What happened?

## THE BOEING 737 MAX SAGA

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• Welcome to the machine

#### The Boeing 737

- Developed in 1960s
  - Take advantage of existing 707/727 tooling
    - Started life as a derivative design
  - Market was envisioned as one of unimproved airfields / developing countries
    - This drove single greatest architectural constraint: 737 sits very low to the ground
- Expansion of model variations has been primarily constrained by distance to the ground
  - Size of engines
  - Length of fuselage
- Primary engineering focus since first market has been
  - Increase passenger capacity w/out raising airplane
  - Increase fuel efficiency (larger engines) w/out raising airplane
- Does not attract "best and brightest" engineers w/in Boeing. Legacy & "not sexy."
- Largest contributor to Boeing's profits, by far

#### What we know about airplanes

- Over their economic lifespan, all successful commercial airliners do two things:
  - They grow in size. New models that carry more passengers
  - They adopt new technologies where the technologies lower seat/mile (fuel) costs
    - This is particularly true with engines and flight controls
- Because of decisions made early in the 737's life, accomplishing the above has been difficult compared to other airplanes
  - Sits too low to the ground to easily adopt to larger and larger engines
  - Sits too low to the ground to easily provide adequate takeoff and landing clearance when lengthened
  - Hampered by early autopilot architecture which is inherently non-redundant
- None of these constraints plague the Airbus A320 series (mid-1980s)

#### The Boeing 737

#### 737-100 (Original)

737 MAX 8





#### What we know about the MAX's competitor

- Airbus A320 series is a direct competitor to the 737 MAX
  - Nearly identical passenger capacity & seat-mile economics
  - *Started* life with the CFM<sub>5</sub>6 engine and much higher ground clearance
  - Started life with an extremely sophisticated "fly by wire" automation architecture that is far more capable, far more redundant and far more reliable than the system(s) in the 737
- Boeing was able to hold off A320 competition throughout the 1990s and 2000s
- With the emergence of the CFM LEAP engine, the 737 faced an existential crisis vs. the A320

#### The Airbus A320

A320-100 (Original)

A320neo



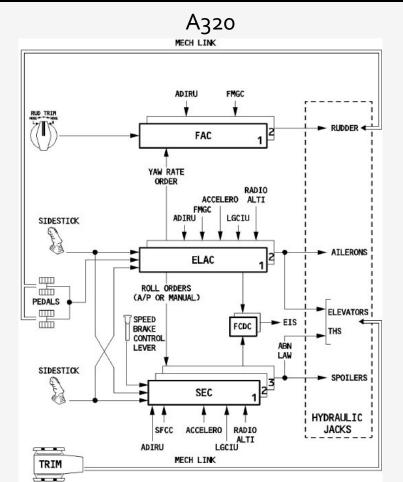
#### *The A320 vs. the 737*

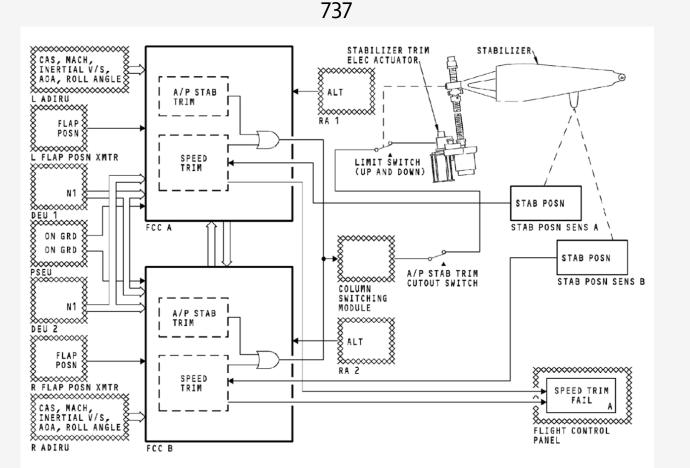


## Notes on the images

- Both the A320neo and the 737 MAX 8 use the CFM LEAP engine
  - However the LEAP engine on the MAX is a smaller version of the one used on the A320 Neo
    - Nonetheless, the nacelle still has to be "flattened" on the 737 MAX 8 to provide adequate ground clearance
- The engine thrust exit (exhaust) on the 737-100 is behind the wing. The thrust exit on the 737 MAX is in front of the leading edge
  - Pitch change difference w/power
- Thrust exit of the A320-100 and A320 Neo are nearly identical
  - No pitch change difference w/power over the development life of the A320 vs. 737
- Distance from bottom of wing (where engine is) to ground:
  - 737 MAX: Approx 8 feet
  - A320Neo: 12.4 feet

#### A320 vs. 737 flight control architecture





#### Notes on the architecture differences

- Flight control in A320 is done via:
  - Flight Augmentation Computers (FAC) (2)
  - Elevator/Aileron computers (ELAC) (2)
  - Spoiler/Elevator computers (SEC) (3)
- Flight control is not integrated with autopilot function
- FACs provide yaw damper function and autopilot rudder control
  - Pilot rudder control is manual (hydraulic)
- ELACs are double redundant. SECs are triple redundant
- SECs can provide elevator/stabilizer control if both ELACs fail
- Both ELACs and SECs can provide roll control
- Software in SECs not written by same entity that wrote software in ELACs (software heterogeneity)
- All external sensors (AOA, pitot, etc.) (ADIRU data) available to all ELACs and all SECs

- Flight control in 737 MAX is done via:
  - Flight control computers (FCC) (2)
- Flight control computers are not actually flight control computers. They are digital autopilot computers "hacked" to provide flight control functions such as speed trim and MCAS
- Only one FCC is "in charge" on a given flight. Other FCC exists only as a "hot standby" and each FCC can only see "its" sensors (two ADIRUS ("L" and "R") are connected to only "their" FCC).
  - Difficult to detect discrepancies
  - THIS IS WHY ORIGINAL MCAS IMPLEMENTATION ONLY USED ONE OF THE TWO AOA SENSORS ON 737
- There is a communication channel between the two FCCs
  - Boeing is NOW apparently going to use that channel to send AOA information from the "inactive" FCC to the active one
- No software heterogeneity

Easy to detect discrepancies

#### Notable difference #1 between A320 / 737

"Mechanical control of the trimmable horizontal stabilizer is available from the pitch wheel at any time, *if the green or yellow hydraulic system is functioning* 

Mechanical control from the pitch trim wheel *has priority over electrical control* " (source: AIRBUS TRAINING, FLIGHT CREW OPERATING MANUAL)

What does this mean?

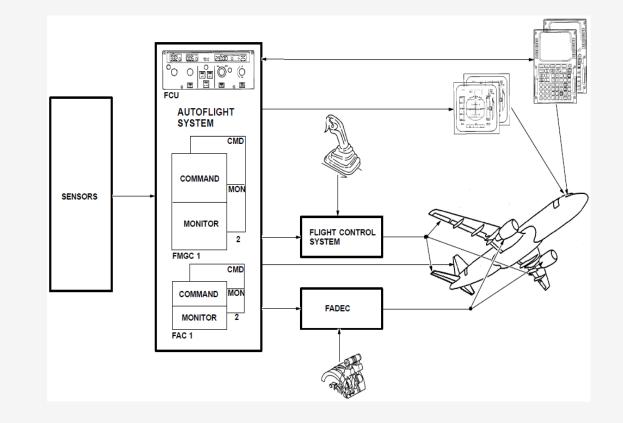
It means two things:

Even manual control of the stabilizer on the A320 is power-assisted (hydraulic). Would not have had the same issues as the Ethiopian 737 flight (aerodynamic forces made manual trimming impossible)
Touching the trim wheel on the A320 STOPS any automatic trim function (contrary to MCAS function)

THIS IS THE DIFFERENCE BETWEEN STEERING AND POWER STEERING IN A CAR. With regard to manual trim, the A320 has power steering. The 737 does not.

#### Notable difference #2 between A320 / 737

- In 737 "flight control" functions (such as MCAS) are incorporated in the autopilot computer
- In A320 "flight control" functions are completely separate from the autopilot
  - Autopilot has its own computers, called "Flight Management Guidance Computers" (FMGC)
- CRITICAL DIFFERENCE: A320 autopilot is subject to exact same "flight control" protections as the pilots are
  - The A320 autopilot NEVER drives the pitch or roll control surfaces directly. It can only drive them through the flight control system



#### What we know about the MAX's origin story

- 2010: Airbus announced A320neo ("New Engine Option") to use the CFM LEAP engine
  - At least 15% more fuel efficient than the previous A320 generation with CFM56 engine
  - Program cost ~\$1.3 billion estimated in 2010
  - First flight 2014
- Boeing initially shrugged it off saying "They're going to have trouble with that" (paraphrase)
- Several airlines began sending messages to Boeing that they were considering ordering new A320neos, instead of 737 NG ("Next Generation"). American in particular
  - How credible a threat this was is not clear
- Boeing looked at its options:
  - Develop a new airframe at expected cost of ~\$12 billion
  - Modify 737 NG airframe to accommodate CFM LEAP engine at expected cost of ~\$3 billion
- We know which option they chose

Source: https://www.flightglobal.com/news/articles/boeing-disputes-737-max-development-cost-report-367504/

#### Then they ran into a great big hassle (apologies to Steve Miller)

- Because of the radical change in engine mounting (Boeing already had experience with the changes in aircraft handling that come with a larger engine (CFM<sub>5</sub>6))
- With the CFM56, they modified the airframe itself with various aerodynamic hardware (vortex generators, larger surfaces, etc.) to mitigate the changes.
  - Those modifications are expensive in both time and money
- They anticipated similar issues with the CFM LEAP (their computer models indicated such)
- Apparently when they got to actual flight testing, they found the changes in aircraft handling to be far greater than they anticipated.
- From the outside, it appears they began to panic

#### Cultural Transformation @ Boeing

- Prior to 1997 McDonnell Douglas merger, Boeing had a bureaucratic/rational/engineering culture
  - Sequential development of "bet the company" airplanes
    - Very painful in short term
    - Very successful in long term (strategic)
- Prior to merger, McDonnell Douglas had a charismatic/irrational/financial culture
  - Focused relentlessly on milking existing airframes, not creating new ones
  - Lost its dominance and never recovered
- Pentagon essentially forced Boeing to acquire McDonnell Douglas so that it would not go out of business
- Terms of the merger heavily favored takeover of Boeing by McDonnel Douglas leadership
  - In particular, John McDonnell and Harry Stonecipher
- Transformation of Boeing began almost immediately

#### Mission confusion @ FAA

- FAA is saddled with a "dual mandate"
  - Regulate the aviation industry
  - Promote the aviation industry
- Congress tried to remove this dual mandate through legislation in 1996
  - However culture trumps strategy. Culturally the dual mandate has never disappeared
- Promotion of the industry gradually eroded the mandate to regulate the industry
  - FAA became very cozy with the manufacturers, often referring to them as "customers."
  - FAA very receptive to lobbying by the manufacturers
- Largest result of this was the development of the DER (Designated Engineering Representative) program and then the Organizational Delegating Authority (ODA) program in early 2000s
  - ODA effectively surrendered then entire certification and regulation function for large aircraft manufacturers to the manufacturers themselves

#### Technological Transformation in the industry

- Airbus pioneered all digital flight controls in commercial aircraft in the 1980s, with the A320
- For a long time Boeing resisted this technology, denigrating it as taking control away from the pilots
- Problem was: The airlines (Boeing's customers) want control taken away from the pilots
  - Increases safety
  - Decreases cost
- Boeing succumbed to customer pressure fully with the 787 Dreamliner
- Inflection point: The arrival of the commodity digital autopilot in early 2000s

Legacy constraints

- Everything about the 737 eventually leads back to:
  - How low it sits to the ground
  - Flight control architecture
- Both of which were determined fifty years ago
- And set in stone by the requirement to add each successive 737 to the original type certificate

#### Four seeds of demise...

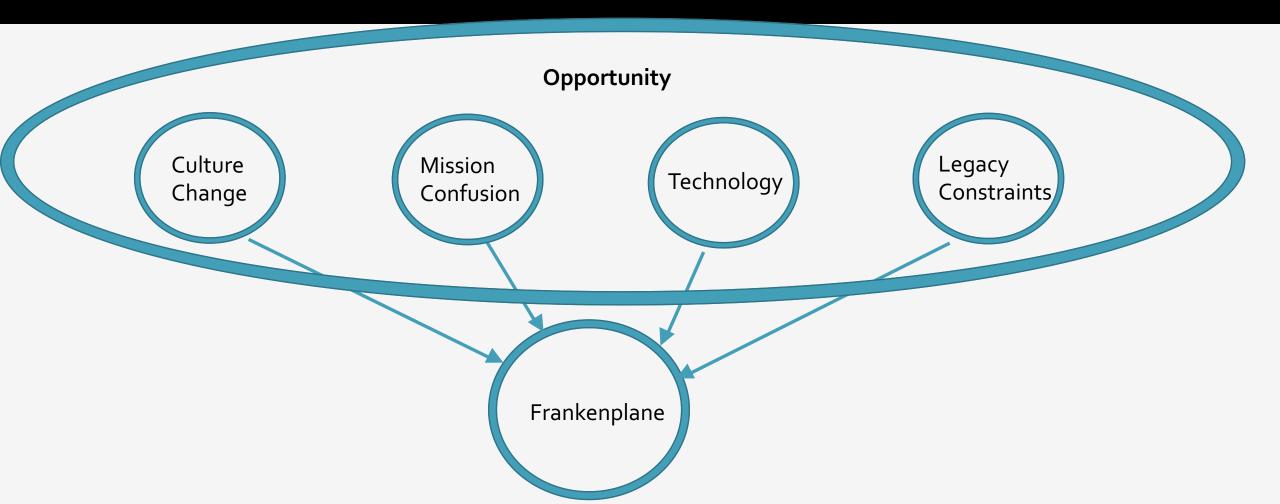
- In the early 2000s, Boeing had decided to replace the hybrid electromechanical/digital autopilot on the 737NG with a new "digital" autopilot (EDFCS-730)
  - A digital autopilot is one whose functionality is almost entirely defined by computer software, not hardware
  - This would produce great efficiencies and cost reductions going forward...
  - Due to its age, however, the 737 was not an appropriate platform for a digital flight control system
  - Cultural transformation @ Boeing allowed this engineering reality to be dismissed
- The ODA process allowed Boeing to hide the engineering defects from the FAA
  - Mission confusion @ FAA allowed Boeing to "self-certify" its own defective designs with no oversight
- The Rockwell Collins EDFMS-730, while never intended to perform a function like MCAS, became an extremely attractive platform for MCAS
  - Technological transformation introduced this option
- Need to grandfather onto existing type certificate
  - This locks in the legacy architectural constraints

#### Four seeds combined to produce a TINA mindset: There Is No Alternative Another word for that is *tragedy*.

# ... killed 346 people and destroyed the company

- Boeing's implementation of MCAS was fatally flawed:
  - Used untested, unverified and hastily-produced software of extremely low quality
  - Hid the details of the software and the whole MCAS system from not only the FAA but also its customers and its own test pilots
  - Architectural nightmare
    - Relied on data from a single sensor (AOA)
    - Did not check the data for sanity
    - "Lives" where it should not live (autopilot computers, not flight control computers (despite Boeing's misleading nomenclature))
    - Used sensor data to drive the most powerful control surface on the airplane at high speed
    - Through repeated actuations could drive that control surface to its stops.
      - Quickly rendered the aircraft uncontrollable by any pilot of any skill level

#### The tragedy of Frankenplane



## The tragedy of Frankenplane

- Competing against Airbus, Boeing again found it necessary to fit larger engines (CFM LEAP) to the 737
- They ran into the same aerodynamic issues they had run into when fitting the CFM56
- It looked like they would have to extend 737 MAX development and significantly increase cost to mitigate the problem "traditionally" (i.e. in hardware)
- They realized they had an option: The EDFCS-730 could be programmed to mask the aerodynamic issues and make them "go away"
- Cultural transformation at Boeing allowed this as an option
- Developed in a panic / chaotically
- Limits of communication between teams
- Increased complexity
- Result: FRANKENPLANE & failure modes not understood by anyone

#### Questions that you might have

- Don't all/most airplanes have some kind of flight augmentation similar to MCAS?
- Will Boeing's proposed fixes "fix" the MAX?
  - Related: Can/should software take care of aerodynamic issues in commercial airplanes?
  - Can software do it on the 737, given its architectural limitations?
- Why didn't the certification process catch this? What is the FAA's role?
- Boeing is making a convincing case that they developed and certified everything according to the rules. Why isn't that good enough?
- I've read that the pilots of the two planes that crashed both came from airlines with poor safety records. What role does maintenance and pilot skill play?

## Questions that I have

- How did this happen?
  - Why were the defects of MCAS not obvious to everyone in the company?
  - Why did no one say "this is going to kill a lot of people and it's going to kill our company?"
  - Why did the autopilot manufacturer, Rockwell Collins, not see this coming?
  - Why is there no accountability?
- Why is Boeing doing such a terrible job of public relations on this?
  - Why can't it get out ahead of the issue(s)?
- What long lasting effects on American institutions will this have?
  - The FAA
  - The aircraft industry
  - Global trade and competitiveness

#### WELCOME TO THE MACHINE

