducting their hazard assessments, Boeing's subject matter experts made a series of assumptions about how a flight crew would react if MCAS failed or did not function as intended. Consistent with established FAA guidance, this included the assumption that the crew would recognize and address uncommanded MCAS activation through normal use of the control column and the electric trim switches, and that the crew would also be able to use the stabilizer cutout switches and rely on manual trimming (as outlined in the Runaway Stabilizer Non-Normal Procedure) to stop any unintended stabilizer motion. Test pilots participated in the simulator testing of MCAS and had vital input into the hazard analysis.

Question 7. Why did you make this decision?

Answer. Please see the response to question 6.

Question 8. Could the decision to label the system as "catastrophic" have prevented the MCAS failure from contributing to the Lion Air and Ethiopian Air crashes?

Answer. Whether hypothetical changes to the MCAS hazard rating could have prevented a failure of MCAS from contributing to the Lion Air and Ethiopian Air crashes is impossible to determine. As Boeing testified at the hearing, if, using hindsight, Boeing could go back and make changes to the MAX that would prevent the accidents, it would do so.

Undue pressure put on Boeing employees to certify 737 MAX aircraft. The *Wall Street Journal* recently reported that internal Boeing surveys revealed that about 30 percent of its employees felt potential undue pressure from managers regarding safety related approvals.

Boeing engineer Curtis Ewbank filed a complaint that asserted, "Boeing management was more concerned with cost and schedule than safety or quality." He further asserted that you, Mr. Muilenburg, publicly misrepresented the safety of 737 MAX aircraft.

The October 11, 2019 Joint Authorities Technical Review report also found several instances of Boeing management exerting undue pressure on its own engineers performing certification activities, which, as a result, "erodes the level of assurance in this system of delegation."

Question 9. Did you at any point misrepresent the safety of 737 MAX aircraft? Please explain.

Answer. No. With that said, Boeing has learned from these accidents, and has made several changes to the MAX to ensure that accidents like these never happen again. Boeing has dedicated over 190,000 engineering and test hours relating to the MAX updates, flown more than 1100 test and production flights, and conducted simulator sessions with 41 international regulators as well as 99 of our airline customers. When the MAX returns to service, we are confident it will be one of the most scrutinized and safest aircraft ever to fly.

Question 10. Did personnel within the company—involved in performing certification activities—have compensation tied to meeting timeline and cost goals? Please explain.

Answer. For members of Boeing's Organization Delegation Authority (ODA), Boeing's ODA manual does not permit the use of timeline and cost goals as part of performance evaluations.

Question 11. Did you ever personally exert production pressures on any of the employees that served under you as Boeing's CEO? If not, have you identified who, or what, in your organization caused that undue pressure?

Answer. Mr. Muilenburg was not the subject of any undue pressure complaint. Boeing provides a number of avenues for employees to report instances of potential or actual undue pressure. In accordance with Boeing's ODA procedures manual, which is reviewed and approved by the FAA, allegations of potential undue pressure must be investigated and rectified, where needed, in a timely manner. Boeing investigates all undue pressure reports and those investigations are reviewed with the FAA. Boeing also conducts regular self-audits and surveys of the workforce to identify and address potential avenues of undue pressure that are not specifically reported by the workforce. In addition, Boeing requires any manager associated with the certification process to take training on undue pressure every two years, to ensure that they can identify and address potential undue pressure issues.

Question 12. What steps have been taken to hold individuals accountable and reform Boeing's safety protocols related to undue pressure being put on employees?

Answer. Boeing takes all allegations of undue pressure seriously. The Boeing Organization Designation Authority manual requires that any allegation of undue pressure be promptly rectified. When appropriate, employee corrective action is taken. More broadly, Boeing has created a Product and Services Safety Organization. This organization will ensure that any safety issue, including issues of undue pressure, will be investigated and evaluated by an independent organization within the company.

The need for Boeing to move away from a system of assumptions. The Joint Authorities Technical Review report stated that Boeing made critical and several unsupported assumptions underlying the certification of 737 MAX aircraft, including a three-second pilot response assumption in the event of a problem.

These assumptions directly contributed to two horrific and preventable crashes.

Question 13. As you have resubmitted a package to return the aircraft to service, what changes in assumptions of pilot response or the other assumptions outlined in that report have you made?

Answer. Boeing's design, analysis and evaluation approach is based on FAA guidance and published industry standards, including FAA Advisory Circular 25-7C² ("Flight Test Guide for Certification of Transport Category Airplanes"). This was the approach used when designing and certifying the 737 MAX. Boeing supports an industry-wide effort to update those standards.

In updating MCAS, Boeing has implemented a number of changes to the MCAS system that will minimize the risk that pilots encounter erroneous, repeated and non-command limited MCAS activation, those include:

- The flight control system will compare inputs from both angle of attack sensors, and MCAS will not activate if the sensors disagree by 5.5 degrees or more.
- MCAS will no longer activate repeatedly. It will provide one input for each elevated angle of attack event.
- Finally, MCAS will never be able to command more stabilizer input than can be counteracted by the flight crew pulling back on the control column.

This design does not require the flight crew to promptly use sustained electric trim to mitigate potential stabilizer failures caused by MCAS. Moreover, this design meets all certification requirements whether or not flight crews follow all of the steps in the Runaway Stabilizer Non-Normal Checklist. Boeing is also in the process of updating flight crew training and manuals to reflect the updates to MCAS, as appropriate.

Question 14. What research have you or the FAA done to justify any of those changes?

Answer. Boeing has engaged in extensive testing of these MCAS updates. As of November 26, Boeing has dedicated over 190,000 engineering and test hours relating to the MAX updates, flown nearly 1100 test and production flights, and conducted simulator sessions with 41 international regulators as well as 99 of our airline customers. Testing has included evaluation of the system in normal operation, operation when subject to failures (in both the normal and operational flight envelopes), and the potential effect of pilot crew error and workload. When the MAX returns to service, we are confident it will be one of the safest aircraft ever to fly.

The lack of documents provided to the Senate Commerce Committee. The House Transportation and Infrastructure Committee had received over 500,000 pages of documents related to the certification of the 737 MAX. Boeing has failed to provide

²FAA Advisory Circular 25-7C was canceled in May 2018 and replaced by FAA Advisory Circular 25-7D, which contains the same guidance on these points. This is true for all references to Advisory Circular 25-7C in this document.

the same documents to the Senate Commerce Committee—inhibiting our ability to carry out our oversight authority.

Question 15. Will you commit to providing these documents to the Senate Commerce Committee as well? Please explain.

Answer. Boeing respects the role of both Committees in the oversight of the aviation industry and is committed to continuing to cooperate with both Committees. To date, Boeing has responded to all requests received from the Chairmen of both Committees, and we intend to continue to cooperate with such requests.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. TOM UDALL TO
DENNIS MUILENBURG

Question 1. As a follow up to my questioning during the hearing, have you and your team engaged on what are ways to improve the ODA process?

Answer. Boeing strongly supports robust FAA oversight of the certification process. As the last major commercial airplane manufacturer in the United States, Boeing believes the certification process, and the FAA's role in that process, are vital to the safety of the traveling public, and have been important factors driving substantial improvements in aviation safety in recent decades.

The Organization Delegation Authority process has helped facilitate these safety improvements. However, there are ways to improve that process. For example, the FAA's System Oversight capability could be strengthened by setting clear expectations for applicants' processes and procedures to ensure compliance for lower risk areas, as identified by the FAA. This would allow FAA to dedicate the majority of its resources on areas the FAA has determined to be the highest safety risk. Boeing will work with all interested stakeholders to learn from these accidents and further increase aviation safety.

Question 2. Accountability is critical. How will you personally or Boeing collectively be held accountable for decisions you made or pressure you exerted on your team that led to minimizing pilot training and failing to disclose critical information in the rush to get these planes in the air?

Answer. Boeing has recently made several high-level leadership changes to ensure that it has the right leadership going forward. As described in more detail in response to Question 4, Boeing has also made several structural changes to enhance the company's culture of safety and accountability. Several external reviews are ongoing. As those conclude, we will evaluate the results of those reviews and will not hesitate to hold individuals accountable, where appropriate.

Question 3. In 2018, you received a \$13 million dollar bonus, based in part on Boeing surpassing a three-year economic profit goal. Was any part of this goal and bonus based on the sales of the 737 MAX 8—which seems to have been rushed to the market? Have you given any of this bonus back?

Answer. Mr. Muilenburg's 2018 compensation is publicly available in Boeing's annual proxy statement, which can be found at www.boeing.com.

Question 4. Please detail the changes recommended by the FAA and other reviewing entities that will be incorporated into Boeing's other product lines and planes like the Boeing 737 MAX 10?

Answer. Boeing is taking into consideration the recent recommendations of a number of reviews, and making improvements to Boeing internal processes as they relate to how we evaluate new airplane system design. Boeing continues to review additional reports and reviews as they are completed, and will continue to incorporate lessons from those reviews.

Based on the recommendation of a special board committee, Boeing is also making several changes to our organization and processes designed to enhance safety culture of the company. These changes include:

- (1) Creating a permanent Aerospace Safety Committee within our Board of Directors to oversee and ensure safe design, development, manufacture, maintenance, and delivery of our products and services;
- (2) Creating a Product and Services Safety organization to review all aspects of product safety;
- (3) Realigning the Engineering function within the company, so that engineers across Boeing will report directly to the Chief Engineer;
- (4) Establishing a design requirements program to further facilitate the incorporation of historical design materials, data and information, best practices, lessons learned, and detailed after action reports to reinforce Boeing's commitment to continuous improvement;

- (5) Enhancing our Continued Operational Safety Program to aid transparency and visibility of safety related issues; the Continued Operational Safety Program now will require the Chief Engineer's review of all safety and potential safety reports;
- (6) To anticipate the needs of future pilot populations, re-examining assumptions about flight deck design and operation in partnership with our airline customers and industry members;
- (7) Expanding our Safety Promotion Center for employees to learn and reflect on our safety culture and renew personal commitments to safety;
- (8) Expanding our anonymous safety reporting system to strengthen safety management systems within Boeing and our supply chain;
- (9) Investing in new capabilities, including enhanced flight simulation and computing, and advanced R&D for future flight decks, as well as pilot and maintenance technician training and STEM education.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. TAMMY DUCKWORTH TO
DENNIS MULENBURG

During the October 29th hearing, I asked the Chairman of the National Transportation Safety Board (NTSB) whether he concurred with my view that, "The most reliable initial human response to an uncommanded nose down dive is to pull back on the yoke."

Chairman Sumwalt provided the following response:

"Yes, I do. I have actually looked at the procedure and it says to grasp and to hold it firmly but as you know as an experienced pilot, your natural reaction would in fact if it is going in a direction you do not intend it to, you would tend to oppose it, which you should. In the older models of the Boeing aircraft that I flew, the 727 and 737, that would engage the stabilizer brake and stop the stab from running. But as you pointed out in the earlier round, it will not do that when MCAS is active on the 737 MAX."

I submitted the following written question to The Boeing Company on May 17, 2019:

"What does Boeing believe is the natural human reaction to stop a nose down trim command runaway?"

Boeing's written response failed to address what Boeing believes the "natural human reaction is to stop a nose down trim command runaway" and cited the steps of the Runaway Stabilizer Non-normal checklist.

Question 1. Yes or no, does Boeing concur with the view that human factors have proven that the most reliable initial human response to a runaway horizontal stabilizer movement trimming airplane nose-down is to oppose the motion by pulling back on the yolk? Please explain your answer.

Answer. Boeing is not aware of specific research that addresses the issue as presented by the question. Flight crews may use the control column, the pitch trim switches, or a combination of both to control the flight path of the airplane in the presence of an uncommanded nose-down stabilizer movement.

Pursuant to FAA guidance, Boeing's design assumes that pilots will take immediate action to reduce or eliminate short-term forces that cause an aircraft to deviate from its intended flight path. Based on that assumption and Boeing's expertise, the reaction to nose-down stabilizer movement is to control the flight path of the airplane using the methods available, including use of the control column and electric trim switches.

Question 2. If the answer to Question 1 is "No," please confirm whether Boeing concurs with the view that human factors have proven that the most reliable initial human response to a runaway horizontal stabilizer movement trimming airplane nose-down is to use both aft column motion and the column trim switch to quickly stop the runaway stabilizer and restore trim? Please explain your answer.

Answer. Based on Boeing's expertise, the reaction to nose-down stabilizer movement is to control the flight path of the airplane. In the 737 MAX, the use of aft column motion, or the column trim switches, or both, could typically be used by a pilot to control the flight path of the airplane.

Question 3. Yes or no, does Boeing concur that for the 707, 727, 737 (except for the MAX), 747, 757 and 767 aircraft, many safe flight hours demonstrate that in non-normal conditions where a uncommanded stabilizer trim movement is causing

a nose-down dive, pilots will reliably respond with aft column travel to both trigger the aft column cutout switch to quickly stop the runaway stabilizer movement and prevent significant mistrim, and command sufficient airplane nose-up elevator to exactly offset the stabilizer mistrim? Please explain your answer.

Answer. The established procedure for responding to uncommanded stabilizer trim movement causing nose down mistrim is contained in the Runaway Stabilizer Non-Normal Checklist. This procedure does not direct pilots to use “aft column travel” to address the mistrim condition; rather, it directs pilots to hold the control column firmly, disengage the autopilot and autothrottle, and then control the pitch attitude of the aircraft manually using the control column or main electric trim, as needed. If the runaway continues, it directs pilots to disable electric trim by use of the aisle stand cutout switch. These steps are designed to assist the flight crew in controlling the flight path of the airplane.

Question 4. Yes or no, does Boeing concur with the view that for approximately 60 years of service, across the 707, 727, 737 (except for the MAX), 747, 757 and 767 aircraft, column cutout switches have enabled pilots to quickly stop the runaway stabilizer movement using column motion only? Please explain your answer.

Answer. For many Boeing models, the column cutout switch is one method that may address a runaway stabilizer movement. However, the memory item procedures contained in the Runaway Stabilizer Non-Normal Checklist, which flight crews are required to learn and memorize, do not include engaging the aft column cutout switch for either the 737 NG or the 737 MAX.

Question 5. Yes or no, does Boeing concur with this statement:

“For every Boeing airplane until the 737 MAX, uncommanded stabilizer runaway is stopped by column motion only. But for the MAX, with MCAS malfunction, the pilot has to also apply manual electric trim within the same three second window?”

Please explain your answer.

Answer. No. On all Boeing airplanes there are possible stabilizer failures where column motion alone may not arrest the failure. The procedure in the Flight Crew Operations Manual for arresting an uncommanded stabilizer runaway on the Boeing 737 NG, as well as the MAX, is the Runaway Stabilizer Non-Normal Checklist. That checklist directs pilots that steps beyond column motion alone may be required to arrest a runaway stabilizer.

In addition, Boeing assumes the “three second window” described in the statement refers to FAA regulations, including FAA Circular 25-7C (now Circular 25-7D), that allows manufacturers to assume, in certain types of testing, that flight crews will not react to a potential hazard for up to three seconds. That guidance relates to the time a manufacturer should assume will pass before the flight crew begins reacting to a hazard, not the time required to complete corrective action.

Question 6. Yes or no, prior to the 737 MAX series aircraft, did the Speed Trim System bypass the aft column cutout switch on the 737 NG or any earlier versions of the 737 that included the Speed Trim System?

Answer. The speed trim systems on the 737 NG and earlier versions of the 737 do not have the aft column cutout bypass feature. That feature was introduced with the MCAS function, and the speed trim systems on the 737 NG and earlier versions of the 737 airplane do not include the MCAS function.

Question 7. On almost any other Boeing aircraft, it would be reasonable to expect a pilot to react instantly to uncommanded stabilizer trim motion in manual flight. However, as installed on the 737 aircraft, the Speed Trim System has desensitized pilots to stabilizer trim motion in manual flight. In speaking with 737 pilots, a few confirmed that the feel and sound of the Speed Trim System moving the stabilizer is normal and something a 737 pilot would be accustomed to in manual flight.

Given that the 737 aircraft appears to be the only Boeing aircraft where an augmentation system exists that results in stabilizer trim motion in manual flight, what analysis or evidence did Boeing rely on to justify its assumption that a 737 MAX pilot would instantly react to stabilizer trim motion in manual flight caused by MCAS activation?

Answer. Automated flight controls that move flight surfaces during manual flight are not unique to the 737. For the 737, during manual flight, the assumption of pilot recognition is predicated on an increase in column forces or deviation from the intended flight path. FAA regulatory guidance, including Advisory Circular 75-7C, allows manufacturers to assume that a flight crew will seek to offload unexpected column forces.

Question 8. On October 30, 2019, you publicly stated, “The original concept from a safety standpoint was to build the MCAS, extend the current Speed Trim System

of the previous generation of the 737, that's a system that had about 200 million safe flight hours on it."

For those 200 million safe flight hours on the Speed Trim System that you referenced, did the aft column cutout switch enable pilots to use column motion only to quickly stop the runaway stabilizer, prevent significant mistrim, and preserve sufficient elevator authority to restore the trim efficiently?

Answer. As explained in response to question 5, on all Boeing airplanes there are possible stabilizer failures where column motion alone may not arrest the failure. Boeing's procedures for responding to a runaway stabilizer do not include engaging the aft column cutout switch.

Question 9. One of Boeing's safety principles is to take safe systems, such as the Speed Trim System, and then incrementally extend them. Presumably, this was the concept behind Boeing's decision to add the MCAS flight control law to the existing Speed Trim System. However, it appears that MCAS did not represent an extension of the Speed Trim System, but rather, MCAS activation must, and does, disable a long-standing safety function: the aft column cutout switch.

Please explain whether the decision to add a new flight control law (MCAS) to the Speed Trim System that bypasses the aft column cutout switch is consistent with Boeing's concept of incrementally extending an existing safety system.

Answer. In designing MCAS for the 737 MAX, the decision to bypass the aft column cutout switch was consistent with safe and sound design principles, and relied on well-established, industry-wide assumptions and long-standing FAA guidance. In addition, as previously explained, engaging the aft column cutout switch was not a part of the memory procedure for addressing a runaway stabilizer.

Question 10. Yes or no, does Boeing concur that MCAS bypassing the aft column cutout switch undermined Boeing's assumptions that limited mistrim to 0.6 units and assumed sufficient elevator authority would always be preserved? Please explain your answer.

Answer. No. MCAS's design has always included bypassing the aft column cutout switch. When MCAS's design was changed to include operation at lower speeds, Boeing subject matter experts—including both engineers and experienced pilots—conducted a targeted assessment of the potential hazards posed by MCAS's greater stabilizer authority at low speeds. In performing this assessment, Boeing's experts applied their engineering judgment and piloting experience to the existing safety analysis and data for the earlier MCAS design, and also considered new performance data generated through piloted simulator testing and computer analysis of MCAS's operation at low speeds. Boeing's subject matter experts concluded that the updated version of MCAS, which still included the aft column cutout switch bypass, met all applicable requirements.

Question 11. Please identify the specific compensating safety features Boeing installed in response to MCAS activation bypassing the aft column cutout switch or confirm that Boeing did not develop a specific compensating safety feature to bypassing aft column cutout.

Answer. On the 737 MAX, pilots had the ability to counteract the effects of MCAS through use of the control column and the electric trim switches, or to disable MCAS through use of the aisle stand cutout switches. As previously stated, the memory procedure appropriate for responding to a runaway stabilizer did not include engaging the aft column cutout switch.

Question 12. Please explain how Boeing demonstrated that when the 737 MAX MCAS flight control law is activated during manual flight, the MAX series aircraft complies with Section 25.255 of Title 14, Chapter I, Subchapter C, Part 25, Subpart B, of the Code of Federal Regulations (14 CFR Sec. 25.255: Out-of-trim characteristics), despite MCAS activation bypassing the aft column cutout switch and tripling the stab trim rate.

Answer. MCAS moves the stabilizer at a rate based on the speed of the airplane. Its maximum stabilizer authority is 0.27 degrees/second. This rate is 35 percent greater than the rate at which the pilot can move the stabilizer using manual electric trim when flaps are up, and less than the rate that the pilot can move the stabilizer using manual electric trim when flaps are down.

Title 14, Code of Federal Regulations, Section 25.255 defines acceptable maneuvering stability and dive recovery requirements for out-of-trim conditions. The magnitude of the out-of-trim condition is defined by a three second movement of the stabilizer at its normal no-load rate. The 737 MAX meets the required characteristics with the mistrim that results from a three second movement of the stabilizer at the flaps up trim rate. Boeing also tested a magnitude of mistrim that was greater than would occur from a three second movement of the stabilizer at the flaps up trim rate and found that MCAS met all applicable regulatory requirements.

Question 13. Please confirm that between October 29, 2018 and March 10, 2019, Boeing conducted tests in a 737 MAX simulator to observe how a pilot—without knowledge of MCAS—responds when he or she realizes that Step One of the Runaway Stabilizer procedure (hold the control column firmly to counter the nose-down trim command of the horizontal stabilizer) does NOT automatically stop MCAS from repeated activations. If Boeing did not conduct such a test, please provide Boeing’s justification for this course of action.

Answer. In the relevant time frame, Boeing did conduct extensive testing of pilot response to repeated MCAS activation. If a pilot only maintains control of the flight path of the airplane through use of the control column to counter MCAS’s nose-down trim, MCAS, as designed and installed on the MAX, will not activate multiple times. MCAS will only reactivate if the flight crew uses electric trim. Thus, the described condition was not tested because it was not a possible failure mode of the MCAS design.

Question 14. Yes or no, does Boeing concur that because of the aft column cutout switch, a Boeing 737 NG pilot, following the Runaway Stabilizer Non-Normal procedure, would be accustomed to, and expect, column motion (and only column motion) to quickly stop an uncommanded runaway stabilizer trimming in opposition to the column motion and ensure the elevator remains effective? Please explain your answer.

Answer. No. The Runaway Stabilizer Non-Normal Checklist for the 737 NG directs pilots to hold the column steady, disengage the autopilot, and to control the airplane pitch attitude manually or, as needed, with the use of the trim switches on the control column; it does not direct flight crews to apply column force until the aft column cutout switch engages.

Question 15. Several of Boeing’s critical assumptions appear to be grounded in the expectation that because the Runaway Stabilizer Non-Normal procedure is identical for both the 737 NG and 737 MAX, pilots flying the 737 MAX should have been prepared to respond to a flight condition caused by repeated MCAS activations resulting from a single erroneous AOA sensor input exactly as they would respond to a runaway stabilizer on the 737 NG. Yet, Boeing was clearly aware that on the 737 MAX, MCAS activation bypasses the aft column cutout switch and triples the stab trim rate.

Prior to JT610 and ET302, did Boeing inform 737 MAX pilots that the aft column cutout switch is bypassed in the 737 MAX and thus column alone will not always stop the uncommanded stabilizer trim movement?

Answer. As noted in the response to Question 14, the aft column cutout switch is not identified in the memory procedure for uncommanded stabilizer motion. Consistent with the established regulatory process, the development of the training requirements and manuals for the MAX was a complex, multi-year effort that involved close coordination between Boeing and the FAA. Many items were considered for inclusion, including MCAS, and the content of the manuals and training evolved over time, as is common. Ultimately, relying on the professional judgment of those involved in this process, Boeing proposed, and the FAA agreed, not to include a description of MCAS in the final version of the Flight Crew Operations Manual for the MAX.

Question 16. The Federal Aviation Administration’s Emergency Airworthiness Directive (AD) 2018–23–51 issued on November 7, 2018, was intended to prevent a catastrophic crash resulting from repeated MCAS nose-down trim commands of the horizontal stabilizer caused by an erroneously high single angle of attack sensor input. However, publishing AD 2018–23–51 failed to prevent ET302.

Following its publication, did any Boeing employee, or employee of a Boeing contractor, express concerns related to AD 2018–23–51?

Answer. Boeing maintain an Employee Issue Tracking System, a single, common system for entering and tracking employee issues and complaints. Boeing has searched EITS and located no records indicating an employee or contractor raised concerns with AD 2018–23–51 to Boeing after it was issued.

Question 17. How many occurrences of AoA malfunction (erroneous high angle reading) have occurred across Boeing aircraft models without significant incident prior to the JT610?

Answer. Boeing’s records indicate there have been 35 total events of erroneous Angle of Attack data and stick shaker across the Boeing fleet since 1998. Of those events, 26 occurred on 737 NGs. All 35 flights resulted in continued safe flight and landing. There have been more than 220 million departures in that timeframe.

Question 18. On ET302, MCAS was activated at a high airspeed that appears to be far above any airspeed that MCAS should trigger. Why did Boeing decide not

to constrain MCAS authority to prevent it from triggering at high airspeeds significantly above any level where MCAS may be safely activated?

Answer. MCAS was initially designed to give the 737 MAX specific handling qualities during certain high speed maneuvers, and thus was intended to be active at high airspeeds. Boeing does not intentionally engineer a system to change the handling characteristics of the airplane in unexpected or uncommon situations, as such a design would introduce significant safety risks.

Question 19. Please describe in detail the flight condition where 75 degrees is a valid angle of attack value.

Answer. Boeing is unaware of any normal flight condition where a plane would have a 75 degree angle of attack. However, as Boeing detailed in our response to your May 17, 2019 letter, Boeing's air data inertial reference unit does not artificially limit the data from its sensors.

Question 20. Please explain why Boeing failed to note that MCAS activation in manual, flaps up flight, bypasses the aft column cutout switch in the Boeing Multi-Operator Message (MOM-MOM-18-0664-01B) sent in November 2018.

Answer. Boeing's Multi-Operator Message is consistent with the procedures described in the Runaway Stabilizer Non-Normal Checklist. These Checklist procedures are also discussed at length in Boeing's Operations Manual Bulletin and the FAA's Airworthiness Directive issued after the Lion Air accident. These are the appropriate procedures to respond to erroneous uncommanded stabilizer trim movement (including erroneous MCAS activation), and they do not include engaging the aft column cutout switch.

Question 21. Please explain why Boeing failed to note that the flight crew must use column trim switch or stabilizer aisle stand cutout switches to override MCAS input, and instead used the following more passive terminology: "The system is designed to *allow* [emphasis added] the flight crew to use column trim switch or stabilizer aisle stand cutout switches to override MCAS input?"

Answer. As noted in response to the previous question, Boeing's Multi-Operator Message was consistent with the procedures in the Runaway Stabilizer Non-Normal Checklist. In addition, it would have been incorrect to state that use of the column trim switch or aisle stand cutout switch is required to override MCAS input. Because MCAS input can be overridden solely by use of the control column in some circumstances, use of the electric trim or aisle stand cutout switches may not be necessary to override MCAS in those circumstances.

Question 22. Please share with the Committee any Boeing communications sent after JT610 emphasizing the critical importance of using manual electric trim to oppose MCAS because aft column cutout switch is bypassed.

Answer. Please see the response to question 20.

Question 23. Following JT610 and prior to ET302, why did Boeing fail to immediately disable MCAS?

Answer. The MCAS software is an integrated part of the flight control system for the MAX as certified by the FAA and cannot be "disabled" per se. Following JT610, Boeing worked with the FAA to establish a plan to revise the MCAS software to eliminate the risk of erroneous AOA data leading to repeated MCAS activation.

On November 6, 2018, a Boeing Safety Review Board ("SRB")—Boeing's established process for evaluating in-service safety issues—determined that the crew workload effects of erroneous AOA input leading to activation of the MCAS function presented a safety issue, and also determined that appropriate pilot action could counteract the condition. That same day, Boeing issued an Operations Manual Bulletin ("OMB") to the fleet calling attention to the airplane effects and flight deck indications of the condition, and directing flight crews to existing procedures to address it. Boeing also moved forward expeditiously to develop an update to the MAX's flight control computer software to eliminate the risk of erroneous AOA data leading to repeated MCAS activation.

On November 7, 2018, a day after Boeing issued its OMB, the FAA issued an Emergency Airworthiness Directive ("AD") requiring airlines to amend their Airplane Flight Manuals to include the OMB guidance. The FAA also convened multiple Corrective Action Review Board ("CARB") meetings—the FAA's analog to Boeing's SRB process—starting in late November to evaluate issues relating to the airplane effects of erroneous AOA data and MCAS activation. Relying on the FAA's independent risk analysis, the CARB process largely concurred with Boeing's analysis of the safety issue and proposed risk mitigation approach. Referencing the FAA's independent risk analysis, an FAA CARB concluded in December 2018 that, as development of the software update proceeded, the MAX fleet could continue operating until the new software was implemented on the FAA-approved schedule.

Question 24. Following JT610 and prior ET302, why did Boeing fail to immediately seek to fix MCAS based on a HAZARDOUS malfunction?

Answer. As described above in response to Question 23, following the crash of JT610, Boeing immediately followed its safety process to determine the appropriate response. As a result of that process, Boeing took steps in conjunction with the FAA to develop and implement a software update to the flight control computer in order to eliminate the risk of erroneous AOA data leading to repeated MCAS activation. The FAA determined that Boeing should implement the software update more quickly than Boeing originally proposed, and Boeing accepted the FAA's schedule.

Question 25. Given the centrality of the Speed Trim System to these matters, please address the following questions:

- Yes or no, is the implementation of the Speed Trim System on the Boeing 757 fail-safe, dual-input and dual-processor design with aft column cutout switch active?
- Yes or no, is the implementation of the Speed Trim System on the Boeing 747-400 fail-safe, dual-input and dual-processor design with aft column cutout switch active?
- Yes or no, is the implementation of the Speed Trim System on the Boeing 737-700 fail-safe, dual-input and dual processor design with aft column cutout switch active?
- If the answer to any of the above three questions is "no," please provide a detailed explanation.

Answer. The Speed Trim System as currently implemented on all the listed models meets all regulatory requirements, and ensures any single failure of the system does not affect the ability of the aircraft to maintain safe flight and landing. The design for each model is dual-processor, but it is not dual-input. The aft column cutout switch is active in each design, though the amount of movement required to activate it varies between models.

Question 26. Yes or no, even though the 737 Speed Trim System is a single threaded design augmentation system that has full control of the stabilizer, does the 737 Speed Trim System survive without greater hazard classification because active aft and forward column cutout switches constrain malfunction?

Answer. Hazard classifications are applied to particular failure modes of a system, not the system itself. There are failure modes of the Speed Trim System (STS), such as a stabilizer runaway driven by the flight control computer, which can be mitigated by the column cutout switches. However, other failure modes of the STS do not rely on those switches for mitigation. The classification of each hazard depends on the specific circumstances of that failure. None of the hazard assessments for MCAS relied on engaging the aft column cutout switch.

Question 27. One of your primary competitors appears to require testing the angle of attack sensor reading at 80 to 100 knots in the takeoff roll when the relative wind reliably aligns the vane to the expected angle of incidence. Will Boeing upgrade Flight Crew Operating Manuals to require such a test during the takeoff roll?

Answer. No. Boeing airplanes already electronically conduct similar checks. The results of those checks are captured and documented to ensure they are addressed by maintenance personnel. With the upgrades to MCAS that will be implemented as part of return to service, if the two AOA vanes on the 737 MAX disagree by more than 5.5 degrees, MCAS will be disabled for the remainder of the flight and pilots will be alerted that speed trim is inoperative. Boeing is continually working to develop ways to increase safety during all phases of flight, including takeoff.

Question 28. On May 17, 2019, I submitted the follow oversight question to the Boeing Company:

"On what date did Boeing first provide the Flight Standardization Board (FSB) with information on the addition of the Maneuvering Characteristics Augmentation System (MCAS) flight control law to the 737 MAX series aircraft to comply with Federal Regulation 25.203—Stall characteristics, paragraph (a)?"

Boeing provided the following response:

"Boeing briefed FAA personnel involved in the FSB process for the 737 MAX about MCAS at least as early as 2012. In the spring of 2014, Boeing and the FAA began more formal discussions about how the FSB process for the 737 MAX would proceed. During this time, Boeing provided the FAA technical briefings on MCAS among other aspects of the evolving airplane design. Following the process set forth in FAA guidance, in February 2015 Boeing submitted a preliminary draft of the Master Differences Requirements and Design Operator Differences

Requirements (ODR) tables to the FAA for evaluation. Boeing included MCAS as one of dozens of airplane features in the draft ODR table.”

I also posed this question to Boeing:

“Please confirm whether Boeing ever recommended that the FSB evaluate the differences between the Speed Trim System (STS) in the 737 NG series and the STS in 737 MAX series that also has MCAS installed, and if so, the earliest date upon which Boeing advised the FSB to evaluate MCAS when conducting the differences assessment.”

Boeing provided the following response:

“As explained in the response to Question #1, Boeing briefed FAA personnel involved in the FSB process about MCAS at least as early as 2012. MCAS is an extension of the pre-existing Speed Trim function, which helps stabilize airplane speed by commanding stabilizer in the direction to oppose a speed change, and which has been used safely on 737 series airplanes for decades. Following a series of technical briefings on MCAS and other airplane features in 2014, in February 2015 Boeing submitted a preliminary draft of the Master Differences Requirements and Design Operator Differences Requirements (ODR) tables to the FAA for evaluation. Boeing included MCAS as one of dozens of airplane features in the draft ODR table. Ultimately, the versions of the FSB report that the FAA posted for public comment and finalized in 2017 did not include MCAS in the ODR table.”

Please explain why Boeing chose not to use either response as an opportunity to share with my office the fact that Boeing proposed removing MCAS from the ODR table.

Answer. As we stated in response to Question No. 1 on May 17, 2019, MCAS was included in the preliminary procedures and ODR tables that were sent to the FAA in February 2015. Boeing recommended removal of MCAS from the ODR Table in March 2016 and FAA agreed with Boeing’s recommendation. Boeing exchanged multiple drafts of the ODR Table with the FAA throughout 2016 and 2017 and the versions of the FSB report that the FAA posted for public comment and finalized in 2017 did not include MCAS in the ODR Table.

Question 29. Beyond MCAS, what other issues related to aircraft systems worry you and require improvement? For example, is Boeing planning to make the Speed Trim System fail-safe on the 737 NG?

Answer. Boeing is continually evaluating the performance of its aircraft. As part of that process, Boeing identifies appropriate enhancements to those aircraft, and will continue to do so. The Speed Trim System as currently implemented meets all regulatory requirements, and any single failure of the system does not affect the ability of the aircraft to maintain safe flight and landing.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. KYRSTEN SINEMA TO
DENNIS MULLENBURG

The Boeing 737 Max 8 received a derivative type certificate from the FAA, which was based on the original type certificate the Boeing 737-100 from 1967.

The original 737-100 was a very different aircraft. It was 94 feet long, carried 115 passengers, required three pilots, and had a maximum takeoff weight of 42,000 kilograms. The current versions of the 737 MAX can be up to 50 percent longer, carry twice as many passengers, and have double the maximum takeoff weight.

The FAA states that getting an amended type certificate can take up to 5 years, but a new type certificate, which is a more detailed analysis, can take up to 9 years.

Question 1. Based on the significant changes in the aircraft since 1967, do you believe that an amended type certificate was appropriate for the Boeing 737 Max 8? And going forward, do you believe FAA should limit the number of times an aircraft design can be amended before a new type certificate is required?

Answer. An amended type certificate was appropriate for the Boeing 737 MAX 8. Building upon existing, safe designs with a proven track record has continuously improved the safety record of the aviation industry for decades. As with all airplane development decisions, we make such decisions deliberately and methodically, after studying the current state of technology and opportunities for improving the existing airplane architecture, among many other factors.

The FAA has robust regulations and processes for evaluating when an airplane should be a new or amended type certificate and what regulations to follow for each process. The MAX certification project followed these regulations. Setting an arbi-

bitrary limit on the number or timing of changes to an airplane does not advance the interest of safety.

The United States has the best airline pilots in the world, and I believe the quality of our pilots is the reason that U.S. commercial aviation is the safest in the world.

But all pilots, regardless of experience or nationality, need all the information about the aircraft to be able to make the right decisions.

Boeing pilot manuals did not reference MCAS or describe an autonomous system to repeatedly lower the nose by 2.5 degrees. But Boeing's safety analysis expected pilots to be the primary backup for the system, if it failed. The pilots cannot be the backup for a system, if they aren't informed that the system exists, and it operates in the background without their knowledge.

Question 2. Please explain Boeing's decision not to include MCAS in the pilot manual or pilot training, and discuss Boeing's future plans to fully inform pilots about background systems.

Answer. In accordance with FAA regulatory guidance, flight training for all Boeing airplanes, including the 737 MAX, is designed to give pilots the knowledge, skills, and abilities necessary to safely operate each model on which they are licensed (or "type-rated"). Rather than diagnose particular failures, flight training and manuals are designed to give pilots the knowledge, skills, and abilities necessary to safely respond to those failures.

Boeing and the FAA coordinated closely over the course of several years in developing the necessary training requirements and flight manual content for the MAX. Since the accidents, the FAA and Boeing have worked together to develop additional MAX flight crew training, as well as flight manual content, that addresses the updates Boeing has made to MCAS. The inclusion of specific training and flight manual content on MCAS is consistent with the feedback Boeing has received from pilots and its customers, and reflects the additional knowledge and understanding that Boeing has gained as a result of these accidents.

In designing aircraft, redundancy is key. The FAA requires aircraft systems that can cause hazardous or catastrophic failure to incorporate multiple levels of redundancy. This way, if FAA requirements are met, no single malfunction can lead to tragedy.

However, the MCAS system on the Boeing 737 Max 8 had zero redundancy. A single faulty or damaged angle-of-attack sensor could cause the MCAS system to engage repeatedly, as was the case for the tragedies in Indonesia and Ethiopia.

These disclosures are leading many to consider revisions to the FAA's Organization Designation Authorization (ODA) program. As you know, the FAA uses the ODA program to authorize organizations or companies to approve certain aspects of FAA aircraft certification.

The DOT Special Committee is making recommendations on FAA certification, but I expect that Boeing has undertaken its own internal review of ODA and the necessary changes.

Question 3. Based on the Boeing 737 Max 8 tragedies, what concrete revisions to the ODA program are required to ensure that only safe aircraft are certified to fly?

Answer. Boeing strongly supports robust FAA oversight of the certification process. As the last major commercial airplane manufacturer in the United States, Boeing believes the certification process, and the FAA's role in that process, are vital to the safety of the traveling public, and have been an important factor driving substantial improvements in aviation safety in recent decades.

The Organization Delegation Authority process has helped improve that safety record. However, there are ways to improve that process. For example, the FAA's System Oversight capability could be strengthened by setting clear expectations for applicants' processes and procedures to ensure compliance for lower risk areas, as identified by the FAA. This would allow FAA to dedicate the majority of its resources on areas the FAA has determined to be the highest safety risk. Boeing will work with all interested stakeholders to learn from these accidents and further increase aviation safety.

During flight testing, Boeing increased the MCAS system from providing a 0.6 degree nose-down correction to a 2.5 degree nose-down correction—without FAA oversight.

And according to reports, once MCAS was adjusted to provide a more powerful input, Boeing never flight-tested a scenario in which a broken angle-of-attack sensor triggered MCAS on its own, instead relying on simulator analysis.

Former Boeing test pilots described a culture of pressure inside the company to limit flight testing, due to project delays. And in the text messages Boeing released

last week, an employee stated: “they’re all so damn busy, and getting pressure from the program.”

Question 4. Was there adequate flight testing of the revised MCAS system, and what will Boeing do to address schedule pressure to get aircraft certificated?

The first tragic crash, involving Lion Air Flight 610, occurred on October 29, 2018. The second crash, involving Ethiopian Airlines Flight 302, occurred five months later.

Answer. The final MCAS design, including MCAS’s operation at low speeds, was tested in flight tests, where multiple conditions involving the design were tested.

Boeing has taken a number of steps to reinforce our safety culture. These include creating a permanent Aerospace Safety Committee within our Board of Directors, creating a Product and Services Safety organization to review all aspects of product safety, and realigning our Engineering function so that all engineers will report directly to the Chief Engineer. Moreover, pursuant to our Organization Delegation Authority, Boeing maintains robust procedures for ODA unit members to report incidents of undue pressure, and Boeing provides all employees multiple avenues to raise safety issues related to our products.

Question 5. Why was the Boeing Max 8 not grounded after the Lion Air crash and prior to the second crash in Ethiopia? What information regarding the MCAS system did Boeing have prior to or immediately after the first crash that lead to concerns related to the Angle of Attack and MCAS system?

Answer. Boeing does not have the authority to ground airplanes. Boeing does, however, provide civil aviation authorities and our airline customers with any relevant information we may receive or develop, so that they can make informed decisions on how to regulate aircraft operations.

After the Lion Air crash, on Sunday, November 4, Indonesian authorities provided Boeing with data downloaded from the airplane’s flight data recorder. That same day, Boeing convened an “out-of-sequence” Safety Review Board (“SRB”) to consider and analyze the available data. The SRB included subject matter experts from various backgrounds, including senior Boeing engineers, test pilots, and executives responsible for safety and regulatory matters. FAA representatives were also in attendance. After considering the limited information available, the SRB decided to defer a decision on the potential safety issue for two days to allow time for Boeing engineers and pilots to conduct further testing and analysis.

The SRB, with most of the same members present, reconvened on November 6, 2018. The FAA was again in attendance. With the fuller information then available, including additional analysis by Boeing’s technical experts and test pilot input, the SRB identified as a safety issue the increased crew workload that might result if erroneous AOA input led to repeated MCAS activation. Although a full quantitative analysis of the issue had not yet been completed, the SRB made this determination based on a preliminary risk assessment and in recognition of the importance of immediately addressing the concerns identified. The SRB further noted the importance of appropriate action by the flight crew to prevent and counteract repeated MCAS activation in this erroneous AOA scenario.

That same day, Boeing issued an Operations Manual Bulletin (“OMB”) to the fleet calling attention to the airplane effects and flight deck indications of the condition, and directing flight crews to existing procedures to address it. Boeing also moved forward expeditiously to develop an update to the MAX’s flight control computer software to eliminate the risk of erroneous AOA data leading to repeated MCAS activation.

On November 7, 2018, a day after Boeing issued its OMB, the FAA issued an Emergency Airworthiness Directive (“AD”) requiring airlines to amend their Airplane Flight Manuals to include the OMB guidance. The FAA also convened multiple Corrective Action Review Board (“CARB”) meetings—the FAA’s analog to Boeing’s SRB process—starting in late November to evaluate issues relating to the airplane effects of erroneous AOA data and MCAS activation. Relying on the FAA’s independent risk analysis, the CARB process largely concurred with Boeing’s analysis of the safety issue and proposed risk mitigation approach—although the FAA did determine that that Boeing should implement the flight control computer software update more quickly than Boeing had originally proposed, an accelerated schedule the Company accepted. Re Referencing the FAA’s independent risk analysis, an FAA CARB concluded in December 2018 that, as development of the software update proceeded, the MAX fleet could continue operating until the new software was implemented on the FAA-approved schedule.

Question 6. And why did Boeing publish a supplementary service bulletin regarding the Angle of Attack sensors and MCAS, but did not take the aircraft out of service?

Answer. Please see the response to the previous question. Boeing does not have the authority to ground airplanes. After the Lion Air accident and continuing to today, Boeing provides civil aviation authorities and our airline customers any relevant information we may receive or develop, so that they can make informed decisions on how to regulate aircraft operations.

Question 7. Do you disagree with any of the findings in the National Transportation Safety Board in Aviation Safety Recommendation Report ASR-19-01 issued on September 19, 2019 titled “Assumptions Used in the Safety Assessment Process and the Effects of Multiple Alerts and Indications on Pilot Performance” or audit report AV-2016-013 the Inspector General of the Department of Transportation issued on January 7, 2016 titled “Enhanced FAA Oversight Could Reduce Hazards Associated With Increased Use of Flight Deck Automation?”

Answer. Boeing is deeply committed to the safety of its products and the safety of the aviation system and values the role of the National Transportation Safety Board (NTSB), as well as the reviews of the Office of the Inspector General (OIG), in promoting aviation safety.

Boeing has already undertaken steps that align with at least one of the NTSB’s recommendations. The NTSB recommended that FAA require manufacturers to consider the way cockpit design can impact pilot reaction to alerts and alarms that may sound in non-normal situations. As a result of a recommendation from a special committee of Boeing’s Board of Directors, the company is already planning to work with our airline customers to re-examine the way we design our cockpits, with the goal of helping pilots to prioritize their attention and their actions when faced with multiple alerts and alarms. Boeing is taking this step with the recognition that pilot training and experience can vary significantly in different regions of the world. Boeing will continue to work with the NTSB, as well as the FAA, to understand the scope of the NTSB’s recommendations and the appropriate way to implement them.

Boeing will also support the FAA as it implements the recommendations from the OIG audit report from January 7, 2016. This report recommends that the FAA develop new guidance for training and standards to determine whether pilots receive sufficient training opportunities to develop, maintain, and demonstrate manual flying skills. Boeing continues to support the FAA’s Air Carrier Training Aviation Rulemaking Committee to discuss, prioritize, and provide recommendations to the FAA concerning these types of operations and training considerations.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. JOHN THUNE TO
HON. ROBERT L. SUMWALT III

Question 1. Your testimony mentioned the inadequacy of the MCAS safety assessment in estimating the crew workload, since it is likely other alerts and indications would be activated simultaneously in the event of an MCAS failure.

The National Transportation Safety Board (NTSB) recommended that the Federal Aviation Administration (FAA) instruct Boeing to better consider crew workload in the event of a system failure, including through the development of tools to improve the timeliness and effectiveness of crew responses.

Do you believe that any of the recent organizational changes made by Boeing will help address this recommendation?

Answer. The NTSB has not evaluated the recent organizational changes made by Boeing.

Question 2. As you know, the aviation system is safer—and catastrophic incidents rarer—than ever before, but the complexity of aircraft flight control systems means that when failures do occur, it can be difficult for crew members to prioritize the appropriate and timely actions in response to that failure.

How could system failure diagnostic tools be better designed to improve the threat and error management used by crew members in responding to system failures?

Answer. The NTSB believes that aircraft systems designed to clearly and concisely inform pilots of the highest priority actions when multiple flight deck alerts and indications are present would minimize confusion and help pilots respond most effectively to emergency and abnormal operational events. By developing design standards for such system diagnostic tools, with the input of industry and human factors experts, we believe the timeliness and effectiveness of pilot response would be improved.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. TOM UDALL TO
HON. ROBERT L. SUMWALT III

Question 1. The NTSB recommended that manufacturers use “less experienced” pilots to test advanced equipment. Are you aware of any resistance to this recommendation?

The NTSB concluded that a standardized methodology and/or tools for manufacturers’ use in evaluating and validating assumptions about pilot recognition and response to failure condition(s), particularly those conditions that result in multiple flight deck alerts and indications is needed. Based on this, the NTSB recommended that the FAA develop robust tools and methods, with the input of industry and human factors experts, for use in validating assumptions about pilot recognition and response to safety-significant failure conditions as part of the design certification process. We are not aware of any resistance to implementation of this recommendation.

Question 2. The Boeing 737 made its first flight in 1967 and has applied for 14 model changes since that time. There have been calls for a complete recertification of the entire 737. Do you agree that the entire plane should be recertified?

The NTSB does not have a position on this.

RESPONSE TO WRITTEN QUESTION SUBMITTED BY HON. TAMMY DUCKWORTH TO
HON. ROBERT L. SUMWALT III

As you are aware, problems originating with a damaged or malfunctioning angle of attack (AOA) sensor are not limited to any single model of aircraft or manufacturer. Enhancing AOA sensors must be a priority for the entire aviation industry and regulatory system. Increasing awareness and improving knowledge represent critical tools in improving aviation safety.

That is why I wrote to then-Acting Administrator Elwell on May 21, 2019 to request that FAA publish a comprehensive advisory circular that standardizes guidance on best practices for manufacturing, operating, testing and maintaining AOA sensors, particularly the AOA wind vane component, to ensure effective compliance with all applicable regulatory requirements.

Following the FAA’s order revoking a repair station certificate from a firm that repaired and supplied the malfunctioning AOA sensor that contributed to the fatal crash of Lion Air Flight 610, I once again wrote to FAA Administrator Dickson to request that FAA publish a comprehensive advisory circular that standardizes guidance on best practices for manufacturing, operating, testing and maintaining AOA sensors, particularly the AOA wind vane component, to ensure effective compliance with all applicable regulatory requirements.

Awareness and knowledge are critical tools in strengthening aviation safety.

Question. Please address how the potential publication of the type of comprehensive advisory circular that I have requested would improve aviation safety.

The NTSB has not issued any recommendations regarding design, manufacturing, operating, testing or maintaining of AOA sensors and therefore does not have a position on this matter.

However, the Komite Nasional Keselamatan Transportasi (KNKT) of Indonesia has issued one related recommendation based on its investigation of the Lion Air 610 crash.¹

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The absence of equivalency assessment required by Xtra Aerospace procedure and unavailability of procedure was not detected by the FAA. This indicated inadequacy of the FAA oversight.

Therefore, KNKT recommends that the FAA improves the oversight to Approved Maintenance Organization (AMO) to ensure the processes within the AMO are conducted in accordance with the requirements.

¹ Komite Nasional Keselamatan Transportasi (KNKT), *Final Report No. KNKT.18.10.35.04*.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. TOM UDALL TO
HON. CHRISTOPHER A. HART

Question 1. Chairman Hart, in the JATR report, there was discussion of the undue pressure placed on employees at Boeing to pressure to employees get the plane certified without any new pilot training or delay. Boeing has said it is restructuring its units, and safety engineers will no longer be required to report directly to a business unit manager. Do you believe this change will relieve some pressure on employees?

Answer. Because of concerns about potential undue influence, the JATR recommended that the FAA review its certification process, as well as Boeing's Organization Designation Authorization (ODA) procedures and work environment, to ensure that there is no undue pressure (*e.g.*, Recommendation 5). Whether a specific substantive change will be helpful is beyond the purview of the JATR because it completed its review when it submitted its recommendations to the FAA, and it was chartered to review the certification process rather than specific substantive changes. I am not in a position to opine about the effectiveness of specific proposed substantive changes.

Question 2. Are there other changes that Boeing should make?

Answer. The JATR's recommendations were addressed to the FAA, not to Boeing, and were about how the FAA could improve its certification process. Although the JATR's improvement recommendations included recommendations to the FAA to review Boeing's processes and procedures, the JATR was chartered to review the certification process rather than specific substantive changes. Examples of Boeing's processes and procedures that the JATR recommended the FAA should review include Rec 5 (ODA work environment and procedures manual), Rec 8.1 (development assurance process), Rec 8.2 (safety analysis process), Rec 8.4 (process for managing assumptions), and Rec 8.6 (process for managing requirements).

Question 3. How can we ensure that pilots are fully prepared for the high-levels of automation in today's cockpits?

Answer. The JATR's recommendations address two aspects of helping to optimize airplane/pilot interactions. First, the recommendations address ways that the certification process can help ensure that aircraft systems are designed to be adequately pilot-friendly, *e.g.*, Rec 2.2, Rec 2.4, Rec 2.7, Rec 2.8, Rec 2.9, Rec 3.8, Rec 3.16, Rec 3.17, Rec 6.1, Rec 6.2, Rec 6.3, Rec 6.4, Rec 6.6, Rec 6.8, Rec 6.9, Rec 6.10, Rec 7.1, Rec 7.2, Rec 8.8, Rec 9.6, and Rec 9.7. Second, the recommendations address ways that the certification process can help ensure that, upon completion of the design, pilots are aware of, and adequately trained regarding, the aircraft automation and other systems, *e.g.*, Rec 3.9, Rec 3.11, Rec 3.14, Rec 9.1, Rec 9.2, Rec 9.3, Rec 9.4, Rec 10.2, Rec 10.3, Rec 10.4, Rec 10.5, and Rec 12.2.

