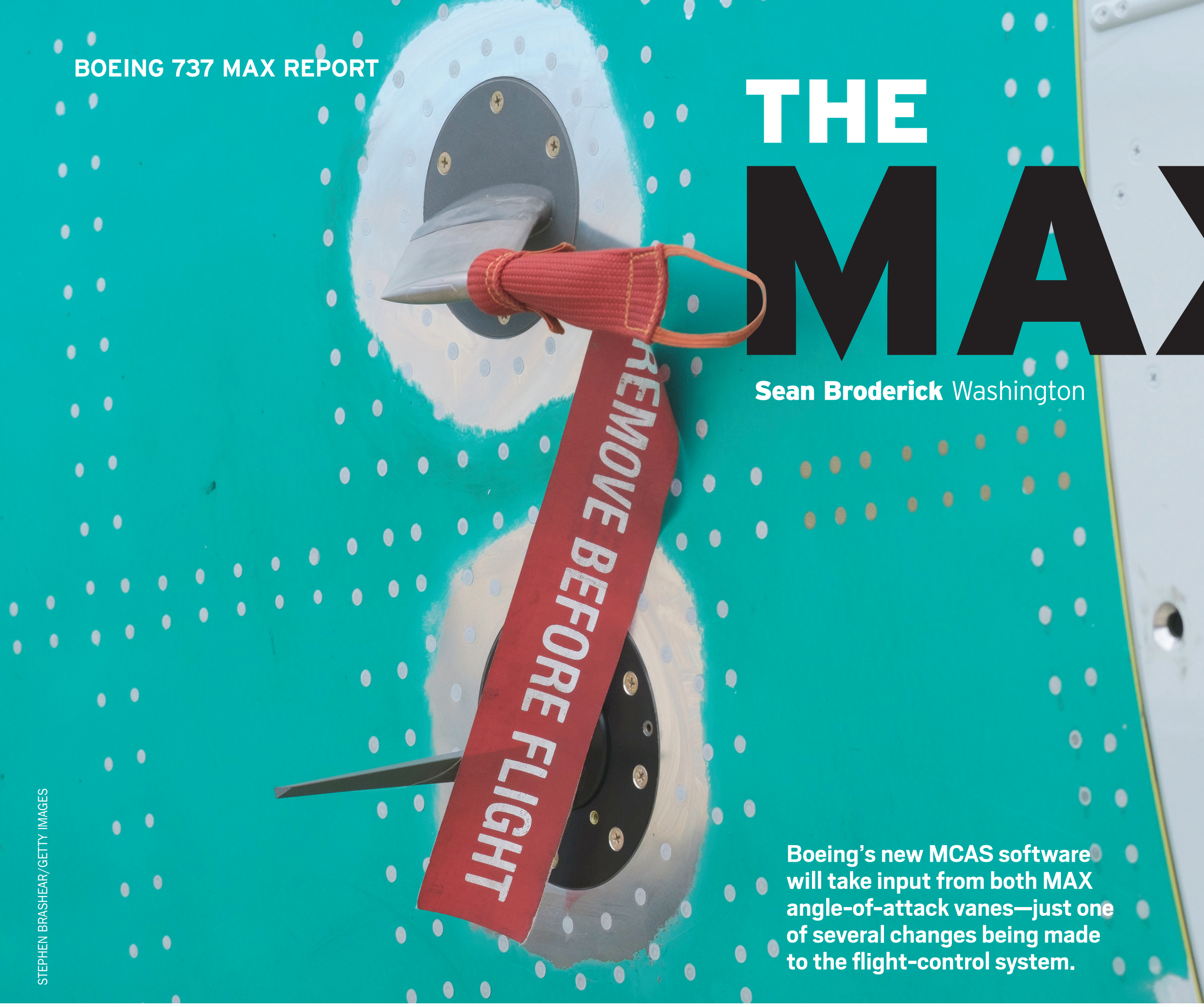


STEPHEN BRASHEAR/GETTY IMAGES

Boeing's new MCAS software will take input from both MAX angle-of-attack vanes—just one of several changes being made to the flight-control system.

THE MAX

What happened, and **what now?**

Sean Broderick Washington

Mid-August marked five months since the last Boeing 737 MAX fleet's revenue flight and customer delivery as well as—most significantly—its second fatal accident. While Boeing is making progress on changes needed to convince regulators that the latest iteration of its venerable narrowbody is safe to fly, the timing remains fluid. The road ahead is littered with unanswered questions. As for how one of the industry's most successful and best-selling models ended up grounded less than two years after entering service, more is known. Following is a recap of how the MAX got here, where it is headed, and—to the extent known—what comes next. Some key issues related to the MAX crisis are not covered in detail. Among them: detailed breakdowns of the two accident sequences as revealed in preliminary investigative reports. While the MAX's Maneuvering Characteristics Augmentation System (MCAS) played a role in both accidents, other concerns—from maintenance practices to the adequacy of pilot training—will likely end up being identified as contributing factors. As with every major accident, the lessons learned go far beyond addressing the primary causal factors. With two accidents to learn from, the MCAS may be close to being updated, but the MAX story's influence on aircraft design, certification and pilot training is only starting to be felt.

Question: **Why did Boeing develop the MAX instead of a clean-sheet successor to the 737?** As the 2010s began, Boeing was looking hard at developing an all-new narrowbody to replace the aging 737, which first flew in 1967. The company's leaders downplayed the belief that a rumored reengining of the A320 by Airbus would force Boeing to follow suit. "Not if we're convinced a new airplane will be coming at or near the end of the decade," then-CEO Jim McNerney told Aviation Week in mid-2010. "I think our customers will wait for us."

But with oil prices soaring, the 15% improvement in fuel efficiency the A320neo offered proved more attractive to airlines than waiting several more years for an even better airplane. By mid-2011, seven months after the Neo's launch, Airbus had won more than 1,000 orders and commitments.

Boeing's hand was finally forced by the prospect of losing one of its marquee customers, American Airlines. The carrier, previously an all-Boeing customer, split a record-setting order for 460 narrowbodies between the two companies—but only after Boeing agreed to launch the MAX. "The American Airlines A320neo deal was probably transformative," John Leahy, Airbus' longtime chief salesman, recalled last year. "Boeing threatened to sue [American] because it all happened before the end of a 20-year exclusivity agreement. But American said if Boeing wanted a share of the order, they would have to produce a [reengined 737]. So they did it, and did not even know what the aircraft was going to be like because they were so focused on the all-new single-aisle."

Ironically, the A320neo was launched as a defensive move. Airbus leaders wanted to blunt the threat to the A320 from the C Series, the cutting-edge Bombardier aircraft program launched in 2008 with Pratt & Whitney geared turbofan engines. Even they had no idea the Neo would generate so many new orders.

"The Neo's success in the marketplace did point out unmistakably that customers would embrace a lower amount of capability quickly," McNerney reflected in 2012. "So that was a factor. We added it all up and decided to move with the MAX."

The birth of the MAX took even its engine supplier by surprise. "Up until a few days before the American Airlines deal, Boeing was still saying they were going to do an all-new airplane," said former CFM executive vice president, GE general manager and deal broker Chaker Chahrour in 2013. "It was amazing how, literally within a few days, things had turned around."

Where did the MCAS come from?
Boeing's decision to reengine the 737 presented several challenges. The most significant one: how to integrate the Leap-1B engines into the design. Key changes included extending the nose gear 8 in., and cantilevering the engine forward and upward of the wing leading edge.

Early in the MAX's development, Boeing discovered that the heavier engines presented a stability and control issue: Their larger nacelles created

737 MAX Timeline

- **JULY 13, 2008 Bombardier launches** the C Series, a cutting-edge 110-130-seat aircraft that pushes into the lower end of the Boeing 737/Airbus A320 market.
- **DEC. 1, 2010 Airbus launches** the reengined A320neo without a customer, promising a 15% gain in fuel efficiency.
- **JULY 20, 2011** Faced with the prospect of losing marquee customer American Airlines, **Boeing announces it will reengine** the 737 instead of developing a clean-sheet successor later in the decade. American commits to 100 of them.
- **JUNE 30, 2012 Boeing submits application** to U.S. FAA to amend type certificate A16WE to include 737-8.
- **JAN. 29, 2016 First flight of the MAX**, 737-8 1A001.
- **MARCH 8, 2017 MAX family baseline**, the 737-8, is certified by U.S. FAA.
- **MAY 22, 2017 MAX enters service** with Malaysia's Malindo Air.
- **OCT. 29, 2018 Lion Air Flight 610,** a three-month-old 737-8, crashes 13 min. after takeoff from Jakarta, Indonesia, killing all 189 on board.
- **NOV. 6, 2018 Boeing issues an operators' bulletin** explaining that the "erroneous (angle-of-attack) data" can cause "the pitch trim system [to] trim the stabilizer nose down in increments lasting up to 10 sec." and references the correct emergency procedures. This is the first public description of the MAX's Maneuvering Characteristics Augmentation System (MCAS), though it is not referenced by name.
- **NOV. 7, 2018 FAA issues emergency directive warning** that data from one faulty AOA sensor creates "potential for repeated nose-down trim commands of the horizontal stabilizer." Operators are ordered to update MAX flight manuals to include Boeing's Nov. 6 bulletin. The MCAS is not referenced.
- **NOV. 10, 2018 Boeing issues bulletin** to operators with more details about the MCAS and identifies the system by name. Many airlines issue internal bulletins to their pilots. This is how most pilots learn that the MCAS exists.

2008 — 2010 — 2011 — 2012 — 2016 — 2017 — 2018 — ***Boeing begins work on MCAS software changes*** →

more lift at high angles of attack (AOA) and high airspeeds. Boeing's solution: Expand the 737NG's speed trim system (STS) by adding the MCAS—software code that expands how the horizontal stabilizer is automatically adjusted as the aircraft approaches its threshold AOA or stickshaker activation. The resistance created by the automatic nose-down stabilizer inputs would ensure pilots felt consistent, linear force—which FAA certification standards require—as they pulled back on the column.

How was the MCAS designed? Using modeling and wind-tunnel data, Boeing linked MCAS activation to two factors: G forces and AOA data. The system's authority was limited to 0.6 deg. of stabilizer movement per MCAS activation cycle. No limit was put on the number of times the MCAS could activate; it would trigger whenever data fed to it determined that it was needed.

During flight-testing in 2016, Boeing discovered that the lower pitch-down moment also was an issue during certain high-AOA, low-airspeed conditions when G force was not a factor. To address this, the MCAS was changed to be fed by AOA data only, and its authority was increased to 2.5 deg. of stabilizer movement per activation cycle. *The Seattle Times* first reported details of the MCAS' evolution.

The system was designed to work in tandem with the active 737 flight control computer (FCC) that was active on each flight (see box, page 36). As on the 737NG, the MAX has two redundant FCCs and two AOA vanes. On the day's first leg or after a full power-down, the left-side (captain's) AOA vane would feed the left-side FCC and, if necessary, activate the MCAS. On the next flight, MCAS activation would come via data from the right-side (first officer's) AOA vane and FCC.

Besides adding software, managing the MAX's lower pitch-down moment required another key change to the 737NG STS. On the NG, pulling back on the yoke activates a column cutout switch that interrupts any automatic stabilizer movement. But on the MAX, the MCAS bypasses this switch.

"On the MAX, we still needed automatic trim when you got to that spot," Mike Sinnett, Boeing Commercial Airplanes vice president of product development and future airplane development, explained in April. "[The] MCAS differs from speed trim at elevated [AOA] because it bypasses that switch by design. To do so, it activates based on AOA rather than speed, which is what speed trim does."

Why didn't pilots know about the MCAS? Boeing designed the MCAS to be transparent to pilots when operating normally, and it succeeded. Both the company and the 2017 Flight Standardization Board that scrutinized the changes from the 737NG to the MAX and flew each aircraft to detect differences determined that training on the system's operation was unnecessary.

Boeing concluded that if the MCAS was activated erroneously, pilots would quickly detect uncommanded stabilizer movements—including the rotation of large, noisy manual trim wheels attached to the center console—and diagnose a runaway stabilizer. They would then execute the "runaway stabilizer" checklist from memory or a quick-reference chart. Among its key steps: Hold the control column firmly and trim the aircraft using control-column-mounted main electric trim switches. If the runaway continued, pilots could flip cutout switches on the center console and disconnect the automatic trim motor. After this step, pilots would have to use the manual trim wheel to move the stabilizer.

Because the system's operation was transparent to pilots and its troubleshooting relied on a common procedure (the 737's runaway stabilizer checklist debuted in 1967 and had not changed since 2013), Boeing decided not to include a description of the MCAS in flight training or flight crew operations manuals. Boeing did not keep it a secret—the MCAS was included on a list of changes from the 737NG during high-level customer briefings and covered in MAX maintenance documentation. But most airline pilots had no idea it existed.

What happened with Lion Air Flight 610? Like most accidents, several factors appear to have contributed to the crash of Lion Air Flight 610 (JT610) on Oct. 29, 2018. But a preliminary report issued in late November suggested that the accident sequence started when the MCAS activated based on faulty AOA data.

The report shows that the three-month-old 737-8, PK-LQP, was not airworthy when it pushed back to begin its trip to Pangkal Pinang, Indonesia. Something caused the aircraft's left-side AOA vane to report a value that was 20 deg. higher than the right vane. This discrepancy, captured by the digital flight data recorder (DFDR) even as the aircraft was taxiing out, triggered a stickshaker stall warning on the captain's side as soon as the aircraft took off.

Once the flaps were retracted, the left-side FCC, reading the faulty AOA data, triggered the MCAS. Nose-down trim was applied for 10 sec. The pilots countered with main electric trim nose-up inputs. At least 25 automatic stabilizer nose-down, pilot-directed stabilizer nose-up exchanges took place and then several nose-down inputs were not countered. The last automatic nose-down input precipitated a dive from about 5,000 ft. that ended with the aircraft hitting the Java Sea 13 min. after takeoff. All 189 people onboard were killed.

How did the key players react? Lion Air was immediately concerned about the possibility of uncommanded stabilizer inputs playing a role in the accident. Within hours after JT610 disappeared, the airline issued a safety reminder to its 737 pilots, urging them "to review several procedures, including memory items of Airspeed Unreliable and Runaway Stabilizer," the Indonesian National Transportation Safety Committee (NTSC) preliminary report released Nov. 28 says. Nothing in the report suggests that the JT610 crew followed the runaway stabilizer checklist.

It did not take long for Boeing to zero in on the accident sequence's key elements. On Nov. 6, the manufacturer issued a Flight Crew Operations Manual Bulletin: "Uncommanded Nose-Down Stabilizer Trim Due to Erroneous Angle Of Attack During Manual Flight Only." The bulletin explained that one source of faulty AOA data can trigger 10 sec. increments of nose-down stabilizer inputs. Electric trim input will stop the automatic nose-down stabilizer movement, but it "may restart" 5 sec. after the electric trim input stops. The only way to stop the cycle is to follow the runaway stabilizer checklist and toggle the console-mounted cutout switches. Boeing also warned that "higher control forces may be needed to overcome any stabilizer nose-down trim already applied." It recommended that operators append the bulletin to flight manuals.

The next day, the FAA issued an emergency airworthiness directive mandating Boeing's recommendation. Neither Boeing's bulletin nor the FAA's directive discussed procedural changes, and neither referenced the MCAS by name.

Did regulators or Boeing consider doing anything else? Following the accident, both the FAA and the European Aviation Safety Agency (EASA) conducted risk assessments of the MAX fleet. They probed flight-safety databases and found no comparable incidents. Their conclusions: The risk was not high enough to take immediate action on the in-service fleet beyond the initial bulletins.

While it appeared the fleet was not at immediate risk, PK-LQP's problems and the JT610 accident sequence convinced Boeing that the MCAS needed improvement, and it began to work on a software upgrade. In early December, the company's projected timeline for delivering the new software was 1-2 months. But the upgrade's scope kept changing and has extended beyond the MCAS. It is still not done.

So when did the world learn about the MCAS? A Nov. 10 message from Boeing to MAX operators shed more light on the system described in the earlier bulletin, using the MCAS' name. Airlines disseminated bulletins to their pilots. For most of them, it was the first time they had heard of the MCAS.

Still, confusion persisted. Pilots at one U.S. major airline were told by their safety committee that the MCAS could be countered by applying opposite control-column input to activate the column cutout switches, which was not true.

What happened to Ethiopian Airlines Flight 302? Ethiopian Airlines Flight 302 (ET302), a five-month-old 737-8 carrying registration ET-AVJ, departed Addis Ababa, Ethiopia, early on March 10 bound for Nairobi, Kenya. The first officer radioed to the control tower, 1 min. into the flight, that the crew had a "flight control problem," the Ethiopian Ministry of Transport's preliminary report on the accident said. The aircraft crashed 5 min. later, killing all 157 people on board.

It took a few days to link ET302 to JT610. But it was soon clear that each accident chain had similar links. Both involved malfunctioning AOA vanes feeding incorrect data to the flight control computer. The data told the FCC that the aircraft's nose was too high, which activated the MCAS as soon as the flaps were up. Like the JT610 pilots, the ET302 pilots did not understand what was happening on their aircraft. The MCAS activated twice, and the crew countered with electric trim. Unlike the JT610 pilots, the ET302 crew flipped the stabilizer trim motor cutout switches, which stopped the MCAS from moving the stabilizer. But after reporting not being able to manually trim the aircraft, they flipped the cutout switches on again. The faulty AOA data was still feeding the left-side FCC, activating the MCAS again and putting the aircraft into a dive.

How did the regulators react, and why was the FAA the last to ban the MAX? Two fatal MAX accidents in five months was enough for many to take action. China was the first big mover, banning all MAX operations within 24 hr. of the ET302 accident. Other regulators and operators quickly followed suit. Notably, the FAA was not among them.

2019

MARCH 10, 2019 Ethiopian Airlines Flight 302, a 737-8, crashes 6 min. after takeoff from Addis Ababa, Ethiopia, killing all 157 on board.

MARCH 11 Chinese regulators ban all MAX operations. The FAA issues update providing details of Boeing's planned MCAS software changes, saying it "anticipates mandating these design changes no later than April 2019."

MARCH 12 Regulators in Singapore, Australia and across Europe ban MAX operations. Boeing releases details of planned changes to the MCAS.

MARCH 13 FAA becomes the last regulator to ban MAX operations, citing refined satellite data and evidence from the ET302 crash site that links the two MAX accidents.

MARCH 14 Boeing pauses MAX deliveries.

APRIL 5 Boeing temporarily cuts 737 production to 42 airplanes per month from 52.

MAY 16 Boeing announces that its MCAS software updates are complete, and it is addressing related requests from the FAA as part of recertifying the MAX.

JUNE 26 Boeing confirms that the FAA has requested another flight-control issue be addressed, further delaying a return to service. This issue is not related to the MCAS.

JULY 18 Boeing announces $4.9 billion in quarterly charges related to the MAX grounding and customer compensation.

JULY 24 Boeing warns it could completely suspend MAX production if return-to-service time frame continues to slip.

Source: AW&ST archives

Late on March 12 Washington time, FAA Acting Administrator Dan Elwell said that the agency's review of MAX in-service data, including what little was known about the second accident, "provides no basis to order grounding the aircraft, nor have other civil aviation authorities provided data to us that would warrant action."

That changed overnight.

Working with Transport Canada, the FAA reviewed what it termed "refined" satellite data that helped map ET302's flightpath. It showed altitude variations that were similar to those JT610 experienced as its crew countered the MCAS' nose-down commands with nose-up inputs. The data was enough to convince the Canadians to ban the MAX. A few hours later, the FAA became the last regulator to issue a ban.

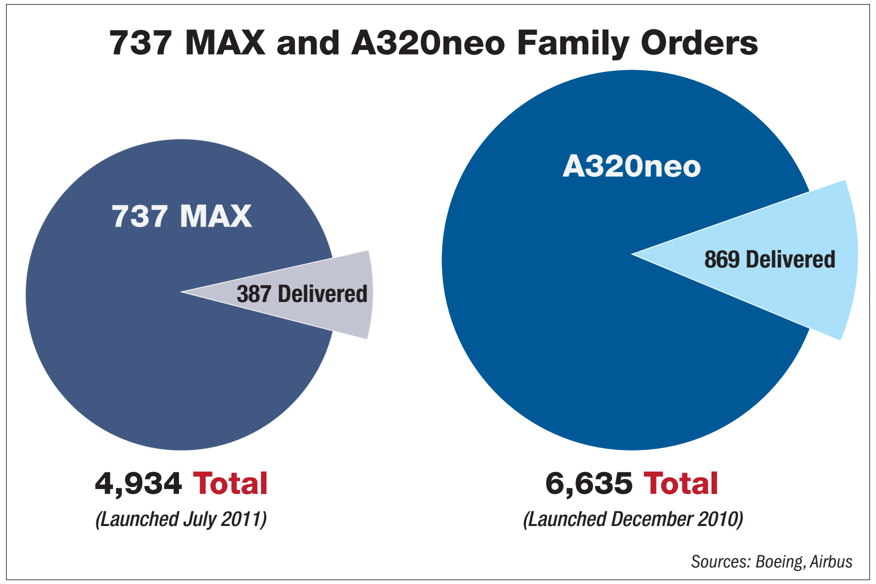
Elwell cited the flight data and a crucial piece of wreckage—believed to be a jackscrew showing that ET302's stabilizer was in a specific position when it crashed—as the evidence that swayed the U.S. agency. The groundings—or, more accurately, operations bans that cover a regulator's airlines and the airspace it governs—remain in place and must be removed one by one, at each regulators' discretion.

Why are the AOA vanes failing? If investigators have discovered a link between the AOA failures, it has not been made public.

Investigators have not explained what happened to the JT610 AOA vane, but the report suggests faulty maintenance played a role. A left-side vane removed from PK-LQP during an overnight stay in Denpasar, Indonesia, following an Oct. 27 flight has been analyzed, but investigators have not released any details. Digital Flight Data Recorder (DFDR) data from JT610 and the previous flight the day before, JT43, showed left-side AOA value disagreements during taxi-out.

But ET302's AOA values were similar until shortly after takeoff, when the left vane's value changed suddenly and significantly. One theory is that a bird or some other object struck the vane, but nothing released by investigators besides the DFDR data readout supports this.

How has the grounding affected Boeing's production? Boeing paused deliveries on March 14 and reduced 737 production—now mostly MAXs destined for airlines—from 52 per month to 42 per month as of April. Newly built aircraft are flown by Boeing production test pilots—many of them contributing to flight-testing the proposed software changes—and then stored.



Deliveries will resume after regulators lift their bans, which Boeing hopes will be sometime in the fourth quarter. If that happens, the OEM plans to ramp 737 production back up in 2020 to a rate of 57 per month—the planned target for 2019 before the second accident and groundings disrupted everything MAX-related. However, Boeing also says all production of MAXs could be temporarily halted if the return-to-flight timeline drags on into 2020.

When will the MAX return to service? Boeing is targeting "the September time frame" for handing over the long-awaited changes to the FAA. They will include new MCAS software, related training and other changes to the flight control system that the FAA has requested.

If Boeing submits its package of changes to the FAA by mid-October, its current target of getting FAA approval sometime in the fourth quarter remains achievable. The FAA will be the first regulator to lift its ban, and at least some are expected to follow in short order—likely days.

Once a regulator clears the MAX to return to service, the process of preparing the aircraft for revenue service begins. In addition to routine work required to get any parked aircraft flying again, Boeing's upgrades must be installed—a process the company says will take a few hours per airframe. Each aircraft will then be flight-tested.

For carriers with just a few MAXs, the return-to-service timeline could be just a few days. But for larger carriers, it will take a month or more—a function of their ability to take only so many aircraft in short order, Boeing's available manpower to support the service returns, and—crucially—ensuring pilots have completed the latest training.

What about Boeing's finances? The longer airlines are without their MAXs, the higher the cost to Boeing will be. The company took a $4.9 billion second-quarter after-tax charge to cover anticipated customer compensation linked to the MAX grounding as well as development of the MCAS changes. That led to a record $2.9 billion quarterly loss.

But long-term damage to Boeing's finances could be limited by the fact that current MAX customers don't have a lot of options. They cannot simply switch orders to Airbus because the A320 family is largely sold out through 2022. And China's new narrowbody—the Comac C919—is unproven and behind schedule in flight-testing. "It's like a world where there are just two car companies," says Bank of America Merrill Lynch aerospace analyst Ron Epstein. "Boeing will come out of this."

How much is the MAX grounding hurting airlines? With affected airlines set to receive compensation from Boeing, the true impact of the MAX grounding is mixed—and the bite may end up being very little for some operators.

Parking the 385-aircraft MAX fleet with just hours notice created significant early disruption. Once airlines realized the aircraft were not coming back in short order, many began to adjust schedules to accommodate for the lost lift. They used every tactic available, from canceling flights to cutting frequencies and shuffling aircraft around. Nonessential maintenance, such as cabin-refresh programs and inflight entertainment installations, were postponed to maximize aircraft availability. The few available aircraft on the lease market were snapped up, and many airlines with the flexibility to extend leases did so.

The grounding has taken an estimated 41 million seats out of the industry through late October, flight schedules specialist OAG says. That adds up to lost revenue of more than $4 billion. But the tightening of capacity has also allowed airlines to command higher ticket prices on some routes, boosting unit revenues. The delay in MAX deliveries has also allowed operators to postpone hefty capital expenditures. Despite the crisis, some MAX operators have reported robust quarterly profits.

According to OAG, China Southern Airlines is the most affected MAX operator—with a loss of 3.6 million seats compared to its February schedule—followed by Air Canada and Southwest Airlines. Some carriers also have had their expansion plans interrupted. United Airlines, which was flying 14 MAXs and had planned to take delivery of 16 more by Oct. 1, has seen the grounding wreak havoc on its flight schedule, forcing it to cancel 1,290 flights in July, 1,900 in August, a projected 2,100 in September and 2,900 in October. The rising cancellations reflect a higher number of MAXs missing as planned deliveries are held up.

At Ryanair—an all-737 operator heavily dependent on a new, higher-capacity version of the 737-8 for expansion—major 2020 changes are already in the cards. It had planned on 50 new MAXs by next summer but now expects just 30. CEO Michael O'Leary says pilot and cabin-crew cuts as well as "some base closures" are inevitable.

While Ryanair is an extreme case—it planned to grow 7% next year, all using new MAX lift—other carriers will face increasing challenges if new MAXs are not flowing in before next year's peak summer period. "If you get to the next summer schedule and the lion's share of [the MAXs] aren't available, I can't imagine how that's not a big problem," says Epstein.

Another upcoming headache is how exactly the MAX will return to service once authorities have cleared commercial flights. Small airlines say their management resources are stretched so much during the peak summer season that they have no bandwidth to accept additional aircraft then. They will either take delivery in the winter or past the summer peak in the fall. They can also not take many aircraft at once. Boeing may very well be faced with many cases in which airlines disagree with its delivery plans that will likely emphasize clearing the backlog of parked aircraft as soon as possible.

How are suppliers handling this? Boeing's trimming of 737 production to 42 per month from 52 created little initial disruption, and initially provided some breathing room to a supply chain that was struggling to keep up with Boeing's plan to raise MAX production to 57 per month. And the segment most exposed to the MAX—aerostructures—is insulated by favorable payment terms Spirit AeroSystems negotiated with Boeing before the MAX crisis.

Ramifications are beginning to ripple through the supply chain as the MAX remains grounded, but many suppliers suggest they will get through largely unscathed as long as production ramps back up in the next six months. "Some but not all Leap 1B [737 MAX engine] suppliers have experienced rate cuts to levels below the 52/month headline rate," Cowen and Co. analysts said Aug. 6. "This reality raises the prospect that suppliers who have been insulated from cuts . . . may experience rate pressure as the MAX grounding delay extends."

CFM, a 50-50 joint venture between General Electric (GE) and Safran, originally kept delivering Leap 1Bs at the 52-per-month rate to catch up to Boeing's pace after lagging behind in 2018. It has since adjusted deliveries to match Boeing's rate.

The OEM's plan includes ratcheting 737 production back up in 2020, eventually hitting the 57-per-month rate that was targeted for this year. But the company acknowledges that any ramp-up will come only after the MAX is back in service and airline deliveries resume.

The uncertainty has left suppliers producing at various rates. The critical aerostructures segment is the most insulated. Boeing and Spirit AeroSystems have agreed to maintain 52-per-month production into early 2020. The deal—the only one of its kind publicly acknowledged by Boeing—means Spirit can keep paying its own suppliers to produce at the old rate, minimizing disruption and cash-flow pain. "There are a lot of small suppliers in the Wichita area that are heavily dependent on the 737 MAX," notes Glenn McDonald, a senior associate at AeroDynamic Advisory. "Going down in rate could harm them or even put some of them out of business."

The deal to stay at 52 per month has not left Spirit completely unscathed. It had hired and invested under the assumption it would be at 57 per month by now. The result: a 5% cut in costs, including some staff reductions, to get expenses back in line.

How will the MCAS change? Boeing's new MCAS software, version 12.1, adds three layers of protection to the previous design (see box, page 36). The new design includes a cross-channel bus between the aircraft's two FCCs, which now allows data from the two AOA sensors, or alpha vanes, to be shared and compared. "In a situation where there is erroneous AOA information, it will not lead to activation of [the] MCAS," says Boeing's Sinnett, who emphasizes that the entire speed trim system, including the MCAS, will be inhibited for the remainder of the flight if data from the two vanes varies by more than 5.5 deg. If an AOA disagreement of more than 10 deg. occurs between the sensors for more than 10 sec. it will be flagged to the crew on the primary flight display.

The second layer of protection is a change to the logic in the MCAS algorithm that provides "a fundamental robust check to ensure that before it ever activates a second time, pilots really want it to activate," says Sinnett.

The third layer of defense ensures pilots always retain some control-column authority to counteract MCAS nose-down stabilizer commands. "The column itself will always provide at least 1.2g of maneuvering capability," he says. "So you don't just have the ability to hold the nose level, you can still pitch up and climb."

What else on the MAX will change? In addition to MCAS-related flight control system changes, Boeing is making other updates at the FAA's request. The regulators' review of the MAX focused on the MCAS but did not stop there. One area of particular interest: safety analyses by Boeing that saw potentially troubling scenarios interrupted by pilot action. The FAA tested one such scenario in June, linked to a computer chip found in both the MAX and 737NG FCCs. The issue was not new, but rather one Boeing identified during certification as being both very unlikely to occur, and if it did, manageable by pilot intervention. The FAA wanted to see what would happen if the scenario did happen and tested it in a simulator. FAA pilots were not convinced that the failure would be recognized quickly enough and asked Boeing to make changes to reduce pilot workload.

A source with knowledge of the situation confirms that Boeing is reviewing similar scenarios that rely on pilot intervention and proactively making changes where possible, largely by using onboard systems, such as the second FCC, to add redundancy before pilot intervention is required.

Will MAX pilots be getting special training before they fly again? Yes. There will be a revamped set of differences training that will include, among other things, an explanation and videos on the MCAS system—the first time such training will be available to pilots. The FAA—relying on input from experienced 737 pilots—still must finalize the minimum required training for pilots to fly the MAX, including a general set of topics and, crucially, the instruction format.

Right now, pilots transitioning to the MAX from the 737NG are not required to spend time in the simulator, since one of the main reasons for reengining the existing design was to minimize design changes and therefore training, While the FAA has not finalized anything, simulator sessions are not expected to be part of the revised minimum-standards package. However, they will certainly be required as part of recurrent training and likely will focus on high pilot-workload scenarios, such as runaway stabilizer.

Outside the U.S., however, regulators and perhaps individual airlines may elect to go beyond the minimum requirements and mandate simulator sessions as part of MAX return-to-flight plans. In some cases, it may come down to simple perception: A MAX return that includes pilots going through the simulator sessions will be easier to sell to skeptics.

Will any other manufacturers benefit from Boeing's problems? It is hard to say. Boeing says it has not lost any MAX orders since the crisis started. Several carriers have reworked their MAX orderbooks, but those decisions appear to be driven more by the airlines' needs than concerns about the MAX. Airbus already holds a commanding 60% of narrowbody orders and has few narrowbody delivery slots available until 2023, save for some extra capacity in the smaller A220 product line.

In the long term, a loss in confidence in the MAX could lead to more Airbus orders. "The risk to Boeing is that MAX has become such a damaged brand that it could permanently lose even more market share than it already has," says Sash Tusa, an aerospace analyst at Agency Partners.

The MAX firm orderbook has been stagnant during the grounding. No new firm MAX orders have been booked by Boeing outside of a four-aircraft delivery-slot reshuffling that was offset by a four-aircraft cancellation.

More than 200 MAXs destined for Jet Airways were wiped out in April, days after the financially ailing carrier stopped flying. Airbus has added about 120 net firm orders to its A320neo backlog in the same time frame.

If the balance shifts too much toward Airbus, Boeing may have to rethink its product development strategy and start work on a MAX replacement sooner. Such a move could collide with the proposed new midmarket airplane (NMA) Boeing has defined as a necessary first step toward a new narrowbody because of the planned changes to its production system.

"We have long suspected that [the] NMA may really be a cover for a much wider program to replace [the] MAX, starting at the top end, where Boeing has lost most share to the Airbus A321, driven by the technical inadequacies of the 737 MAX," Tusa writes. "It would have been necessary to hide the program because making it public would immediately damage MAX sales. That is now much less of a consideration and was already headed that way given that long backlogs were already impacting orders."

The shock of not having one of the two current-generation workhorse narrowbodies available also could have other implications. "Maybe this is something that encourages the industry to have a third player," says Epstein. "It's a duopoly that has in its hand a big aspect of global growth. Is it good to have another player in another region of the world—not next week, but over time?"

Will the MAX situation change aircraft certification and global regulatory cooperation? It already has. The FAA's latest request to change flight control software beyond the MCAS came out of closer scrutiny of Boeing's safety analysis and related assumptions, for example.

Boeing 777X development and certification already appear to have been affected. The company is taking a very cautious approach to flight-test of the large widebody, delaying the start to ensure fixes being put into the new General Electric GE9X powerplants are flying on all test aircraft.

In the long term, the FAA and other regulators will continue to collaborate and rely on each other's analysis. But acceptance of each other's work—a critical method of sharing resources and safely streamlining certification globally—will likely involve many more questions than in the past. Those seeking to validate will want to be walked through the analysis and, if needed, have the supporting data to justify their trust. Expect this not just for agencies dealing with the FAA, but any agency seeking to accept another's technical analysis.

The FAA also faces scrutiny of its delegation program, which relies on industry's engineering expertise to help validate that products meet certification standards. Several studies are reviewing certification, and the National Transportation Safety Board is finalizing a set of recommendations.

—Joe Anselmo, Michael Bruno, Jens Flottau, Guy Norris, and Graham Warwick contributed to this report.

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