WELCOME!

INCOSE Enchantment Chapter Monthly Meeting

We’re glad you’re here.

We respectfully request:

ComputerHope.com

- Mute your audio when you are not speaking
- *6 toggle or in GlobalMeet left-side, your name

Discussion and questions are encouraged!

Put questions in the chat box or unmute yourself to speak up.

Meeting Materials

Slide presentations can be downloaded prior to start of the meeting from the Meeting Materials page of our website:

https://www.incose.org/incose-member-resources/chapters-groups/ChapterSites/enchantment/resources/meeting-materials

If recording is authorized by speaker, the video will be posted at the link above within 24 hours.

SEP Training

CSEP Courses by *Certification Training International:*

CTI currently is offering online course offerings, see
https://certificationtraining-int.com/incose-sep-exam-prep-course/

Our chapter has two SEP mentors:
Ann Hodges alhodge@sandia.gov
Heidi Hahn drsquirt@outlook.com

Upcoming meetings

- April 14, 2021: Raymond Wolfgang – INCOSE's Guide to Verification and Validation: Context, Progress, and Content
- May 12, 2021: Cheryl Bolstad, Systems Engineering Human Factors

Introductions

- Please type your name, position, and organization in the Chat window

Photo by Adam Solomon on Unsplash

Survey

The link for the online survey for this meeting is

- www.surveymonkey.com/r/2021_03_MeetingEval

Your feedback is important!

Enchantment Chapter Monthly Meeting

Perspectives on the Boeing 737MAX Maneuvering Characteristics Augmentation System (MCAS)

Abstract: Using publicly available news articles and reports we examine the system design and characteristics of the Boeing 737MAX MCAS (Maneuvering Characteristics Augmentation System) in the context of two fatal crashes in 2018 and 2019. The rationale for the system is explained. The system architecture and operational characteristics are described. Hazard severity classification is examined, along with the required reliability per the regulations. The role of the pilots in compensating for failure is highlighted. The regulatory and business environments are also discussed as contributors. We describe how assumptions regarding pilot responses were apparently not validated, and contributed to the fatal crashes of the two airplanes. The human factors implications for automation, training, simulators and manuals are described. Ongoing modifications to the 737MAX, organizational design, and regulations are described.

The attendees will receive an overview of the MCAS including rationale, architecture, and operations during normal and failure conditions, and understand some consequences of the program and system design assumptions and implementation. Specific implications for the role of systems engineering are discussed

Download recording from the Library at www.incose.org/enchantment

NOTE: This meeting will *not* be recorded

Speaker Bio

Dr. Ron Carson is an Adjunct Professor of Engineering at Seattle Pacific University, an Affiliate Assistant Professor in Industrial and Systems Engineering at the University of Washington, a Fellow of the International Council on Systems Engineering and a certified Expert Systems Engineering Professional. He retired in 2015 as a Technical Fellow in Systems Engineering after 27 years at The Boeing Company. He is the author of numerous articles regarding requirements analysis, failure modes and effects analysis, and systems engineering measurement. His current interests are in quantitatively incorporating sustainability considerations in systems engineering methodologies and education. Dr. Carson has a PhD from the University of Washington in Experimental Plasma Physics, and a BS from the California Institute of Technology in Applied Physics. ronald.s.carson@gmail.com

Perspectives on the Boeing 737MAX MCAS

Ron Carson, PhD, ESEP, INCOSE Fellow

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2020 INCOSE Western States Regional Conference – Seattle, WA

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Outline

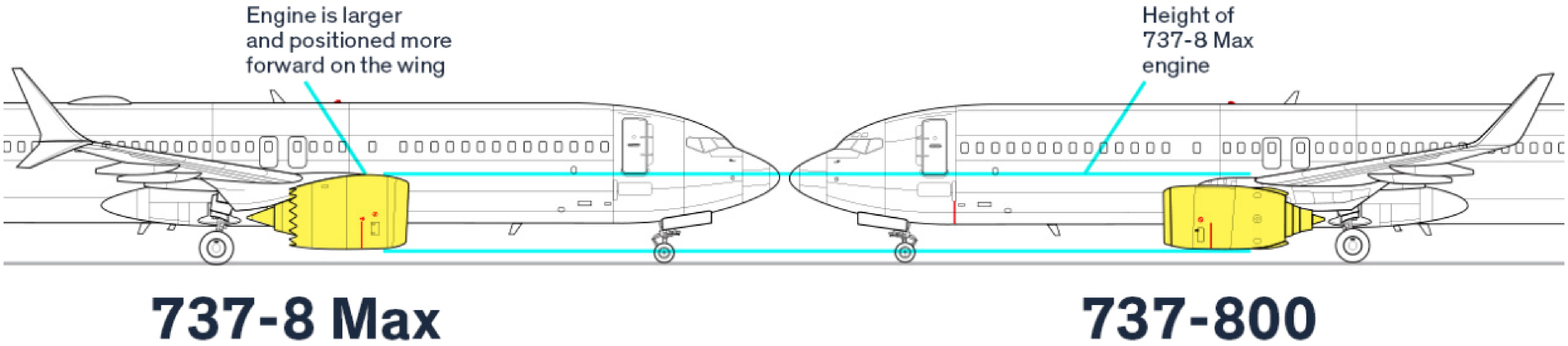
- Background of this presentation
- What / Why MCAS
- 737MAX Operation with MCAS
- MCAS system design and operation
- Failure severity classification and analysis
- Root-cause analysis
- Implications and Summary

- Reminder: no Boeing proprietary material (presentation or discussion)!
  - NOTE: Material marked “Boeing Proprietary” is from US Congressional Report from materials Boeing submitted

Background

- This presentation began as a special lecture for EGR4610, “Systems Design” (juniors and seniors) at Seattle Pacific University – see paper #4
- The objective was to demonstrate how several course topics come together…
  - Safety and reliability (failure rates, severity classification, redundancy, fault trees,)
  - Laws and standards (safety standards, especially ARP4761)
  - Human-systems integration (operator reaction to information, physical capability)
- ….And what can happen if we don’t get it right – our technical and ethical obligations
- This presentation augments the original course materials based on published reports as well as the original news and trade articles (Seattle Times, IEEE Spectrum)

What / Why MCAS –
Maneuvering Characteristics Augmentation System



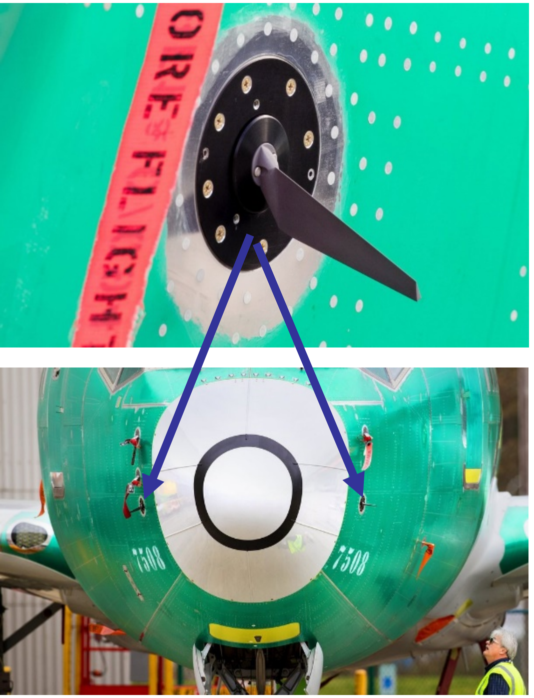
Engine is larger and positioned more forward on the wing
Height of 737-8 Max engine
737-8 Max
737-800

- MCAS is a software *Function* that was added to MAX family to limit tendency to “pitch up” at higher thrust levels (e.g., climbing from takeoff) because of more forward engine position
- “Pitch up” can lead to “stall” – loss of wing lift
- MCAS causes horizontal stabilizer to force nose down (“pitch down”) when a stall is being detected by existing Angle of Attack sensor(s)

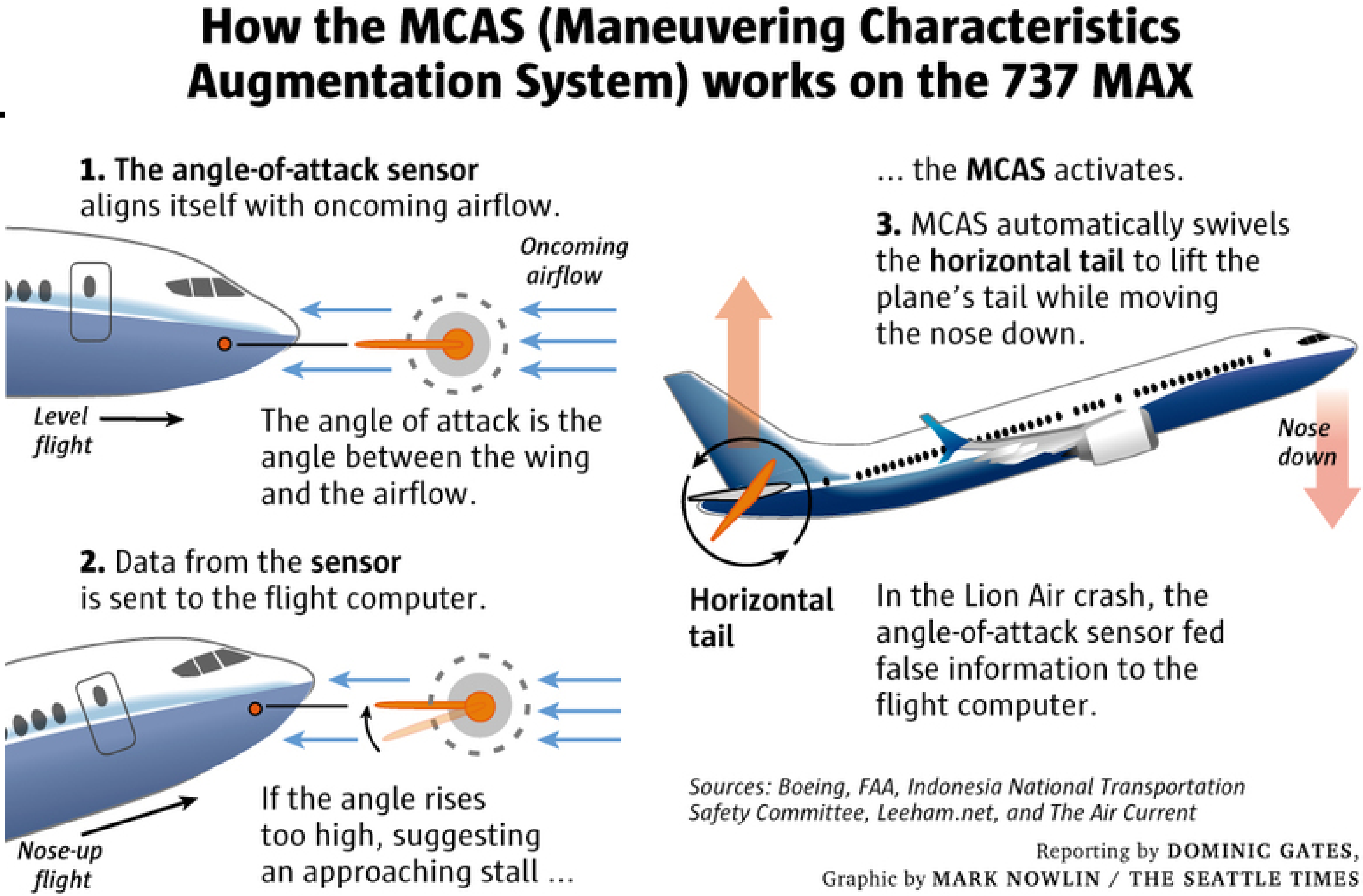
https://spectrum.ieee.org/aerospace/aviation/how-the-boeing-737-max-disaster-looks-to-a-software-developer

MCAS Operation

AOA Sensors



https://www.seattletimes.com/business/boeing-aerospace/a-lack-of-redundancies-on-737-max-system-has-baffled-even-those-who-worked-on-the-jet/



How the MCAS (Maneuvering Characteristics Augmentation System) works on the 737 MAX

1. The angle-of-attack sensor aligns itself with oncoming airflow.

The angle of attack is the angle between the wing and the airflow.

2. Data from the **sensor** is sent to the flight computer.

If the angle rises too high, suggesting an approaching stall …

… the **MCAS** activates.

3. MCAS automatically swivels the **horizontal tail** to lift the plane's tail while moving the nose down.

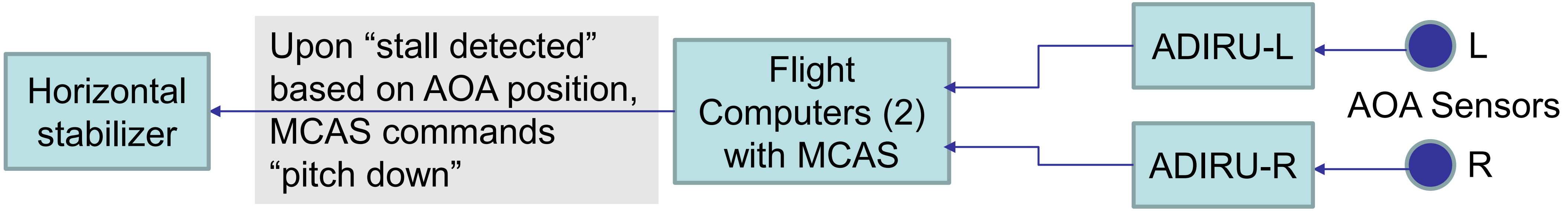
In the Lion Air crash, the angle-of-attack sensor fed false information to the flight computer.

Sources: Boeing, FAA, Indonesia National Transportation Safety Committee, Leeham.net, and The Air Current

Reporting by DOMINIC GATES,
Graphic by MARK NOWLIN / THE SEATTLE TIMES

https://www.seattletimes.com/business/boeing-aerospace/failed-certification-faa-missed-safety-issues-in-the-737-max-system-implicated-in-the-lion-air-crash/

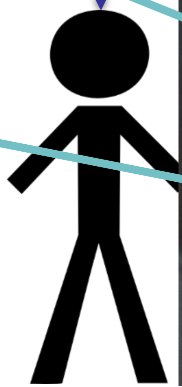
System Design and Operation

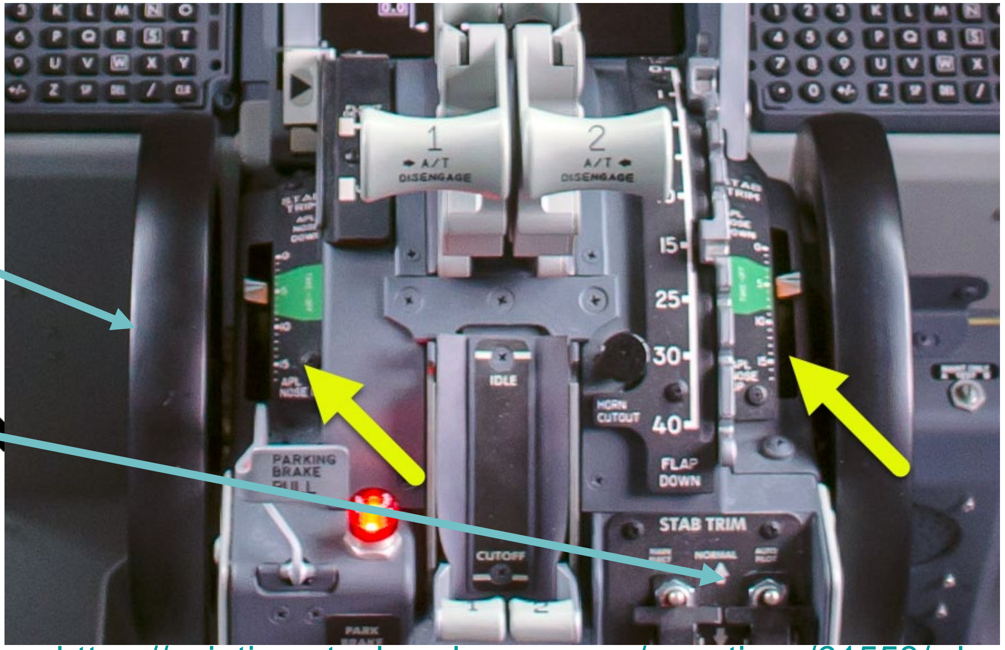

Horizontal stabilizer
Upon "stall detected" based on AOA position, MCAS commands "pitch down"
Flight Computers (2) with MCAS
ADIRU-L
ADIRU-R
L
AOA Sensors
R

MCAS software is hosted on the two Flight Computers

MCAS uses input from **ONE** AOA sensor, alternating between flights

- Single failure of AOA is not reported to pilots
- Erroneous AOA input can cause MCAS to announce "stall" and pitch nose down
  - Assumption: pilots would quickly recognize and could override MCAS by turning it <u>off</u> and manually control the horizonal stabilizer via the <u>wheels</u> on the center console
- Pilots
  - Don't know about MCAS (automation)
  - May react to erroneous stall warning by pushing nose down, **<u>as trained</u>**
  - May not be able to override horizontal stabilizer position because of forces at high speeds
- MCAS can self-reactivate (multiple pitch-down commands)





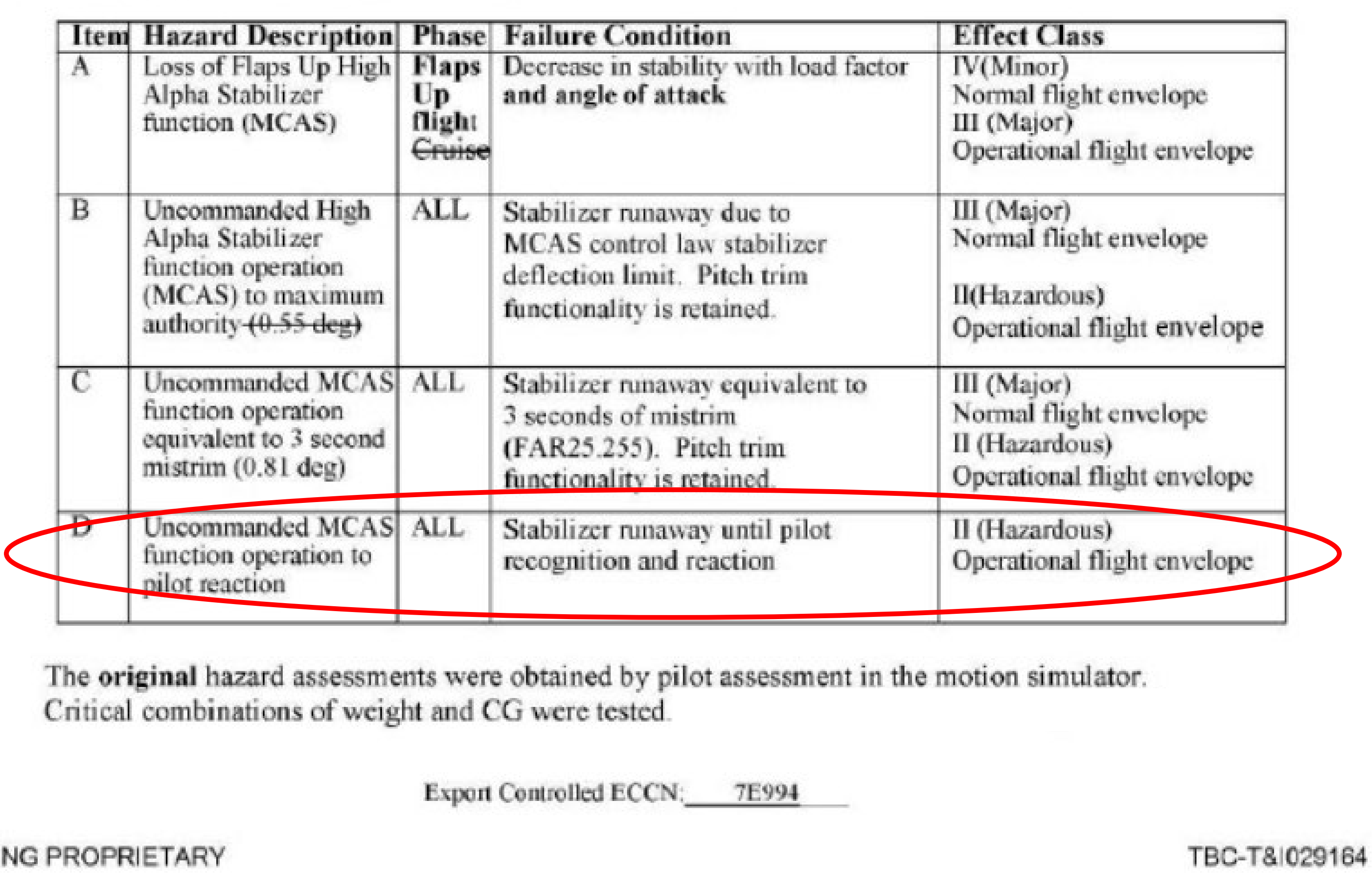
https://aviation.stackexchange.com/questions/61553/why-do-the-stabiliser-trim-wheels-not-move-exactly-in-sync

Relevant Severity Classification Basis: Can the Pilots Recover?

- "For the stabilizer runaways in the WUT [wind-up turn] maneuver (i.e. in the operational envelope) to the CLAW [structural] limit, the runaways were found Major [10^{-5}/hr*], and the 3 second runaways found Hazardous [10^{-7}/hr]. The Hazardous category was applied mainly due to the tendency to overspeed during the recovery rollout for those cases where the WUT was performed near the maximum operating speeds."….
- "With pilot training to recognize the runaway and use of teamwork, the failure was found Hazardous, which is the same as the item C finding. A typical reaction time was observed to be approximately 4 seconds. A slow reaction time scenario (> 10 seconds) found the failure to be catastrophic [10^{-9}/hr] due to the inability to arrest the airplane overspeed." [emphases added]

➢ Delay in pilot response is catastrophic

  ➢ Pilot ability to react to failure is a critical part of the system design



Item	Hazard Description	Phase	Failure Condition	Effect Class
A	Loss of Flaps Up High Alpha Stabilizer function (MCAS)	Flaps Up flight ~~Cruise~~	Decrease in stability with load factor and angle of attack	IV(Minor) Normal flight envelope III (Major) Operational flight envelope
B	Uncommanded High Alpha Stabilizer function operation (MCAS) to maximum authority ~~(0.55 deg)~~	ALL	Stabilizer runaway due to MCAS control law stabilizer deflection limit. Pitch trim functionality is retained.	III (Major) Normal flight envelope II(Hazardous) Operational flight envelope
C	Uncommanded MCAS function operation equivalent to 3 second mistrim (0.81 deg)	ALL	Stabilizer runaway equivalent to 3 seconds of mistrim (FAR25.255). Pitch trim functionality is retained.	III (Major) Normal flight envelope II (Hazardous) Operational flight envelope
D	Uncommanded MCAS function operation to pilot reaction	ALL	Stabilizer runaway until pilot recognition and reaction	II (Hazardous) Operational flight envelope

The **original** hazard assessments were obtained by pilot assessment in the motion simulator. Critical combinations of weight and CG were tested.

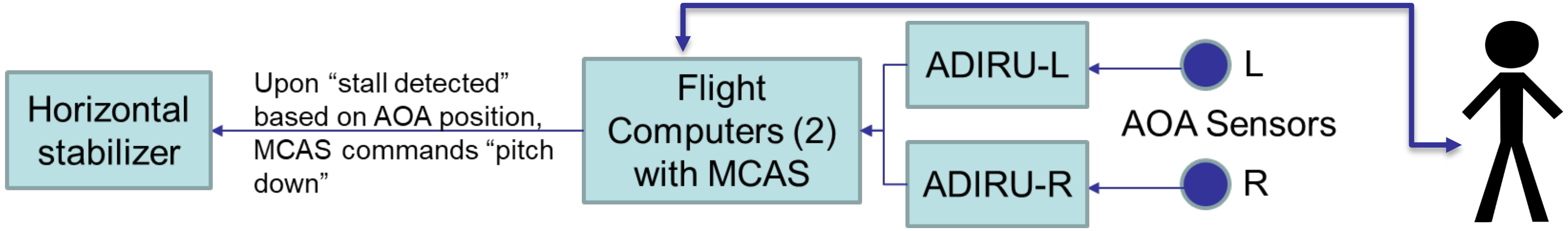
Export Controlled ECCN: 7E994

BOEING PROPRIETARY TBC-T&I029164

From Boeing Coordination Memo Aero-B-BB1\8-C12-0159, Rev. C, compiled in https://www.govinfo.gov/content/pkg/CHRG-116hhrg38282/pdf/CHRG-116hhrg38282.pdf as artifact TBC-T&I 029164-65 (footnote 46 of GOVPUB-Y4_T68_2)

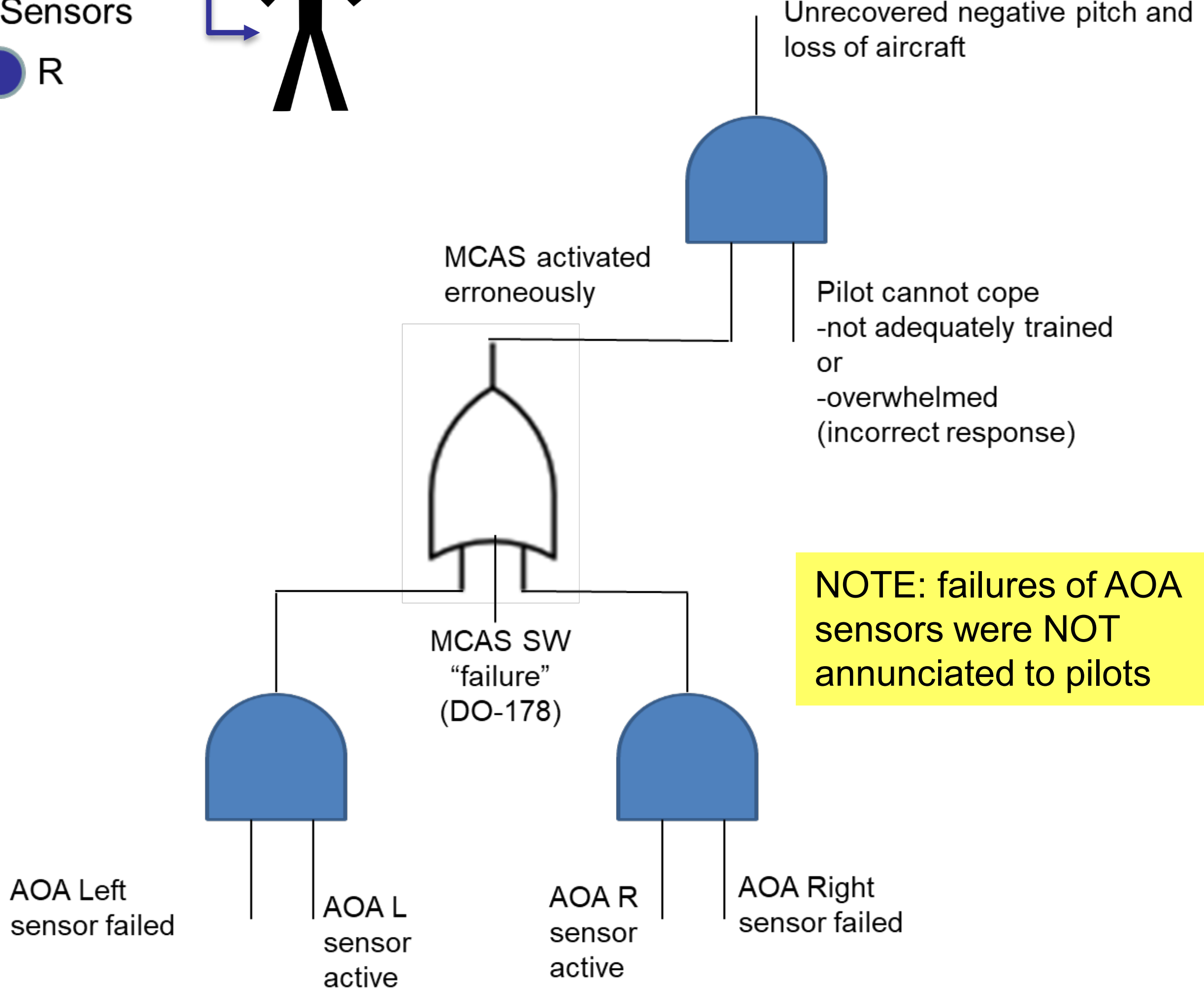
*Allowable failure rates from ARP4761, "**Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment**"

System Design: Fault Tree and Human Factors


Horizontal stabilizer
Upon "stall detected" based on AOA position, MCAS commands "pitch down"
Flight Computers (2) with MCAS
ADIRU-L
ADIRU-R
L
AOA Sensors
R

- Certification was Amended Type Cert (ATC): limits scope of analysis and test
- In assessing allowable failure rate, the scope of "MCAS" is critical (SW-only, or include existing hardware and pilots?)
- Flight manuals did not address MCAS (hidden automation)
- Training updates did not include MCAS or criticality of "runaway" response
  - No changes to simulator training

Partial Fault Tree



NOTE: failures of AOA sensors were NOT annunciated to pilots

Why did this happen? Root-cause analysis

- Three reports:
  - KNKT.18.10.35.04, “Aircraft Accident Investigation Report, PT. Lion Mentari Airlines, Boeing 737-8 (MAX); PK-LQP” (Republic of Indonesia) 29 October 2018
  - Joint Authorities Technical Review (JATR), “Boeing 737 MAX Flight Control System: Observations, Findings, and Recommendations Submitted to the Associate Administrator for Aviation Safety, U.S. Federal Aviation Administration October 11, 2019 [review of certification process]
  - US House Committee on Transportation & Infrastructure, “The Boeing 737 MAX Aircraft: Costs, Consequences, and Lessons from its Design, Development, and Certification - Preliminary Investigative Findings”, March 2020:
    1. “Production Pressures”
    2. “Faulty Assumptions”
    3. “Culture of concealment”
    4. “Conflicted Representation”
    5. “Boeing Influence over FAA Oversight”

“Production Pressures”

- Business context: 737MAX was developed in sales/delivery competition with Airbus A320neo with pressure to control costs, maintain schedule
- “Schedule” and business considerations contributed to “update” vs. new, leading to engine placement and resulting MCAS results
- “Boeing’s business objective for the 737 MAX from the start was to build an airplane that required no simulator training for pilots who were already flying the 737 NG.” [see footnote 21, p. 5 of US House report (Boeing internal e-mail, “Subject: 737MAX Firm Configuration Status/Help Needed,” May 4, 2013, (see “Differences Pilot Training” section), TBC T&I 048706-048708, accessed here: https://www.govinfo.gov/content/pkg/CHRG-116hhrg38282/pdf/CHRG-116hhrg38282.pdf p. 129)

“Faulty Assumptions”

- Pilot capability:
  - “Boeing’s own analysis showed that if pilots took more than 10 seconds to identify and respond to a “stabilizer runaway” condition caused by uncommanded MCAS activation the result could be catastrophic. The Committee has found no evidence that Boeing shared this information with the FAA, customers, or 737 MAX pilots.”
    - Also acknowledged by Boeing President David Calhoun interview (February 2020), https://www.king5.com/video/tech/science/aerospace/boeing/boeings-new-ceo-reacts-to-what-went-wrong-with-the-737-max/281-e0ebd2c3-8b66-4547-bb53-13985a179c02
  - “The 10-second reaction time and the potential for it to result in catastrophic consequences was discovered early on in the development of the 737 MAX program. [see footnote 46, p. 9 of US House report: Coordination Sheet—Revision D—TBC-T&I 029160–029166, accessed here: https://www.govinfo.gov/content/pkg/CHRG-116hhrg38282/pdf/CHRG-116hhrg38282.pdf]
  - “Multiple Boeing ARs were aware of these findings and never reported them to the FAA.”
- Training
  - “In July 2014, two years before the FAA made a decision regarding pilot training requirements for the 737 MAX, and at a time when the FAA was questioning Boeing on its presumption that no simulator training would be required, Boeing issued a press release asserting: “Pilots already certified on the Next-Generation 737 will not require a simulator course to transition to the 737 MAX.”[see footnote 51, p. 10 of US House report: “Boeing Selects Supplier for 737 MAX Full-Flight Simulator,” Boeing Press Release, July 11, 2014, accessed here: https://boeing.mediaroom.com/2014-07-11-Boeing-Selects-Supplier-for-737-MAX-Full-Flight-Simulator]
  - Updated simulator training was **not required** for pilots moving from NG to MAX configurations.

"Relax! I know this road perfectly!
I've been driving it all my life!"

https://www.shelterwood.org/wp-content/uploads/2014/01/Screen-Shot-2014-12-15-at-7.12.10-PM.png

“Culture of Concealment”: US House Report, page 3

- “In several critical instances, Boeing withheld crucial information from the FAA, its customers, and 737 MAX pilots. This included
- “hiding the very existence of MCAS from 737 MAX pilots [13] and
  - Note 13: Benjamin Shang, “Boeing’s CEO explains why the company didn’t tell 737 Max pilots about the software system that contributed to 2 fatal crashes,” Business Insider, April 29, 2019, accessed here: https://www.businessinsider.com/boeings-ceo-on-why-737-max-pilots-not-told-of-mcas-2019-4 .
- “failing to disclose that the AOA disagree alert was inoperable on the majority of the 737 MAX fleet, despite having been certified as a standard cockpit feature.[14] This alert notified the crew if the aircraft’s two AOA sensor readings disagreed, an event that occurs only when one is malfunctioning.
  - Note 14: Julie Johnsson, Ryan Beene and Mary Schlangenstein, “Boeing Held Off for Months on Disclosing Faulty Alert on 737 Max,” Bloomberg, May 5, 2019, accessed here: https://www.bloomberg.com/news/articles/2019-05-05/boeing-left-airlines-faa-in-dark-on-737-alert-linked-to-crash .
- “Boeing also withheld knowledge that a pilot would need to diagnose and respond to a “stabilizer runaway” condition caused by an erroneous MCAS activation in 10 seconds or less, or risk catastrophic consequences.[15]”
  - Note 15: Boeing Coordination Sheet, Revision D, 3/30/16 TBC-T&I 29160 – TBC-T&I 29166 at TBC-T&I 29166, accessed at p. 164 here: https://www.govinfo.gov/content/pkg/CHRG-116hhrg38282/pdf/CHRG-116hhrg38282.pdf .

“Conflicted Representation” (US House Report, page 4)

- “Boeing ARs failed to represent the interests of the FAA in carrying out their FAA-delegated functions.
  - “For example, at least one AR [Authorized Representative] concurred on a decision **not** to emphasize MCAS as a “new function” because of Boeing’s fears that “there may be a greater certification and training impact” if the company did and the Committee has no evidence the AR shared this information with the FAA.” [18] [emphasis in original]
    - Note 18: Boeing internal email, “Subject: PRG – 37MAXFCO-PDR_AI22 – MCAS/Speed Trim,” June 7, 2013, accessed at p. 93 here: https://transportation.house.gov/imo/media/doc/Compressed%20Updated%202020.01.09%20Boeing%20Production.pdf .
  - “In addition, the Committee has found no evidence to date that any Boeing ARs who were aware of the fact that Boeing had evidence suggesting a slow pilot reaction time to address a runaway stabilizer event caused by uncommanded MCAS activation could result in catastrophic consequences informed the FAA of this critical information.”
  - “The Committee also discovered that one AR who was aware that Boeing knowingly delivered aircraft with inoperable AOA Disagree alerts to its customers took no action to inform the FAA. Not all of these instances violated FAA regulations or guidance, but they indicate that Boeing ARs are not communicating with the FAA enough about issues of concern.”
- JATR, cover letter, p. 2: “The specific recommendations include reviewing whether the ODA process can be made less cumbersome and bureaucratic to avoid stifling needed communications…[and]... revisiting the FAA's standards regarding the time needed by pilots to identify and respond to problems that arise.”

Illustration by Robert Neubecker
https://compote.slate.com/images/13036372-e8b6-42ae-b6ca-e40b9900a6a9.jpg

“Boeing Influence Over FAA Oversight”

- [Overlaps “Conflicted Representation”]
- “In at least one instance, the FAA failed in its duty to hold Boeing accountable for violations of FAA regulations in the 737 MAX program.[20]
  - Note 20: “Letter from FAA Acting Administrator Daniel Elwell to Chair Peter DeFazio, July 11, 2019, (on file with Committee (regarding the mandatory installation of functional AOA Disagree alerts on all Boeing 737 MAX aircraft)).”
- Contributing: Limited FAA capacity and capability to independently evaluate information [JATR “Finding F5.2-A: There may be a lack of capacity and depth of experience of BASOO engineering members to approve and make findings of compliance for retained items.”]

https://vevscientific.com/wp-content/uploads/2019/03/Compliance.jpg

SW configuration error – not per requirements and approved design – violates DO-178

Summary: 737MAX Program Constraints and Actions

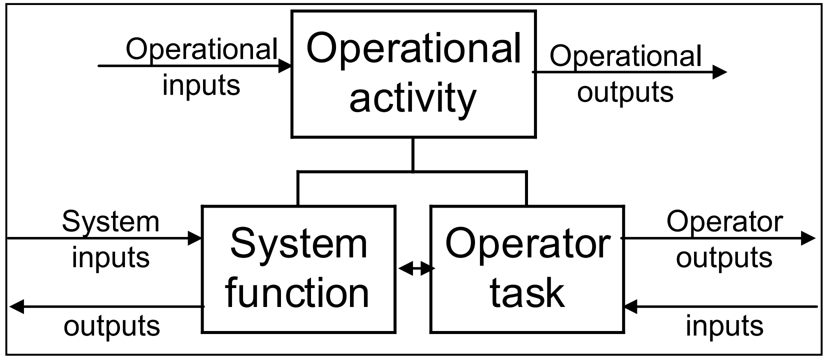
Program choice	Alternate choice	Rationale
Update 737, ATC	New, airplane TC	?
Retain fuselage and landing gear	Modify aircraft for larger engines	?
Define MCAS as “Speed Trim” addition (US House Rpt, p. 8)	MCAS as new system	?
Don’t disclose time-criticality of pilot response	Disclose time-criticality of pilot response	?
No new Simulator training	New simulator training	$1M/ airplane (SWA) (US House Rpt, p. 10)
Don’t disclose “Disagree Alert” inoperability	Disclose “Disagree Alert” condition	?
“Disagree Alert” not fixed immediately	Update/release new software	Planned release in MAX-10 update (US House Rpt, p. 8)

Results: Changes

- Regulatory: FAA Emergency Airworthiness Directive (AD) 2018-23-51 (7 November 2018) defined pilot procedures after Lion AIR crash
- Technical:
  - MCAS understood to be safety-critical
  - MCAS software updated to incorporate redundancy and “AOA disagree” alert – note: no hardware required to implement redundancy
  - Manuals and simulator training (mandatory) being updated
- Organizational
  - Boeing and FAA: JATR recommendations to review ODA process regarding FAA interaction with airplane manufacturers
  - Boeing internal structure: engineering to report separately from “project” https://www.nytimes.com/2019/09/15/business/boeing-safety-737-max.html

SE Implications

- **Incremental system design** (add or modify existing system) has inherent risks of overlooking an *emergent* (unplanned, unexpected, undesired) behavior (JATR, p. IV):
  - "The JATR team reviewed how the Changed Product Rule process was applied to the certification of the flight control system of the B737 MAX. The JATR team determined that the Changed Product Rule process was followed and that the process was effective for addressing discrete changes. However, the team determined that the process did not adequately address cumulative effects, system integration, and human factors issues. The Changed Product Rule process allows the applicant to only address in a limited way changed aspects (and areas affected by the change) and does not require analysis of all interactions at the aircraft level." [emphasis added]
- **Operators** must be considered as "part of the system" when they are relied upon for failure compensation
  - Operator requirements must be *validated* for feasibility of the functional allocation and required performance
- **Automation** can reduce workload, and can also create confusion because of incomplete information



Carson & Sheeley, "Functional Architecture as the Core of MBSE", Proceedings of INCOSE 2013.

Summary

- 737MAX is a tragedy on many levels
  - Passenger and crew lives lost
  - Boeing financial impact and reputation
- Many contributing causes
  - Primary issue is the baseline design that pilots would effectively cope with MCAS failure
- Continuous vigilance in safety is paramount
  - It’s not just about “complying with rules”
  - For engineers, “hope is not a plan”

Questions? In order, by category

1. Corrections of presented information based on public domain information
2. Questions requesting clarification of presented information
3. “What if” and “why” questions that require additional inference and/or speculation

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